

به نام خدا



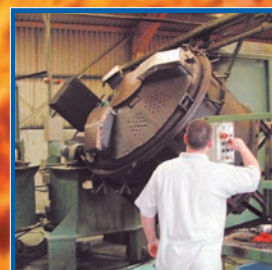
مرکز دانلود رایگان مهندسی متالورژی و مواد

www.Iran-mavad.com



Practical Guide to Rotational Moulding

Roy J. Crawford
and Mark P. Kearns



rapra
TECHNOLOGY

www.iran-mavad.com

مرجع دانشجویان و مهندسين مواد

Practical Guide to Rotational Moulding

by

R.J. Crawford and M.P. Kearns
Queen's University, Belfast

rapra
TECHNOLOGY

Rapra Technology Limited

Shawbury, Shrewsbury, Shropshire, SY4 4NR, UK

Tel: +44 (0)1939 250383

Fax: +44 (0)1939 251118

<http://www.rapra.net>

www.iran-mavad.com

مرجع دانشجویان و مهندسين مواد

The right of R.J. Crawford and M.P. Kearns to be identified as the authors of this work has been asserted by them in accordance with Sections 77 and 78 of the Copyright, Designs and Patents Act 1988.

© 2003, Rapra Technology Limited

ISBN: 1-85957-387-8

Cover images reproduced courtesy of ICO Polymers, Bonar Plastics, Caccia Engineering SpA, Clarehill Plastics Limited, Mold In Graphic Systems®, NOVA Chemicals, Persico SpA and Polivinil Rotomachinery SpA.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopying, recording or otherwise—without the prior permission of the publisher, Rapra Technology Limited, Shawbury, Shrewsbury, Shropshire, SY4 4NR, UK.

Typeset, printed and bound by Rapra Technology Limited.
Cover printed by LG Davis Design and Print Solutions, Birmingham.

www.iran-mavad.com

مرجع دانشجویان و مهندسين مواد

Contents

Preface	v
Chapter 1 – Introduction to the Rotational Moulding Process	1
1.1 Introduction.....	1
1.2 The Rotational Moulding Process	8
1.3 Overview of Rotational Moulding	16
1.4 Special Nature of Rotational Moulding.....	18
1.5 Advantages of Rotational Moulding	20
1.6 Disadvantages of Rotational Moulding.....	21
1.7 Common Applications for Rotomoulded Products.....	22
1.7.1 Material Handling Products.....	22
1.7.2 Industrial Products.....	23
1.7.3 Environmental Products.....	23
1.7.4 Leisure Products.....	24
1.7.5 Marine Products.....	24
1.7.6 Road Signage	25
Bibliography	26
Chapter 2 - Moulds	29
2.1 Introduction.....	29
2.2 Mould Materials	30
2.3 Sheet Steel.....	30
2.4 Aluminium.....	31
2.5 Electroformed Nickel	31
2.6 Comparison Between Mould Materials	32
2.7 Mould Design	33
2.7.1 Mould Frame	34
2.7.2 Moulded-in Inserts	35
2.7.3 Moulded-in Handles.....	36
2.7.4 Temporary Inserts.....	36
2.7.5 Movable Cores	37
2.7.6 Threads	38
2.7.7 Mould Venting.....	39
2.7.8 Mould Surface Finish	40
2.8 Mould Release	41
2.8.1 Mould Preparation for Release Agent	41
2.8.2 Reactive Systems.....	42
2.8.2.1 Spray-on Zinc Stearates	42
2.8.2.2 Silicones	42
2.8.2.3 Disiloxanes	42
2.8.3 Conventional Systems	43
2.8.4 Permanent Systems	43
2.8.5 Hybrid Systems	44
2.9 Mould Cooling	44
2.10 Mould Ancillaries	47
2.11 Moulding Aids.....	49
2.12 Kiss-Offs.....	51
2.13 Calculation of Charge Weight	52
Chapter 3 – Rotational Moulding Machinery	55
3.1 Introduction.....	55
3.2 Types of Rotational Moulding Machines	55
3.2.1 Carousel Machines	55
3.2.2 Shuttle Machines	57

3.2.3 Clamshell Machines	58
3.2.4 Rock and Roll Machines.....	61
3.2.5 Other Types of Machines	63
3.3 Mould Swing	66
3.4 Mould Speed.....	68
3.5 Speed Ratio	68
3.6 Oven Air Flow Amplification	69
3.7 Cooling.....	71
3.8 Developments in Machine Control.....	71
3.9 Internal Air Temperature Measurement in Rotational Moulding	72
3.10 Preparation of Rotolog for Moulding Trials	76
3.11 Monitoring Pressure Inside a Mould	80
Bibliography	87
Chapter 4 – Materials for Rotational Moulding	89
4.1 Introduction	89
4.2 Typical Characteristics of Rotationally Moulded Plastics	90
4.3 Materials Used in Rotational Moulding	90
4.4 Polyethylene	92
4.4.1 Low Density Polyethylene (LDPE)	94
4.4.2 High Density Polyethylene (HDPE)	94
4.4.3 Medium Density Polyethylene (MDPE)	94
4.4.4 Linear Low Density Polyethylene (LLDPE)	94
4.4.5 Metallocene Polyethylene.....	95
4.4.6 Ethylene-Vinyl Acetate (EVA)	95
4.4.7 Ethylene-Butyl Acrylate (EBA)	96
4.5 Polypropylene (PP)	96
4.6 Polyamides (Nylons)	96
4.6.1 Nylon 6.....	96
4.6.2 Nylon 11 and Nylon 12	97
4.6.3 Reaction Injection Moulding (RIM) Nylon.....	97
4.7 Amorphous Materials	97
4.7.1 Polyvinyl Chloride (PVC)	97
4.7.2 Fluoropolymers	97
4.8 Other Plastics.....	98
4.9 Additives Used in Rotational Moulding Materials.....	99
4.9.1 Fillers	99
4.9.2 Plasticisers	100
4.9.3 Lubricants	100
4.9.4 Stabilisers	100
4.9.5 Anti-Oxidants.....	100
4.9.6 Ultraviolet Stabilisers.....	100
4.9.7 Flame Retardants.....	101
4.9.8 Crosslinking Agents.....	101
4.9.9 Foaming Agents	101
4.9.10 Pigments	104
4.10 Powders for Rotational Moulding – Grinding or Pulverising	105
4.10.1 Introduction	105
4.11 Particle Size Distribution	111
4.12 Dry Flow.....	112
4.13 Bulk Density	114
4.14 Factors Affecting Powder Quality	115
4.14.1 Gap Size	115
4.14.2 Number of Mill Teeth	116
4.14.3 Grinding Temperature	116

4.15 Micropelletising.....	117
4.16 Colouring of Plastics for Rotational Moulding.....	118
4.17 Types of Pigments.....	121
Bibliography	123
Chapter 5 – Quality Control in Rotational Moulding	129
5.1 Introduction.....	129
5.2 Wall Thickness Distribution.....	129
5.3 Shrinkage	133
5.3.1 Shrinkage Guidelines.....	133
5.3.2 Control of Shrinkage	134
5.3.2.1 Effect of Release Point on Shrinkage.....	134
5.3.2.2 Other Factors Affecting Shrinkage	135
5.4 Warpage.....	136
5.4.1 Control of Warpage.....	137
5.5 Residual Stress	140
5.5.1 Short-Term Effects of Residual Stresses	142
5.5.2 Long-Term Effects of Residual Stresses	143
5.5.3 Cures for Residual Stress Problems	144
5.6 Surface Decoration.....	144
5.6.1 Painting	144
5.6.2 Hot Stamping.....	145
5.6.3 Adhesives	146
5.6.4 In-Mould Decoration	146
5.6.5 Post Moulding Decoration.....	150
5.7 Foaming in Rotational Moulding	151
5.7.1 Chemical Blowing Agent Technology.....	153
5.7.2 Design of Foamed Sections	154
5.7.3 Solid/Foam Cross-Sections	156
5.7.4 Solid/Foam/Solid Cross-Sections.....	156
Bibliography	158
Chapter 6 – The Future for Rotational Moulding.....	163
6.1 Materials.....	163
6.2 Moulds.....	164
6.3 Moulding Equipment.....	166
6.4 The Challenges	168
6.5 The Role that the Moulder Must Play.....	168
6.6 The Role that the Suppliers Must Play.....	169
Abbreviations and Acronyms	171
Index.....	173

Preface

Rotational moulding is becoming a highly sophisticated manufacturing method for plastic parts. New mould and machine features, and advanced process control technologies, are becoming available at regular intervals. This gives designers, and end users, access to new opportunities to create novel and innovative plastic mouldings.

The ever-changing nature of this industry means that it is very important for those involved in the manufacturing operation to keep abreast of the advances that are being made. The industry is becoming more competitive and customers are making increasing demands in terms of part quality and performance.

A characteristic feature of those in the rotational moulding industry is that there has always been a strong desire to utilise new technology and to be innovative in the use of new information. Throughout the world it has been evident that in this industrial sector there is a hunger for new information and a willingness to try new things.

In order to assist the industry to keep abreast of new developments, an “Advanced Hands-on Rotational Moulding Seminar” was developed at Queen’s University Belfast in the mid 1990s. The purpose of this 3-day seminar was to demonstrate the benefits of many of the new techniques that were becoming available to the industry. Moulders, material suppliers, machine and tool manufacturers all had the opportunity to see and try for themselves new technologies such as mould internal air temperature measurement, mould pressurisation, one shot foaming, etc.

Initially these seminars were held in Belfast, in English and in some other European languages. In the late 1990s the Association of Rotational Molders offered these Seminars in the USA and Canada and they have proved to be very popular in the industry. The key features of the seminars are that they combine presentations on the theory of new technologies with the opportunity to try the techniques on full-scale rotational moulding machines and moulds.

This book – *A Practical Guide to Rotational Moulding* – has arisen out of these seminars. It presents in simple language the basic nature of rotational moulding and includes information on the latest state of the art developments in the industry. A key feature of the approach is to use photographs wherever possible to illustrate the points that are being made. It is hoped that this approach will make the book useful to those new to the industry, as well as those who are experienced in some aspects of the process. It is also hoped that the highly visual approach will assist those whose first language is not English.

The contents of the book reflect the rotational moulding research activities of the Queen’s University of Belfast over a period of 25 years. We have also included new developments that have emerged from other sources. The authors do not claim ownership of the knowledge – we are reporting on the outcomes of many research theses at Queen’s University and on the innovative nature of many people in the industry. We acknowledge with gratitude the efforts of all the excellent research students that have worked for their PhD degrees in rotational moulding at Queen’s University – John Scott, Paul Nugent, Eileen Harkin-Jones, Alvin Spence, Stephen O’Neill, Kevin Walls, Wang Xin, Xu Liang (Linda), Wang Xiumin, Clara Cramez, Jorge Godinho, Michael Wright, Brendan Wisley,

Raquel Soares, Arnaud Robert, Gareth McDowell, Eunan O'Brien, Julia McDaid, Niamh Corrigan, Louise Pick, Edward Archer and Raji Khouri.

There have also been a very large number of Masters degree students and undergraduates who have contributed through their project work. These have all contributed to our understanding of the rotational moulding process. We are also grateful to Paul Nugent and Alvin Spence in their roles as the Managers of the Rotational Moulding Research Centre, during the period when we were getting established with our research investigations and seminar work.

We would also like to acknowledge the contribution and support from staff and colleagues at the Polymer Processing Research Centre (PPRC), in particular: Centre Director, Prof. Raymond Murphy; Process Engineers, Michael Murphy, Neil Callan, Mark McCourt and Paul Hanna; and Senior Laboratory Technician, John Kissick.

In the preparation of this book we have received very willing support from the following companies:

Association of Rotational Molders
Alan Yorke Engineering
Anchor Inserts
Atofina Chemicals Inc
Atlas Plastics
Borealis AS
Bonar Plastics
Ciba Speciality Chemicals
Chem-Trend
Chroma Corporation
Caccia Engineering SpA
Clarehill Plastics Limited
Dutchland Plastics Corp.
Equistar Chemicals
Ferry Industries Inc
Formed Plastics
ICO Polymers
Persico SpA
Kingspan
Maus GmbH
Mold In Graphic®
Norstar Aluminium Molds
Nova Chemicals
Rotation Magazine
Rototek Limited
Poly Processing Company
Pioneer Plastics
PPA Teo
Plastic Consulting Research Services
Polivinil
Roto Plastics Corporation
Reinhart Roto-Machines

Reduction Engineering
Sorcerer Rotational Moulding Machinery
SAT
Solar Plastics
STP Equipment
Wheeler Boyce

They have given freely of their time to assist us and to provide photographs for inclusion in the book. We thank you for all your help.

Finally we would like to thank Sally Humphreys at Rapra for her help. Sally had the original idea for the book and was very supportive, helpful and patient as we wrote the book and tried to retain some credibility in our day jobs.

Roy Crawford
Mark Kearns

June 2003

Chapter 1 – Introduction to the Rotational Moulding Process

1.1 Introduction

Rotational moulding, also known as rotocasting or rotomoulding, is a low pressure, high temperature manufacturing method for producing hollow, one-piece plastic parts. As with most manufacturing methods for plastic parts, rotational moulding evolved from other technologies. The basic principle of forming a coating on the inside surface of a rotating mould dates back for many centuries, but the process did not gain recognition as a moulding method for plastics until the 1940s. The ceramic pottery process, known today as ‘slip casting’, is depicted in ancient Egyptian, Grecian and Chinese art. In Switzerland in the 1600s, the formation of hollow objects, such as eggs, followed the development of chocolate from cocoa. A British patent issued to Peters in 1855 (before plastics existed) cites a rotational moulding machine containing two-axis rotation through a pair of bevel gears. It refers to the use of a split mould having a vent pipe for gas escape, water for cooling the mould and the use of a fluid or semi-fluid material in the mould to produce a hollow part.

The earliest commercial application of the concept of rotational moulding for plastics used vinyl plastisols to coat the inside surface of a hollow metal mould. Typical products included play balls and toy dolls. This process using PVC is still in widespread use today. In the 1950s the use of the rotational moulding process expanded more quickly due to the introduction of powdered polyethylene grades specifically developed for the process. Nowadays polyethylene accounts for over 90% of the total tonnage of plastics used in rotational moulding worldwide. This is mainly because the powder flow, melt flow and thermal stability of this material are ideally suited to the process.

Currently rotational moulding is a very competitive alternative to blow moulding, thermoforming and injection moulding for the manufacture of hollow plastic products. This is because it offers designers the opportunity to achieve the economic production of stress-free articles, with uniform wall thickness and potentially complex shapes.

Typical moulded parts include bulk containers, tanks, canoes, toys, medical equipment, automotive parts and ducts, as illustrated in Figures 1.1-1.11 and Section 1.7.



Figure 1.1 Rotationally moulded storage tanks
Courtesy of Poly Processing Co.

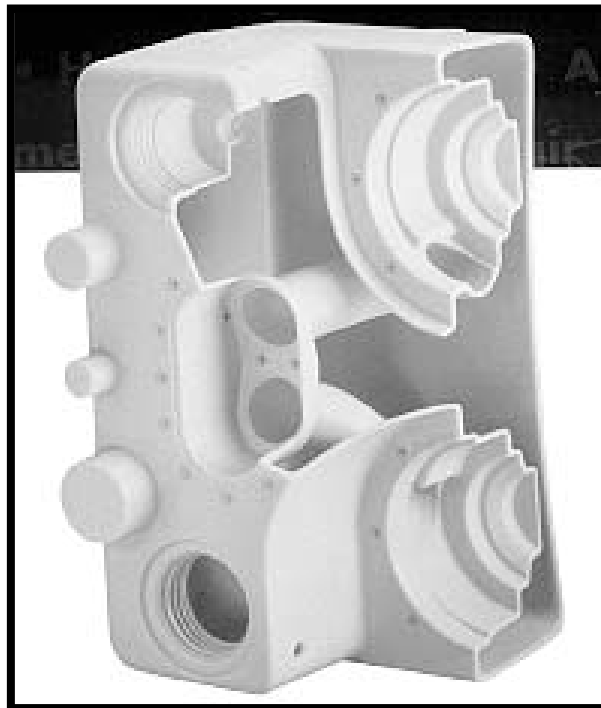


Figure 1.2 Cutaway section of complex rotomoulded part

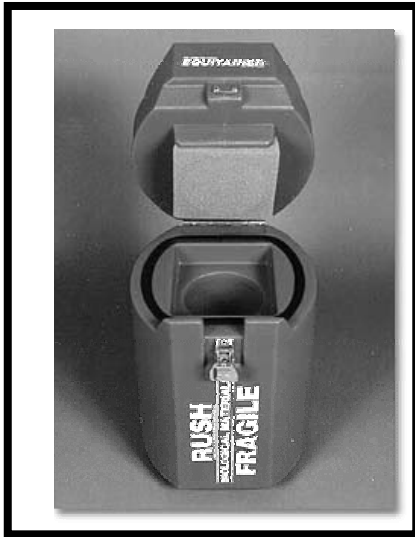


Figure 1.3 Biomedical housing
Courtesy of Formed Plastics Inc.

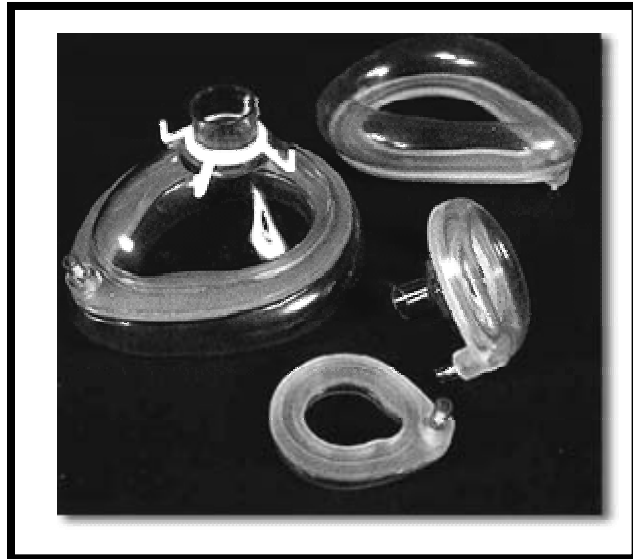


Figure 1.4 Rotomoulded PVC oxygen masks
Courtesy of Roto Plastics Corp.

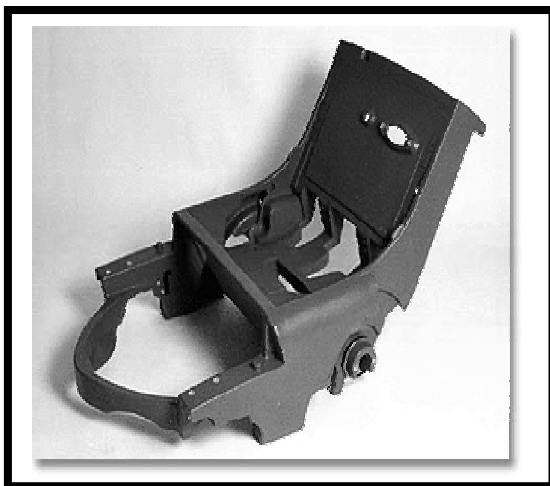


Figure 1.5 Cleaner housing
Courtesy of Pawnee Rotational Moulding Co.



Figure 1.6 Rotomoulded body of electric car
Courtesy of Bonar Plastics



Figure 1.7 Point-of-display items
Courtesy of Association of Rotational Molders



Figure 1.8 Protective casing
Courtesy of New England Plastics Corp.



Figure 1.9 Decorative items
Courtesy of Dutchland Plastics



Figure 1.10 Machine housing
Courtesy of Association of Rotational Molders



Figure 1.11 Painted PVC cowboy figurine

A drawback of rotational moulding is that the cycle times are relatively long compared to other plastic fabrication processes. Table 1.1 shows typical processing conditions, tooling costs and production rates associated with blow moulding, thermoforming and rotational moulding. In general, rotomoulding is best suited to applications where the volumes are not large. There are, of course, always exceptions to this generalisation and the versatility of rotational moulding means that nowadays it is being used in most market sectors. Over the past decade, rotational moulding has enjoyed the fastest growth rate of any manufacturing method for plastics, mainly because the economics are attractive to designers and as it is a low pressure process, the moulded parts are essentially stress-free.

Table 1.1 Comparison between blow moulding, thermoforming and rotational moulding			
Factor	Blow moulding	Thermoforming	Rotational moulding
Plastics available	limited	broad	limited
Feedstock	pellets	sheet	powder/liquid
Mould materials	steel/aluminium	aluminium	steel/aluminium
Mould pressure	<1 MPa	<0.3 MPa	<0.1 MPa
Mould cost	high	moderate	moderate
Wall thickness uniformity	Tends to be non-uniform	Tends to be non-uniform	Uniformity possible
Inserts	feasible	no	yes
Residual stress	moderate	high	low
Part detailing	very good	good, with pressure	adequate
In-mould graphics	yes	possible	yes
Cycle time	fast	fast	slow
Labour intensive	no	moderate	yes

It is difficult to get precise figures for the size of the rotational moulding market due to the large number of small companies in the sector. In 1995, the North American market was estimated to be about 800 million pounds (364 ktons), this figure was estimated to be around 1 billion pounds (455 ktons) in 2001. The corresponding 1995 figure for Europe was a consumption of 101 ktons and this had risen to 173 ktons by 1998. In 1997, the North American market had a value of about US\$1650 million and for most of the 1990s, the US market grew at 10% to 15% pa, spurred on primarily by demand for outdoor products such as chemical tanks, children's play furniture, kayaks, canoes, and mailboxes. In the latter part of the 1990s the North American market growth slowed to single figures (around 7%) but still represented an estimated market value of over US\$2100 million. Independent analysts saw this as a temporary dip and explained it in terms of a readjustment of market sectors and increasing competition from other sectors. The distribution of rotomoulders worldwide is illustrated in Figure 1.12. The number of rotomoulders in each region is estimated in Figure 1.13.

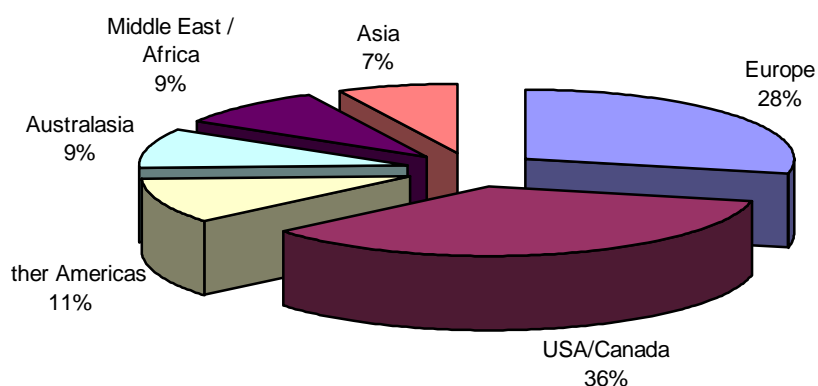


Figure 1.12 Rotomoulders worldwide (region by percentage)

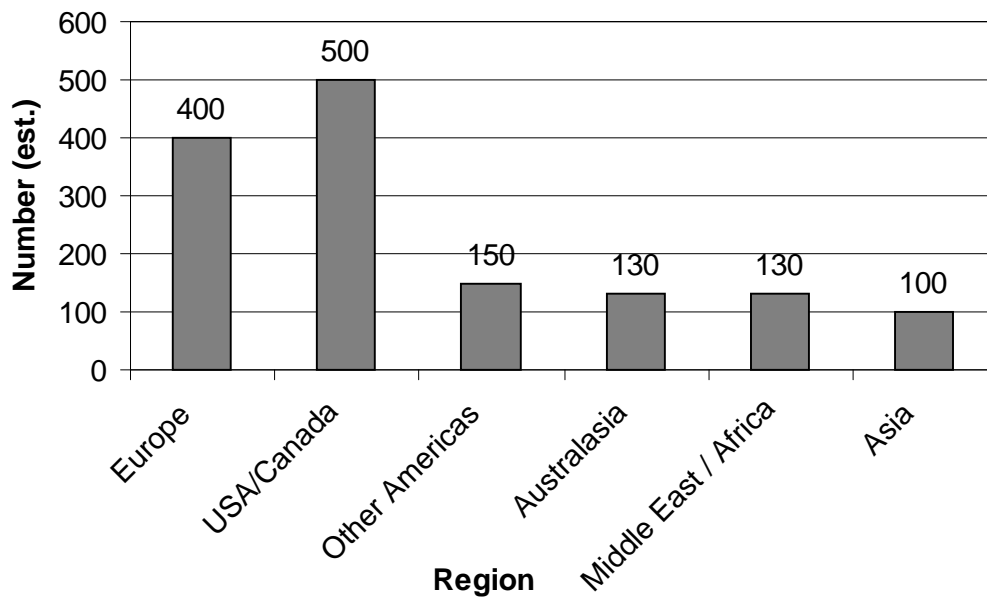


Figure 1.13 Number of rotomoulders worldwide

In North America the toy industry took to the rotational moulding process in a big way, representing over 40% of the consumption in that part of the world in 1995, this declined gradually to around 20% in 2001 with tanks now leading at 27% (as shown in Figure 1.14). In Europe (see Figure 1.15), the nature of the market has always been different, with toys representing less than 5% of the consumption and other sectors such as containers, tanks, etc., tending to dominate.

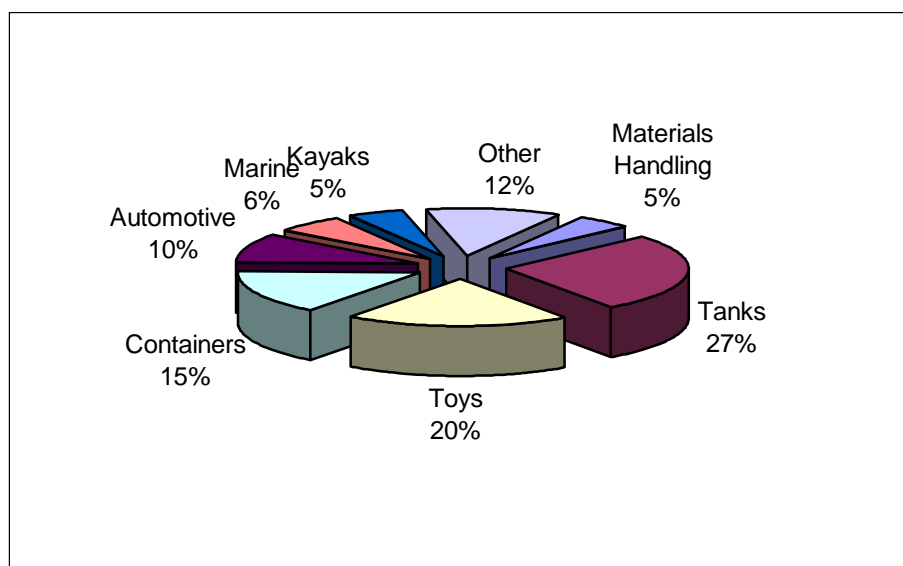


Figure 1.14 North American market sectors by product type

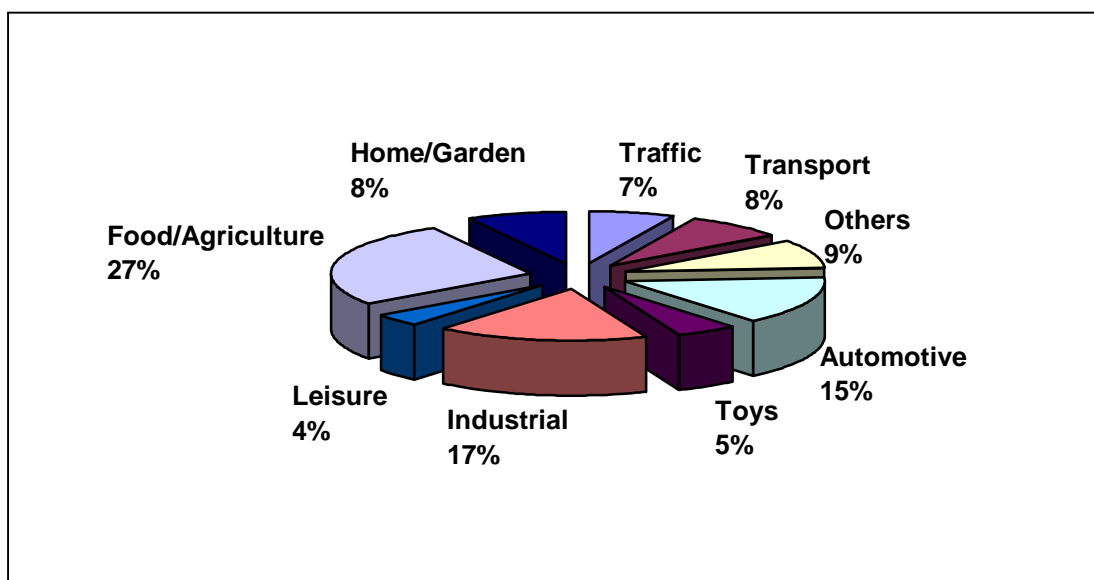


Figure 1.15 European market sectors by product type

1.2 The Rotational Moulding Process

The various stages in the rotational moulding process are shown in Figure 1.16 and Figures 1.17a – 1.17m.

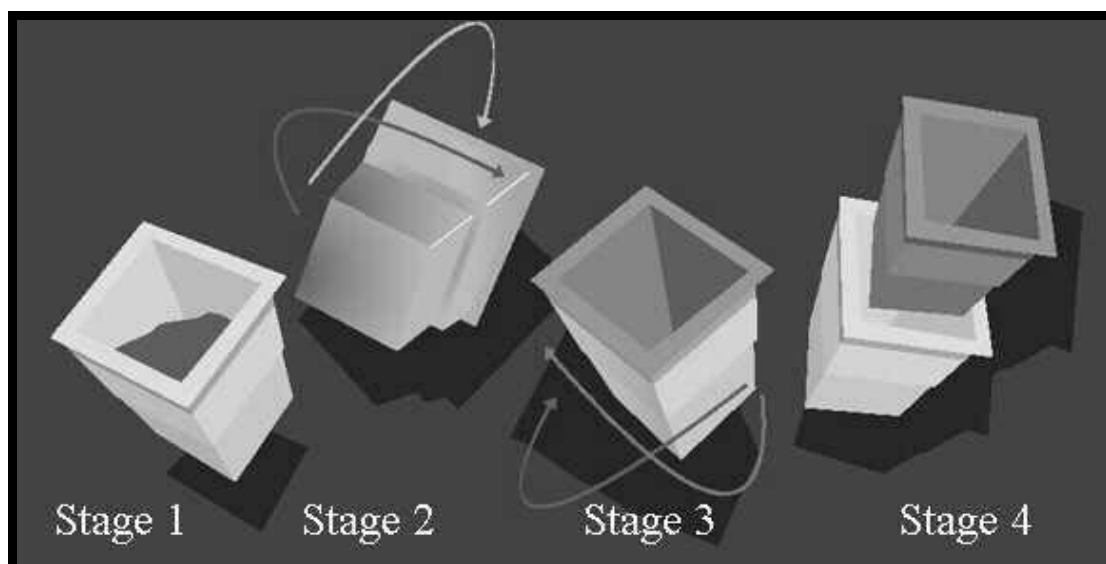


Figure 1.16 The four main stages of the rotational moulding process

In Stage 1, a hollow metal mould (at room temperature) is charged with a predetermined quantity of powdered (or liquid) plastic, which is equal to the desired part weight. The size of the charge can be determined on the basis of the surface area of the mould, the required thickness of the final moulding and the density of the plastic. An important advantage of

rotational moulding is that there is no material wastage – all the plastic placed in the mould is used to make the part.



Figure 1.17a Operator begins charging mould



Figure 1.17b Powder pouring into mould



Figure 1.17c Clamping of mould



Figure 1.17d Securing clamp

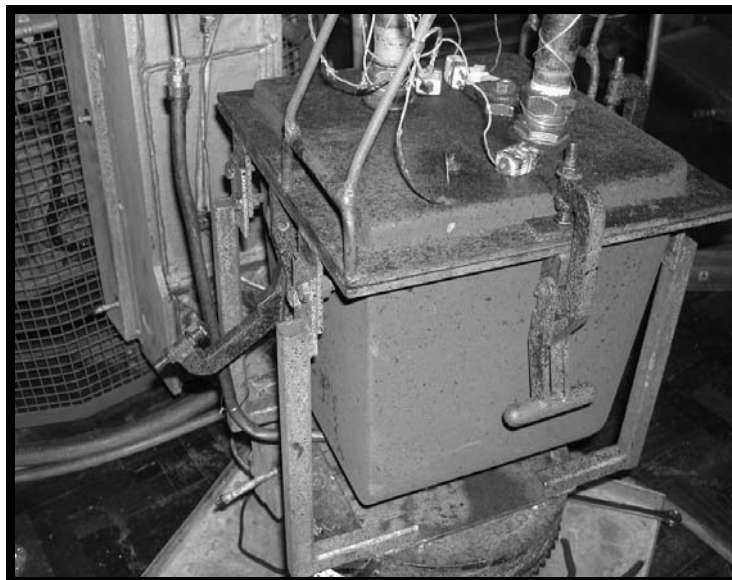


Figure 1.17e Top of mould is attached and clamped

In Stage 2, it can be seen that the other half of the mould has been clamped into position and the mould begins to rotate in a heated environment. This is often a hot air convection oven, but the mould could be heated by a variety of methods that include electricity, infrared, hot oil or open flames.

It is important to note that the mould rotation is relatively slow – typically up to 12 rev/min. Thus the process should not be confused with centrifugal casting in which the mould rotates at high speed and the plastic is thrown out against the mould wall. Although it might be attractive to rotate the mould at high speeds to increase productivity, the complex shape and size of moulds do not permit this. In rotational moulding, the plastic lies in the bottom of the mould and as the heated mould rotates, all points on the surface of the mould dip into the powder pool and pick up molten plastic. By altering the speeds of rotation about the perpendicular axes of rotation it is possible to control the wall thickness of the end product. Areas that need to be thick should enter the powder pool more regularly than other parts of the mould surface.

The ratio of the speeds about the two axes can be set to different values, depending on the shape of the plastic part. The speed ratio is the speed of the major (arm) axis divided by the speed of the minor (plate) axis. A speed ratio of 4:1 is commonly used to get a uniform wall thickness part. If it is desired to get a uniform wall thickness moulded part, a good practical way to get the correct speed ratio for a new mould is to put in the mould just enough powder to achieve a thin film coating over the entire surface of the mould. Different speed ratios can then be investigated in order to ensure that all parts of the mould surface are adequately coated. When the full charge of material is used, this should give a uniform thickness part. Alternatively, computer simulation programs such as RotoSim (see Section 2.13) can be used to determine the correct speed ratio before the mould is set up on the moulding machine. The importance of using the correct speed ratio is discussed later.



Figure 1.17f Arm with mould & Rotolog™ moving into oven



Figure 1.17g Arm begins to rotate as oven doors close

The basic rotational moulding process involves heating of plastic powder, or liquid, through the increase in temperature of the rotating mould. When the temperature of the inside surface of the mould becomes high enough, the plastic starts to adhere to it. As the mould continues to rotate, the cavity will pass through the pool of plastic material again and again, until all of the plastic material has been deposited onto the inside surface of the mould.

In Stage 3, the hot mould is removed from the oven and the cooling cycle begins. Figure 1.17h shows the mould in the cooling bay. The mould continues to rotate during this stage and cooling is usually assisted by high velocity air and sometimes a fine water spray is

used to increase the cooling rate after the plastic has solidified. If water cooling is used too early then the moulded part may become warped or distorted. This is explained later.

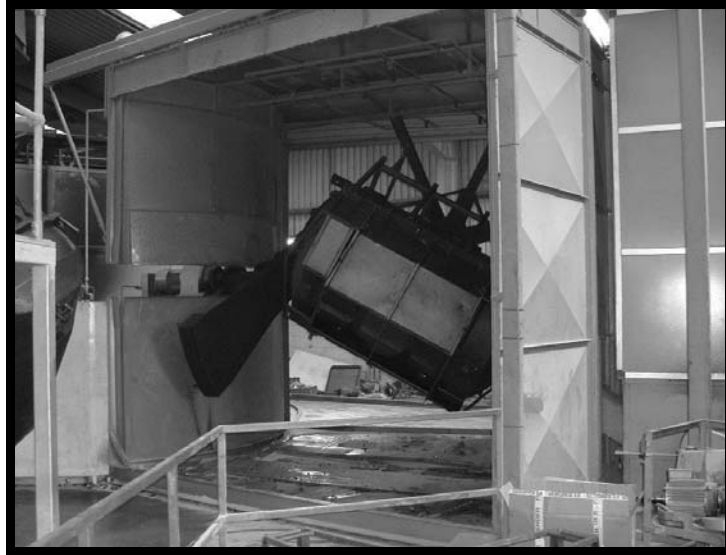


Figure 1.17h Tank mould in cooler
Courtesy of Clarehill Plastics Limited

As the plastic material cools, it changes from being a viscous liquid to a semi-solid, and finally into a solid part. Once the part has cooled sufficiently, the mould can then be opened. In Stage 4 (Figure 1.16), the finished part is removed from the cooled mould (see Figures 1.17k – 1.17l) and the process can be repeated.



Figure 1.17i Mould in demoulding bay being rotated into a convenient orientation to assist demoulding
Courtesy of Clarehill Plastics Limited



Figure 1.17j Removal of mould-in insert holder
Courtesy of Clarehill Plastics Limited



Figure 1.17k Lid removal using a crane
Courtesy of Clarehill Plastics Limited



Figure 1.17l Final part removal from mould
Courtesy of Clarehill Plastics Limited



Figure 1.17m Moulding ready for finishing operations
Courtesy of Clarehill Plastics Limited

1.3 Overview of Rotational Moulding

Modern rotational moulding is characterized as being an atmospheric pressure process that begins with fine powder and produces nearly stress-free parts. It is an essential requirement that the plastic withstands elevated temperatures for relatively long times. As no pressure is used in forming the plastic, rotational moulds usually have thin walls and can be relatively inexpensive to fabricate. For simple parts, mould delivery times can be days or weeks. Modern, multi-armed machines allow multiple moulds of different size and shape to be run at the same time. With proper mould design, complex parts that are difficult or impossible to mould any other way, can be rotationally moulded. With proper mould design and correct process control, the wall thickness of rotationally moulded parts is quite uniform, unlike structural blow moulding or twin-sheet thermoforming. And unlike these competitive processes, rotational moulding has no seams or weld lines.

Although the rotational moulding process has numerous attractive features it also has limitations. The most significant limitation is the shortage of materials that are amenable to rotational moulding. In theory it should be possible to rotomould any plastic that melts when heated, and goes solid when cooled. In practice, most plastics degrade during rotational moulding. This is primarily due to the severe demands placed on the polymer due to the prolonged periods at high temperatures. Rotomoulding grades of most plastics could be made available but the material suppliers will not invest in the development costs until the market is guaranteed. And of course it is difficult to be confident about market projections until the material is available. Where special resins have been made available, the prices are high, due to the development costs that are passed through to the user, and the additional cost of small scale grinding of the plastic granules to powder. Figures 1.18 and 1.19 show examples of polyurethane and PVC rotomoulded parts.



Figure 1.18 Polyurethane rotomoulded head

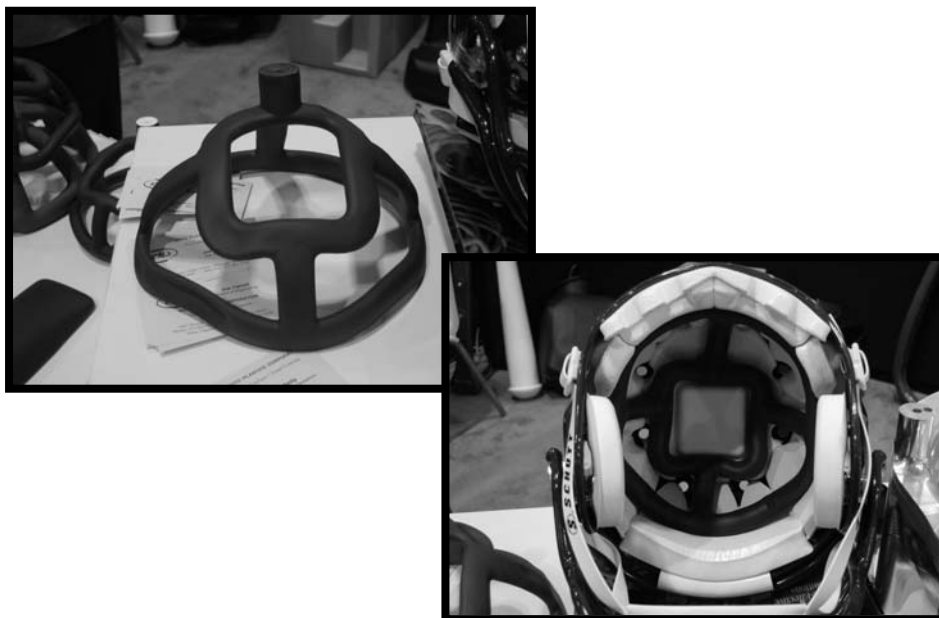


Figure 1.19 PVC protector for sports helmet
Courtesy of Roto Plastics Corporation

Another challenge that the rotomoulding industry must face is getting designers familiar with the basic nature of rotational moulding. Most designers are very familiar with injection moulding, blow moulding and thermoforming and know how to design for manufacture with these processes. In general, designers are less familiar with rotational moulding and so are less confident about the features that can or cannot be rotomoulded. For example, some of the basics that part designers must adjust to in rotational moulding include the use of generous radii and relatively coarse surface textures imposed by the process. Also, ribs cannot be used in rotomoulded parts and so other less common stiffening features such as corrugations or ‘kiss-off’ sections must be used. However, complex one piece parts can be rotomoulded – note the internal grids and other features in the rotomoulded roof tile shown in Figure 1.20.

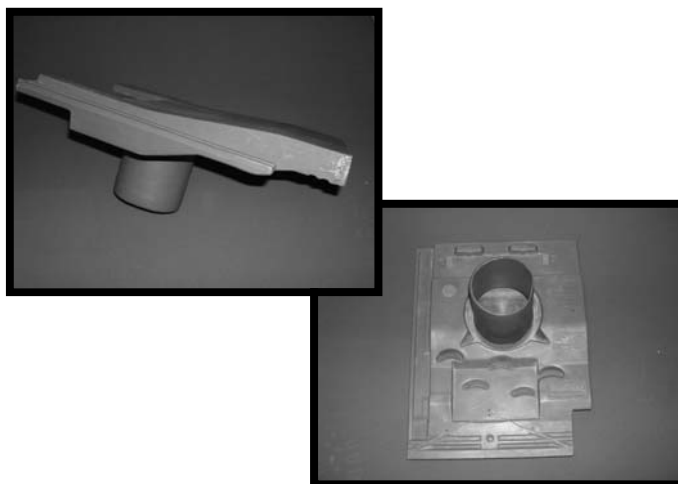


Figure 1.20a Vented roof tile

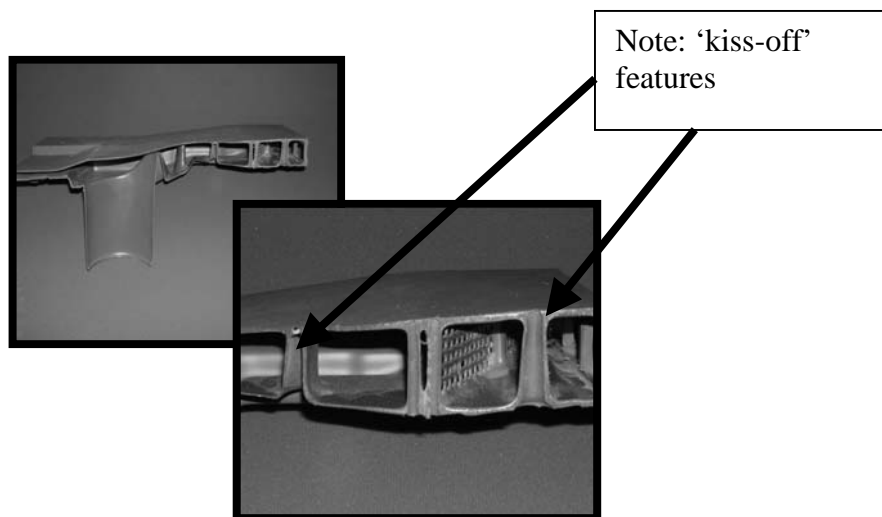


Figure 1.20b Cross-section of roof tile showing kiss-off detail
Courtesy of Rototek Limited

1.4 Special Nature of Rotational Moulding

Rotational moulding is a unique manufacturing method in that the plastic starts at room temperature and it is placed in a mould that is also at approximately room temperature. The whole assembly is then heated up to the melting temperature for the plastic, and subsequently it must be cooled back to room temperature. When the mould rotates in the oven, its metal wall becomes hot, and the surface of the powder particles becomes tacky. The particles stick to the mould wall and to each other, thus building up a loose powdery mass against the mould wall (see Figure 1.21). A major portion of the cycle is taken up in coalescence of the loose powdery mass until it is a homogeneous melt. The irregular pockets of gas that are trapped between the powder particles slowly transform themselves into spheres and under the influence of heat over a period of time they disappear. These pockets of gas, sometimes referred to as bubbles or pin-holes, do not move through the melt. The viscosity of the melt is too great for this to happen, so the bubbles remain where they are formed and slowly diminish in size over a period of time (see Figure 1.22).

Normally the only controls on the process are the oven temperature, the time in the oven and the rate of cooling. Each of these variables has a major effect on the properties of the end product. If the oven time is too short, or the oven temperature is too low, then the fusing and consolidation of the plastic will not have time to complete. This results in low strength, low stiffness and a lack of toughness in the end product. Conversely, if the plastic is heated for too long, then degradation of the plastic will occur and this results in brittleness. In a commercial production environment the optimum 'cooking' time for the plastic often has to be established by trial and error. A practical 'tool' used by moulders is to look at the extent to which there are pin-holes in a small shaving taken through the thickness of the part. If there are no pin-holes then there is a danger that the part has been overheated or heated for too long and this will result in brittleness. If there are too many pin-holes then the part is 'undercooked'. The condition that is thought to be best is a small number of pin-holes towards the inner, free surface.

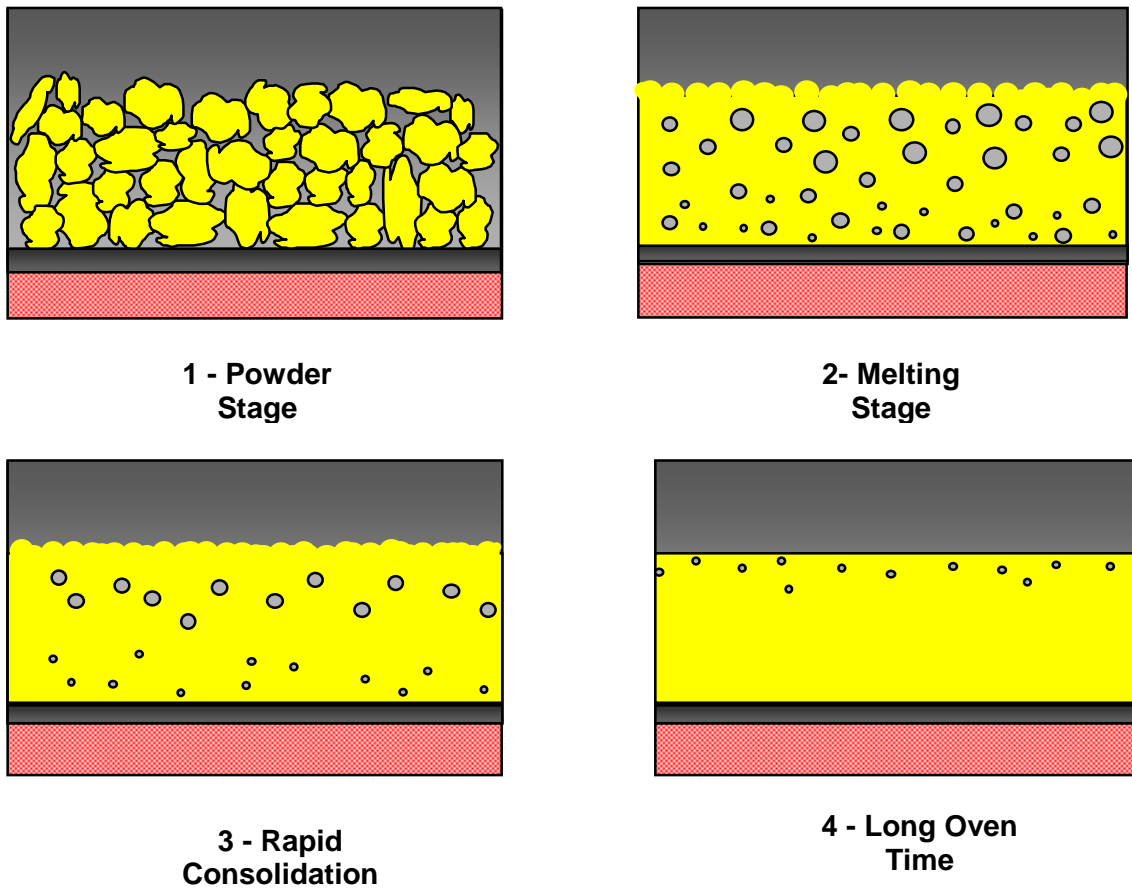


Figure 1.21 Stages during oven heating

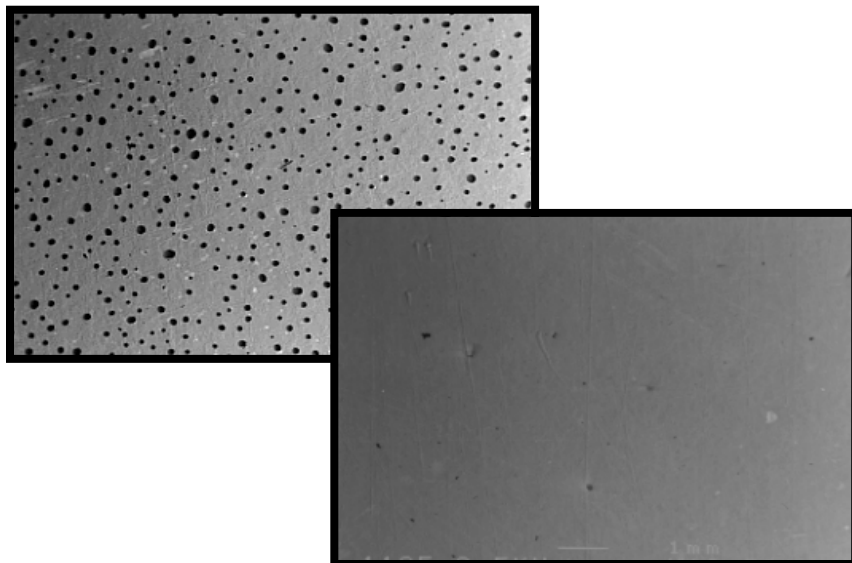


Figure 1.22 Rotomoulded parts with and without bubbles

Other indications of the quality of rotomoulded polyethylene parts relate to the appearance of the inner surface of the part and the smell of the interior of the moulding. The inner surface should be smooth with no odour, other than the normal smell of polyethylene. If the inner surface is powdery or rough then this is an indication that the oven time was too short because insufficient time has been allowed for the particles to fuse together. If the inner surface has a high gloss, accompanied by an acrid smell then the part has been in the oven too long. Degradation of the plastic begins at the inner surface due to the combination of temperature and air (oxygen) available there.

Even if the oven time is correct, the method of cooling can have a significant effect on the quality of the end product. The most important issue is that, in rotational moulding, cooling is normally only from the outside of the mould. The unsymmetrical nature of the cooling can result in warpage and distortion of the moulded part. The structure of the plastic is formed during the cooling phase. Rapid cooling (using water, for example) will result, effectively, in a different material compared with slow cooling (using air) of the same resin. The mechanical properties of the plastic will also be quite different in each case. Slower cooling tends to improve the strength and stiffness of the plastic but reduces its resistance to impact loading. Fast cooling results in a tougher moulding but it will be less stiff. The shape and dimensions of the part will also be affected by the cooling rate.

In recent years it has been shown that a more reliable approach to process control is to record the temperature of the air inside the mould throughout the moulding cycle. If this is done, it is possible to observe, in real time, all the key stages in the process and accurate process control can be achieved. This will be discussed in detail in Section 3.9.

1.5 Advantages of Rotational Moulding

The previous Sections have given a brief overview of rotational moulding. Most of the points raised will be discussed in detail later in the chapters on materials, moulds and machinery. At this stage it is worth summarising the main points.

There are many advantages associated with the rotational moulding process. Firstly the moulds are simple and relatively cheap. This is because rotational moulding is a low-pressure process and therefore it is not necessary to manufacture the moulds from expensive metal alloys, as in the injection moulding process. The wall thickness of parts produced by rotational moulding is more uniform in comparison to products from other processes and it is possible to alter the wall thickness of the part without altering the mould. Complex parts with undercuts and intricate contours can be manufactured relatively easily by rotomoulding (Figure 1.23). It is also possible to produce double wall mouldings. During rotational moulding relatively little waste is produced since the required weight of the part is placed inside the mould.

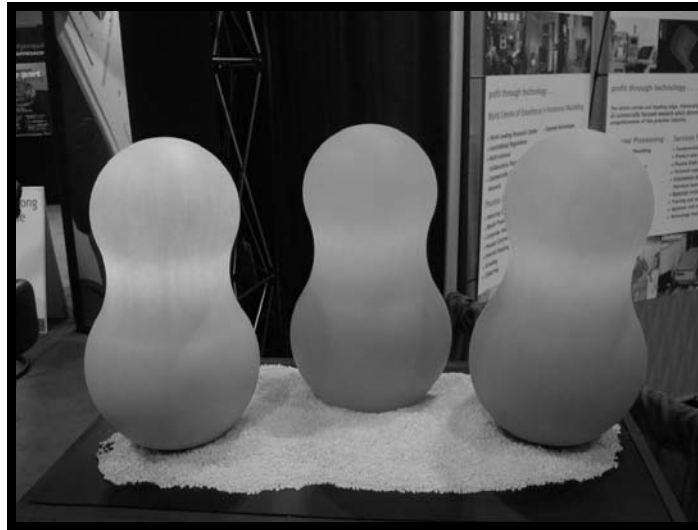


Figure 1.23 Decorative lamp shades

It is also commonplace for a number of different types of parts to be moulded at the same time. These moulds can be of different sizes and shapes – the different moulds are simply located side by side on the plate of the moulding machine. Parts manufactured by rotational moulding will be hollow, seamless and virtually stress-free.

The main attractions of rotational moulding are:

- A hollow part can be made in one piece with no weld lines or joints
- The end-product is essentially stress-free
- The moulds are relatively inexpensive
- The lead time for the manufacture of a mould is relatively short
- Short production runs can be economically viable
- There is no material wastage in that the full charge of material is normally consumed in making the part
- It is possible to make multilayer products
- Different types of product can be moulded together on the one machine
- Inserts are relatively easy to mould in
- High quality graphics can be moulded in

1.6 Disadvantages of Rotational Moulding

One of the main disadvantages associated with rotational moulding is that the number of materials suitable for the rotational moulding process is more limited than for other processes. Also, the raw material costs are higher since plastics are usually available in pellet form and hence grinding is required to produce a fine free-flowing powder.

Rotational moulding is usually not suitable for large production runs of small parts, since the long cycle times would make it uneconomical. Another drawback of the process is that it is labour intensive as a result of the manual loading and demoulding operations. Also,

the cycle times are much longer than those of other processes because both the plastic and mould must be heated from room temperature to the moulding temperature for the plastic and then subsequently cooled to room temperature during each cycle. Products with bosses or solid ribs cannot be easily moulded, due to poor cavity filling by the powder during rotation and heating. Such design features may also lead to difficulties during the demoulding operation.

The main disadvantages of rotational moulding are:

- The manufacturing times are long
- The choice of moulding materials is limited
- The material costs are relatively high due to the need for special additive packages and the fact that the material must be ground to a fine powder
- Some geometrical features (such as ribs) are difficult to mould

1.7 Common Applications for Rotomoulded Products

Since the initial development of the rotational process, a large number of products have been manufactured and a range of these products are shown below:

1.7.1 Material Handling Products



Figure 1.24 Shipping containers / tanks

Examples:

Tanks (agricultural, chemical, fuel, septic), chemical drums, shipping containers, wheeled bins, hoppers, coal bunkers

1.7.2 Industrial Products

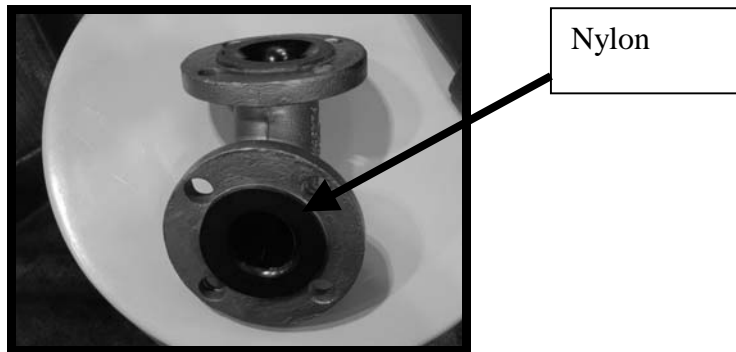


Figure 1.25 Nylon roto-lined pipefitting
Courtesy of Atofina

Examples:

Pump housings, pipefittings, effluent ducts, air ducts, sewer linings, safety helmets, stretchers, light fittings

1.7.3 Environmental Products



Figure 1.26 Rotomoulded recycle bins
Courtesy of Kingspan Environmental

Examples:

Litter bins, sanitation bins, bottle banks

1.7.4 Leisure Products



Figure 1.27 Rotomoulded child's playhouse

Examples:

Canoes, kayaks, windsurfing boards, boats, trailers, toys, playground furniture, mannequins

1.7.5 Marine Products



Figure 1.28 Marine float

Examples:

Floats, buoys, life belts

1.7.6 Road Signage



Figure 1.29 Road signs / cones
Courtesy of Mold In Graphic Systems®

Examples:

Road barriers, road cones, road signs

Bibliography

1. D. Ramazzotti, Rotational Molding, in *Plastic Product Design Handbook*, Ed., E. Miller, Dekker, New York, 1983, 75-104.
2. G.L. Beall, *Rotational Molding - Design, Materials, Tooling and Processing*, Hanser, Munich, 1998, 245.
3. R.J. Crawford and J.L. Throne, *Rotational Molding Technology*, William Andrew Publishing, New York, 2002, 399.
4. *Rotational Moulding of Plastics*, 2nd Edition, Ed., R.J. Crawford, Polymer Engineering, Research Studies Press, London, 1996, 260.
5. R.J. Crawford, Introduction to Rotational Moulding, in *Rotational Moulding*, Ed., R.J. Crawford, Research Studies Press, 1996, 1-24.
6. R.J. Crawford, The Challenge to Rotational Moulding from Competing Technologies, in *ARM Spring Conference*, Barcelona, Spain, 1999.
7. R.J. Crawford and S. Gibson, Rotational Molding - The Basics for Beginners, *Rotation*, 2000, **9**, 3, 40.
8. P. Nugent, *Rotational Molding: A Practical Guide*, 2001, USA: paulnugent.com. 809.
9. M. Paloian, Rotational Molding Parts: Design Made Easy, *Rotation*, 2002, **11**, 2, 36.
10. M. Paloian, Rotational Molding: Lowers Cost and Improves Customer Appeal, *Rotation*, 2000, **9**, 6, 52.
11. W. Roels, New Developments in Rotational Moulding. in *BPF Rotamoulding Conference*, Leicester, UK, 1995.
12. S. Scaccia, Future Trends in Rotational Molding, *Rotation*, 2002, **11**, 3, 38.
13. S. Scaccia, A Dream of the Future: A Challenge for Today, *Rotation*, 2000, **9**, 6, 48.
14. J. Stout, What's New in Rotational Molding and Tooling, *Rotation Buyers Guide*, 1999, 15.
15. J.L. Throne, Rotational Molding, in *Polymer Powder Technology*, Ed., N.a.R. Narkis, N, Wiley, New York, 1995, 301-347.
16. Anon, Rotational Moulding, Telford: Plastics Processing Industry Training Board, 1990.
17. G. Beall, Rotational Molding: Today and Tomorrow, *Plastics Engineering*, 1998, February, 33.
18. G. Beall, A Designers Guide to Rotational Molding, *Rotation*, 2001, **10**, 3, 38.
19. P.F. Bruins, Basic Principles of Rotational Molding, New York, Gordon and Breach, 1971.
20. P.T. Dodge, Rotational Molding - The Basic Process, The Association of Rotational Molders, Chicago, 1995, 13.
21. P. Dodge, Rotational Molding, in *Modern Plastics Encyclopedia*, 1996, 171.
22. J. Fawcett, Putting the Right Spin on Rotational Molding, *Machine Design*, 2000, May 18, 67.

23. T. Gillan, Advances in the Rotational Moulding Industry, *Rotation Buyers Guide*, 1999, 8.
24. Anon, *Introductory Guide to Designing Rotationally Molded Plastic Parts*, The Association of Rotational Molders, Chicago, 1999, 25.
25. Anon, *Rotational Molding - A World of Applications*, Association of Rotational Molders: Oakbrook, Illinois, USA, 1995.
26. Anon, *AMI's Guide to the Rotational Moulding Industry in Western Europe*, 2nd Edition, Applied Market Information, Bristol, 1995.
27. Anon, Rotational Molding Industry in Western Europe, *Rotation*, 1993, **2**, 2, 47.
28. Anon, *Rotational Molding - An Operating Manual*, Quantum Chemical Corp., Cincinnati, 1993.
29. P.J. Mooney, *New Market Dynamics in Rotomolding*, Plastics Custom Research Services, Advance, North Carolina, USA, 2003, 162 pages.
30. P.J. Mooney, *The Recent Pace and Pattern of Growth In North American Rotational Moulding*, Plastics Custom Research Services, New Canaan, USA, 1997.
31. P.J. Mooney, *An Analysis of the North American Rotational Molding Business*, Plastics Custom Research Services, New Canaan, USA, 1995.
32. P. Mooney, *The New Economics of Rotational Molding*, Plastics Custom Research Services, New Canaan, USA, 1999.
33. R.J. Crawford, Vision 2020 for Rotational Moulding, *Rotation*, 2000, **9**, 6, 40.
34. R.J. Crawford, Rotational Molding Vision 2020 through 2002, *Rotation*, 2003, **12**, 1, 16.

Chapter 2 – Moulds

2.1 Introduction

In the rotational moulding industry, the vast majority of moulds are made from metal - usually sheet steel, nickel or cast aluminium. The moulds are relatively thin, shell-like structures because the forces on the mould are small and it is desirable to transfer heat quickly to and from the mould. In most cases, the complexity and size of the part dictates the type of metal and method of manufacture used for the mould. For large parts with simple shapes, such as tanks, the moulds are normally fabricated from sheet metal - either carbon steel, stainless steel or aluminium. Cast aluminium is used for parts that are small to medium in size and have some degree of complexity. For highly detailed parts, such as doll heads, and where liquid vinyl is used to produce the moulded part, electroformed nickel is recommended. Examples of sheet metal and cast aluminium moulds are shown in Figures 2.1 and 2.2.



Figure 2.1 Sheet metal mould for a vertical tank



Figure 2.2 Cast aluminium mould
Courtesy of Persico SpA

2.2 Mould Materials

Many metals and many grades of metals are used in rotational moulding. Typical characteristics of mould materials are given in Table 2.1.

Table 2.1 Properties of common mould materials		
Material	Thermal conductivity, K, W/m K (Btu/ft h F)	Specific heat capacity, C_p J/kg K (Btu/lb F)
Aluminium (Duralumin)	147 (153)	917 (0.4)
Carbon steel (medium C)	51.9 (54)	486 (0.21)
Stainless steel (304)	14.5 (15.1)	490 (0.21)
Nickel (Monel 400)	21.7 (22.6)	419 (0.18)

2.3 Sheet Steel

Sheet steels are identified in terms of their Standard Gauge size. The properties of typical gauge sizes are given in Table 2.2. A variety of conventional metal shaping methods and welding are used to fabricate sheet metal moulds. Arc welding is usually satisfactory for most low volume applications, but inert gas welding is recommended to avoid porosity and blow-hole problems. Although sheet metal is the preferred choice when mould shapes are

simple, such as tanks or pipe junctions/joints, complex shapes can be made using advanced metal forming techniques, such as pressure rolling or hydroforming.

Low carbon steel is usually acceptable for most low volume applications, although galvanized steel is used in situations where rusting may be a problem. Stainless steel, particularly the 300 series of weldable stainless steels, is used when corrosion may occur due to the type of mould cooling, or because the moulds have to be stored outdoors.

Table 2.2 Data for different sheet steel gauges

Gauge	Thickness mm (inch)	Weight kg/m ² (lb/ft ²)
10	3.57 (0.1406)	27.46 (5.625)
12	2.78 (0.1094)	21.36 (4.375)
14	1.98 (0.0781)	15.26 (3.125)
16	1.588 (0.0625)	12.21 (2.5)
18	1.27 (0.0500)	9.765 (2.0)
20	0.952 (0.0375)	7.324 (1.5)
22	0.794 (0.0312)	6.1 (1.25)

2.4 Aluminium

Aluminium sheet can be formed and welded into simple shapes using forming methods similar to those used for sheet steel. Aluminium has excellent thermal conductivity and so it is often thought that it will provide better heat transfer than steel. However, aluminium is softer and less stiff than steel and so aluminium moulds need to have thicker walls. This reduces their thermal effectiveness and so most commercial aluminium moulds heat up, and cool down, less quickly than steel moulds. Aluminium is easily machined and can be textured with grit blasting and chemical etching. Computer numerically controlled (CNC) machining is a cost-effective way of making a series of identical moulds.

Although fabricated aluminium moulds can be made, the most common way of producing aluminium moulds is by casting. There are three general casting approaches.

1. Atmospheric casting
2. Pressure casting
3. Vacuum casting

Great care must be taken to avoid porosity in cast aluminium moulds. Toolmakers have therefore developed special variations of the basic casting methods in order to offer high quality moulds for rotomoulding.

2.5 Electroformed Nickel

The nickel plating process has been modified to produce moulds for the blow moulding, thermoforming and rotational moulding industries. Electroformed nickel moulds are used where extreme detail is required, as with liquid plastisol PVC for doll parts. A typical example is shown in Figure 2.5.

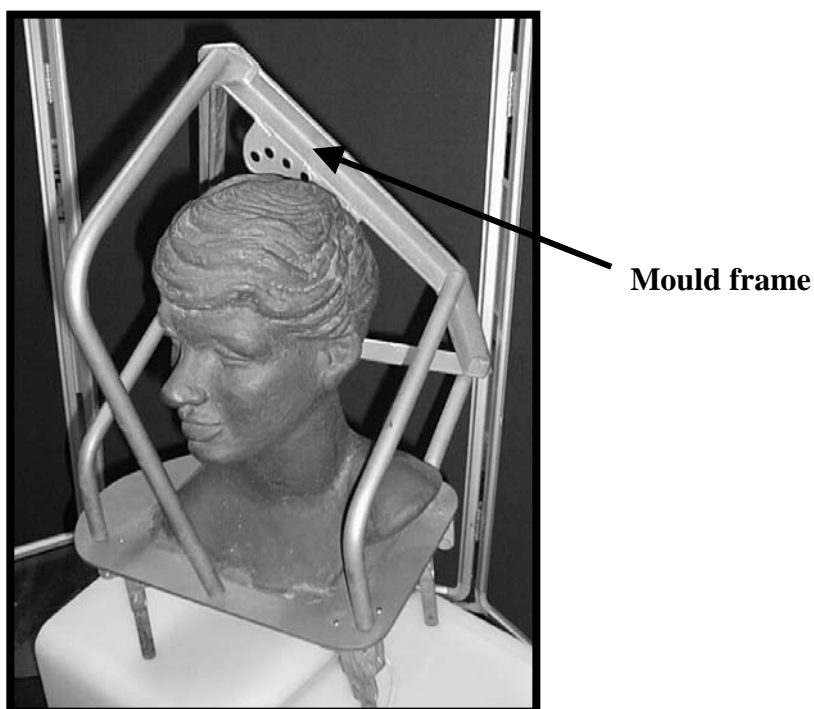


Figure 2.5 Electroplated nickel mould of mannequin head

2.6 Comparison Between Mould Materials

A comparison of the heating characteristics of typical aluminium and steel moulds in a rotational moulding oven is given in Figure 2.6. This is based on the moulds having the same stiffness. The graphs show that, for example, a typical steel mould (1.6 mm thick) is equivalent, in heat transfer terms, to an aluminium mould that is about 5 mm thick. As most aluminium moulds are thicker than this, they tend to heat up less quickly than steel moulds.

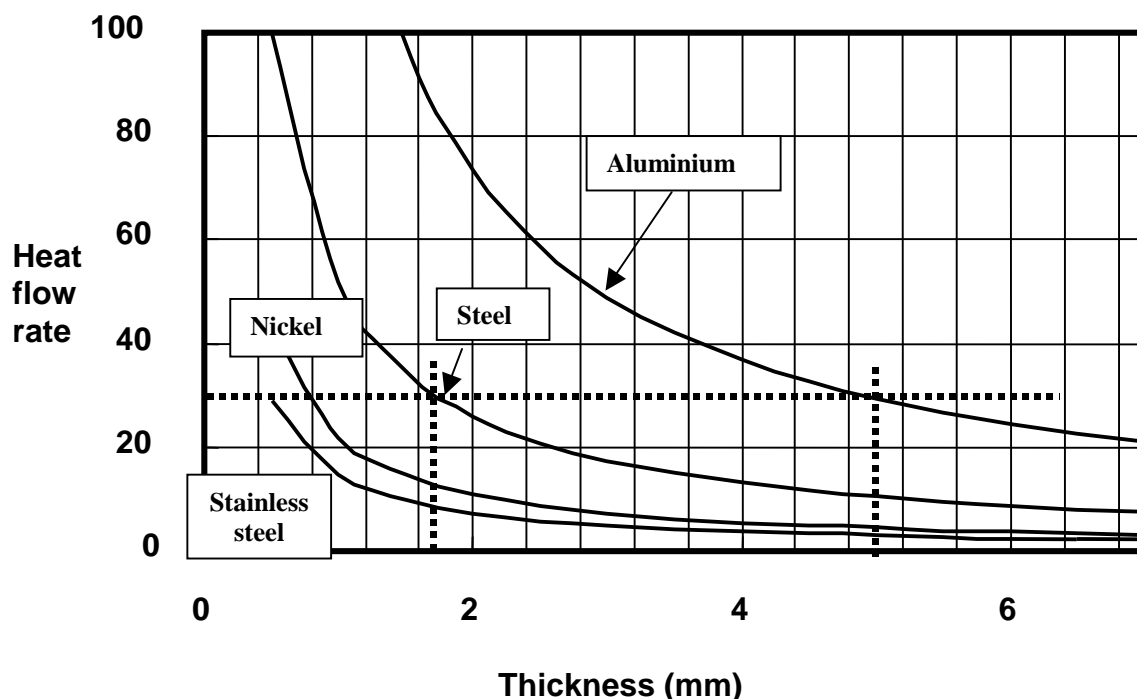


Figure 2.6 Comparison of heating characteristics of different mould materials

2.7 Mould Design

Rotational moulding does not use pressure to get the plastic to form a coating on the inside surface of the mould. Thus the mould can be of a thin, shell-like construction. It only needs to have sufficient strength and stiffness to support its own weight and that of the plastic part.

When the polymer cools and solidifies, it shrinks away from the mould surface. Relatively simple designs can have zero or even negative draft angles and the parts will release cleanly from the mould. For designs containing internal ribs, stand-up bosses, kiss-offs, or deep double walls, the cooling polymer will shrink onto the male surface. As a result, adequate draft angles must be provided, with additional allowances made for texture on the surface. Release agents are normally used to facilitate easy removal of the plastic from the mould.

Most rotational moulds are comprised of two pieces. Three and four-piece moulds are used when the part is more complex or has substantial undercuts. The interface between mould sections is called the *parting line*. For simple parts such as tanks, the parting line is usually planar. For heavily contoured parts such as toys, gasoline tanks and ducts, the parting line may have complex curvature. The integrity of the parting line is important to rotational moulding. Mould sections must remain mated without in-plane or vertical shifting during the heating and cooling cycle. In order to minimize parting line damage that can occur when clamping bolts are tightened, moulds are typically spring-mounted to the mould

frame, with spring compression adjusted with a threaded bolt that is cast or welded into a non-critical section of the mould body. The J-clamp draws the mould halves closed by looping the shaft over an adjustable J-bolt, then shortening the distance by mechanical linkage. Manual clamps, such as C-clamps and Vice-Grips™, can be used to clamp directly on the parting line flanges.

2.7.1 Mould Frame

It is common practice to mount mould halves in frames, as shown in Figure 2.7. This ensures that all forces act against the frames, not the mould shell, during assembly of the moulds after filling and during disassembly after cooling. A potential problem is that each attachment point represents a heat sink during heating and a hot spot during cooling. One compromise is to provide many attachment points with dimensions as small as possible, particularly where the attachments contact the mould surface. Another possibility is to provide attachment points on peripheral portions of the parting line flanges, where there is little additional chance of altering the heat transfer to the sintering powder or cooling melt. Angle iron, H-channel, rectangular channel or hollow square section tube steel are the common shapes used for mould frame construction.



Figure 2.7 Multiple moulds on frame
Courtesy of Persico SpA

2.7.2 Moulded-in Inserts

Moulded-in inserts are used to provide, for example, metal screw locations in a moulded part. They are affixed to the mould surface during the servicing stage of the cycle. The method of holding the insert depends to a great degree on the size, number, and function of the insert. There are two general classes of moulded-in inserts. Plastic inserts are used where the dimensional tolerance of a rotationally moulded region is unacceptable, or where rotational moulding is impractical due to wall thickness or mould dimensions. Care must be taken during the rotational moulding process to minimize thermal damage and heat distortion to the insert while ensuring that there is sufficient fusion of the sintered and molten polymer to the insert to provide integrity in the moulded part. Typically, the critical portions of the insert are thermally insulated, while the regions for fusion are exposed. Moulding with plastic inserts requires lower oven temperatures and longer cycles than normal.

Metal inserts can either be incorporated at the time of the moulding process, or be inserted as a post moulding operation. When incorporated as part of the moulding process, the operator normally loads the inserts. Most inserts are made from metals, usually brass – see Figure 2.8.



Figure 2.8 Typical brass inserts
Courtesy of Anchor Inserts

2.7.3 Moulded-in Handles

Tubes, pipes, rectangular channels and other hollow shapes can be moulded into a part to provide handles. Extending the shape through the mould walls can achieve this effect. If the shape surface is roughened, some adhesion of the plastic onto the handle is possible. If plastic must uniformly coat the handle, oven air must be positively directed down the inside of the shape. If a pass-through hole is needed, rather than a moulded-in handle, the shape should be made of an insulation material. Of course, provision must be made for parting the mould at the handle.

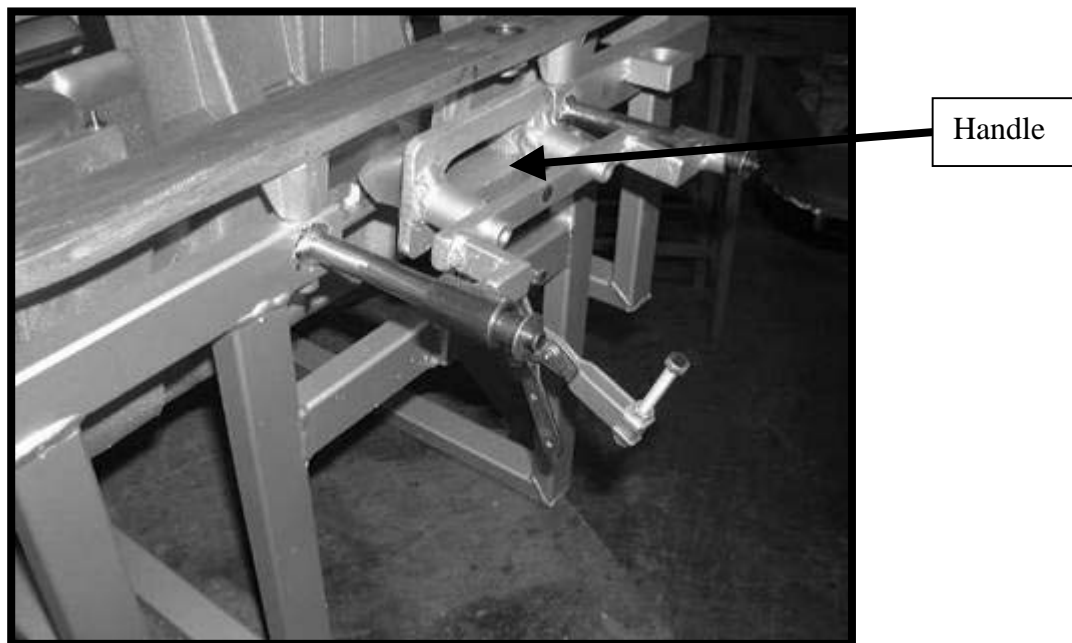


Figure 2.9 Moulded-in handle
Courtesy of Persico SpA

2.7.4 Temporary Inserts

In some cases, moulded parts must contain company logos, information panels and production dates. These inserts are usually temporarily fixed through an appropriate access in the mould wall. In some cases where texture is to be changed locally, for example, entire sidewall panels may be made as temporary sections. Heat transfer to these temporary inserts should be the same as that to the surrounding mould material, to minimise differential heat transfer and consequential variations in wall thickness. Furthermore, the temporary insert must fit tightly against the surrounding mould material to minimize blowholes at the edges of the insert.

2.7.5 Movable Cores

In some cases the mould will have cores that can move – to facilitate part removal from the mould.

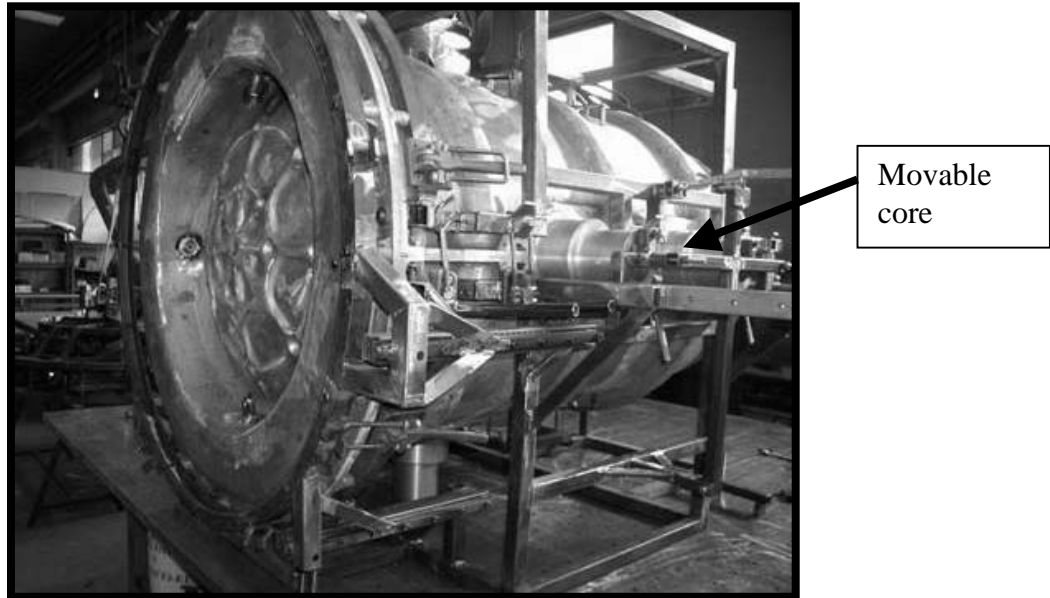


Figure 2.10 Large mould with movable core to aid demoulding
Courtesy of Persico Spa

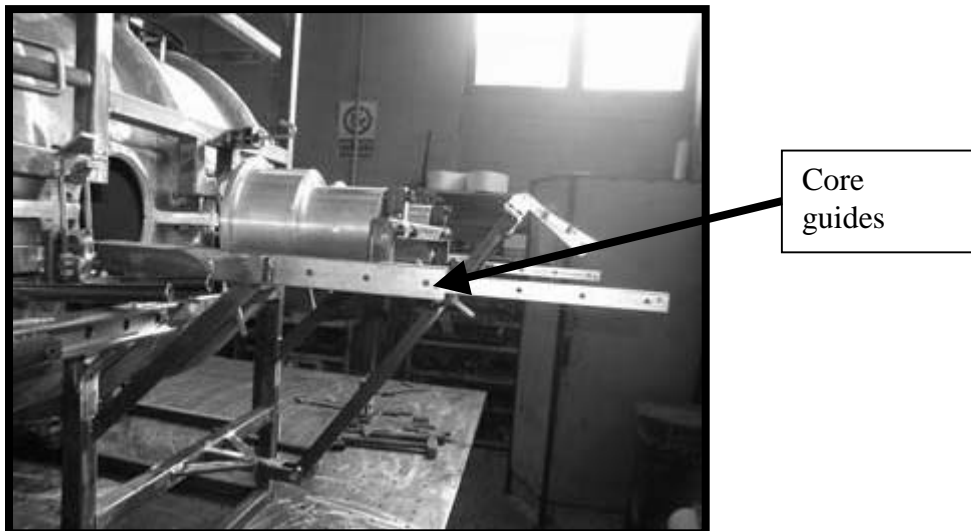
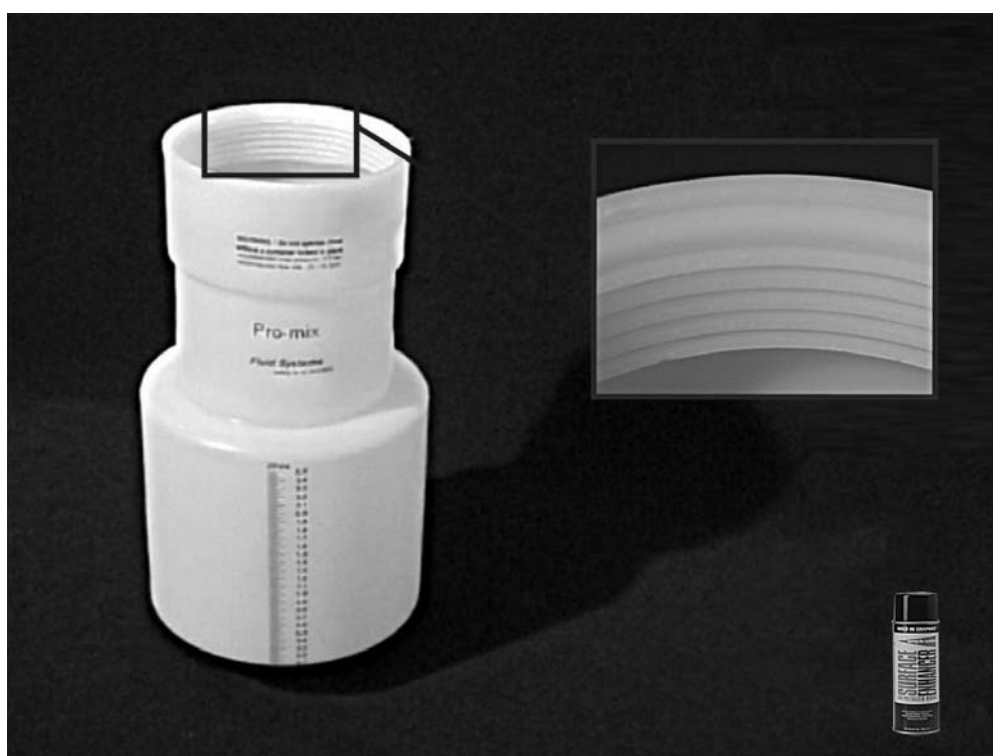


Figure 2.11 Movable core detail

2.7.6 Threads

Internal threads on rotomoulded parts are possible but thread design is extremely important, since the powder must flow into the thread base. Problems can arise because the insert can act as a heat sink and/or an obstacle during powder flow. The thread-forming insert can be made of bronze, phosphor bronze, brass or beryllium-copper to improve its heat transfer. Preferably, threads should be of short length and of large diameter to facilitate good heat transfer. Thread shape is critical since differential shrinkage during cooling can distort the thread geometry, and this can lead to thread stripping when the mating threaded component is inserted.

Commercial products are available to enhance the quality of moulded-in threads. An example is illustrated in Figure 2.12. The enhancer is sprayed into the mould and appears to act as an adhesive.



**Figure 2.12 Thread detail improved through
Mold In Graphic Systems® Surface Enhancer**
Courtesy of Mold In Graphic Systems®

2.7.7 Mould Venting

It is normal on a rotational mould to have a vent port to maintain atmospheric pressure inside the mould throughout the moulding cycle. The vent allows air to leave the mould during the heating stage and re-enter the mould during the cooling stage. If the mould were completely sealed, with no vent, then the gas trapped in the mould would expand when it is heated. This would lead to a pressure build-up inside the mould. Such a pressure increase could cause the molten plastic to be forced out at the parting line, resulting in a blowhole in the part or, in severe cases, the mould may distort.

In general, the guideline for the size of the vent is that it should be as large as possible, but not so large as to allow powder to pass through it during the early part of the cycle. There are some quantitative 'Rules of Thumb' that are used in the industry but these can vary widely in what they recommend. One of the most common rules of thumb is that the vent should be 13 mm for each 1 m³ of mould volume (or 0.5 inch in diameter for each cubic yard).

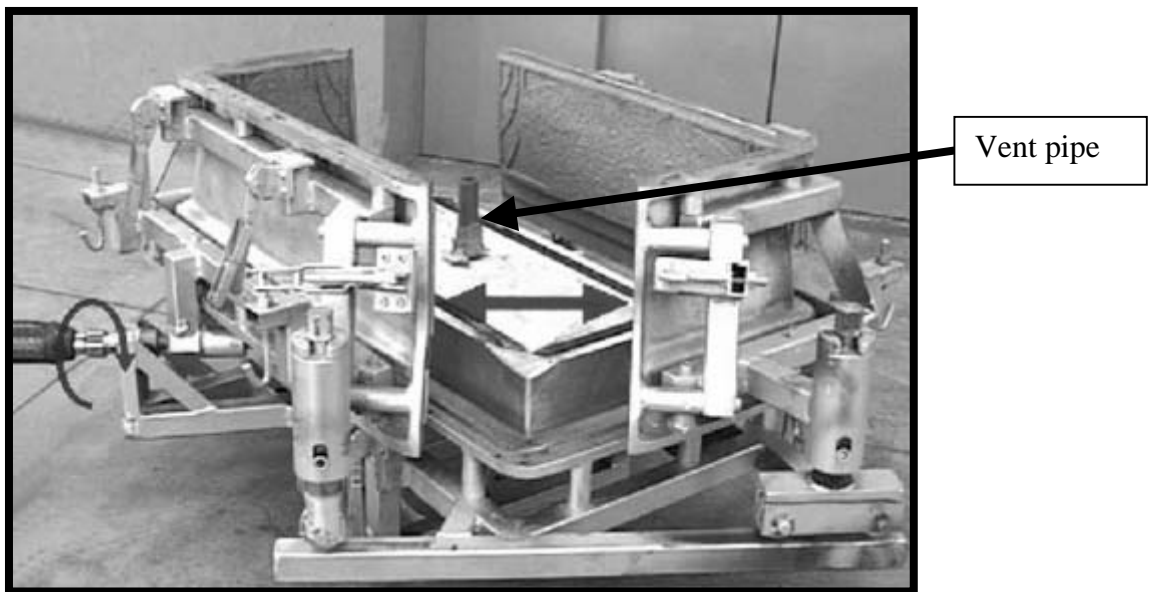


Figure 2.13 Movable mould showing central vent
Courtesy of Persico SpA

2.7.8 Mould Surface Finish

Since rotational moulding is a zero-pressure process, highly polished moulds cause problems because the plastic powder will not adhere effectively to a very smooth mould. What tends to happen is that the powder pool does not tumble inside the mould – it slides along the bottom of the mould. This leads to problems such as a non-uniform temperature through the powder bed. In addition, the molten polymer cannot adequately replicate the surface of a highly polished mould.

Typically, moulds are finished by sand or grit blasting, using 100 to 200 mesh particles. In this way, a matte finish is applied to the mould surface. Chemical etching is used when a specific surface texture such as leather is required. Porosity can occur during etching with cast aluminium moulds, and welded areas on steel and stainless steel moulds usually do not etch to the same level as surrounding areas. Uniform surface finishes are difficult in deep recesses. All draft angles must be increased as the depth of texture increases. One rule of thumb is that all draft angles should be increased one degree for each 250 μm (0.010 inch) of texture depth. The production of the desired surface finish is usually labour intensive and can be very costly. It should be noted that the initial surface texture can be substantially altered if permanent mould releases are added to the mould surface.

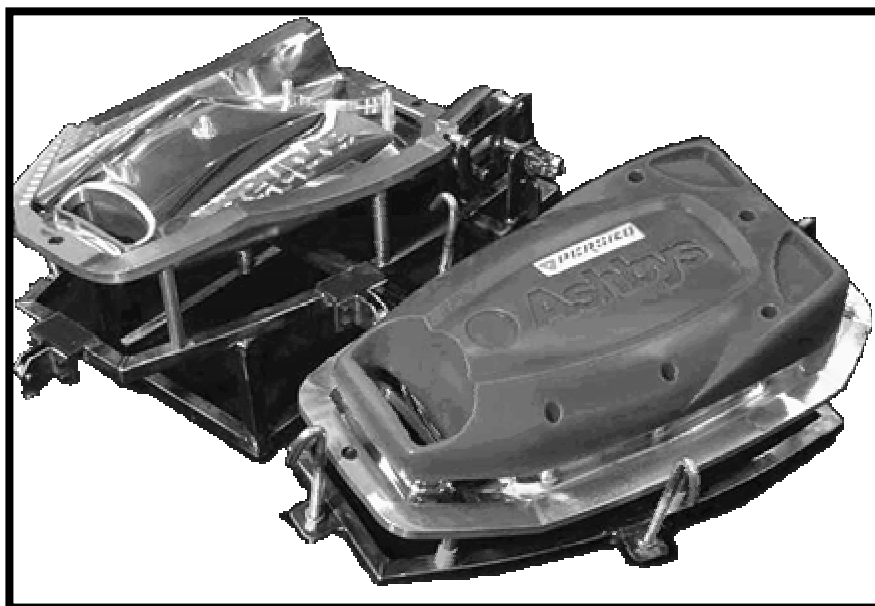


Figure 2.14 Highly polished mould
Courtesy of Persico SpA

2.8 Mould Release

The object of the mould release agent is to reduce the natural tendency for the polymer to adhere to the mould surface. In effect the release agent reduces the surface tension of the mould. The use of the correct release agent is a very important part of rotational moulding because it can influence part quality in many ways. The function of the release agent is complex in that it is necessary to have some adhesion to the mould wall in order that the plastic reproduces the shape of the mould. On the other hand the moulded part must separate easily from the mould when it is opened.

There are many types of mould release agents, ranging from those that operate for one cycle of the moulding machine to permanent mould releases on both the inside and outside of the mould. The following sections describe the main methods used to control the release of the plastic part from the mould.

Mould release systems are known to influence the shape of rotomoulded parts by having an effect on the plastic shrinkage during the cooling cycle. Correct choice of release system can have a positive effect on the control of the release process and hence the quality of the finished part. By understanding the technology behind a release system, other key parameters such as mould preparation and cleaning, touch-up, and post-moulding finishing operations can be improved.

2.8.1 Mould Preparation for Release Agent

In common with the application of any surface coating, successful results will be more readily achieved if the proper surface preparation regime is adopted. Whichever release system is chosen, and through whatever mould attachment method the system employs, it will function better if the substrate is correctly prepared. This principle applies whether or not the mould is new, has been taken off line for repairs, is being switched to an alternative release system or a touch-up coat of release system is about to be applied.

Over time, a build-up of the release agent will be evident on the mould surface. The build-up will be influenced by, but not solely attributable to, the release system in use. Once the build-up reaches the point where part quality is compromised, usually through surface appearance, some sort of mould cleaning will be needed. Generally speaking, the gentlest cleaning method, which will do the job adequately, should be chosen for the task. The basic requirement is to produce a surface, which is similar in nature to the substrate material and has an appearance consistent with the desired part finish.

There are typically four attachment mechanisms for release systems:

- (a) Reactive systems
- (b) Conventional systems
- (c) Permanent systems
- (d) Hybrid systems

2.8.2 Reactive Systems

In reactive systems, the cleanliness of the mould surface will have a greater influence on the success of the release agent than in the other systems. In other words, the cleaning process, which causes surface oxidation of the metal, produces bonding sites for the reactive release system. The surface is said to have been made 'functional'. Whether sprayed, wiped or brushed, the release system will attach itself to the surface by the same mechanism. Strong covalent bonds between the release agent and the mould surface are created. The rate of formation of these bonds may be influenced by the use of a catalyst to drive the chemical reaction. Some release systems require external heat to drive the reaction at a practical rate; other systems use chemistry, which is activated by moisture in the air. It is possible, however, to refresh a surface coated with one of these systems and add more release agent, to renew the release capability. Systems of this type are often referred to as 'semi-permanent'.

In order to clean the metal substrate back to its original condition (when this is eventually required) it is quite normal to resort to strongly alkaline and/or abrasive cleaners.

Examples of semi-permanent mould release agents are as follows:

2.8.2.1 Spray-on Zinc Stearates

These are usually in powdered aerosol form, and can be sprayed onto the mould in particularly difficult areas. However, manual application rarely yields a controlled film and ultimately the build-up becomes uneven. When this occurs, the moulds must be thoroughly cleaned and the application process repeated. An attraction of this type of release agent is that they are relatively cheap.

2.8.2.2 Silicones

These are chemically inert slip agents that simply form a mechanical interference between the plastic and the mould. They cannot be used for aerospace applications and certain US Food and Drug Administration (FDA) applications. Some advanced silicones crosslink and temporarily bond to the mould. Usually, silicones are temporary mould release agents, so that they must be replaced every few cycles.

2.8.2.3 Disiloxanes

These are semi-permanent mould release agents. Disiloxanes chemically bond to the mould surface to form a layer that is about 4 μm thick. They are thermally stable to 425 °C – 480 °C (800 °F to 900 °F). Typically 1 to 1000 parts can be produced in a disiloxane-coated mould before it needs to be recoated.

2.8.3 Conventional Systems

Conventional release systems work in a completely different manner from reactive systems. There tends not to be chemical bonding or attachment of any type at the interface of the dried release system and the mould surface. Typically, conventional systems consist of silicone oils and wetting agents that are specifically selected for their low reactivity or functionality. A conventional system is normally spread over the entire surface of the mould by either wiping, brushing or spraying. It remains essentially unchanged throughout the heat exposure cycle since it possesses no reactive sites. On completion of the moulding cycle, the release agent detaches itself from the mould wall during the cooling cycle and is removed with the moulded part. This requirement is very difficult to achieve and is probably the main reason that in modern rotomoulding, conventional release agents are rarely employed.

2.8.4 Permanent Systems

Unlike any of the other release systems, permanent coatings usually require the rotomoulder to employ the services of an outside contractor, both for preparation of the mould surface substrate and more especially for the coating process itself. A dispersion of polytetrafluoroethylene (PTFE), either in solvent or in a water/solvent blend is sprayed on to the surface of the mould and the carrier is allowed to evaporate. The coated mould is heated to approximately 340 °C (650 °F), which takes the PTFE to its melt point, allowing the particles to fuse into a continuous layer.

Since PTFE is a very viscous material in the molten state, a combination of related fluoropolymers are often used which help to compensate for the limited coalescence afforded by the use of PTFE alone. The fused, continuous layer of polymer forms a surface film which relies totally upon surface wetting to lock it in place. The non-functionality of a PTFE coating, which gives rise to its impressive non-stick attributes, is a double-edged sword. The coating contractor has to prepare the tooling surface very carefully to accept such a film and to provide a strong bond with the metal mould. Figure 2.15 shows a PTFE coated mould.

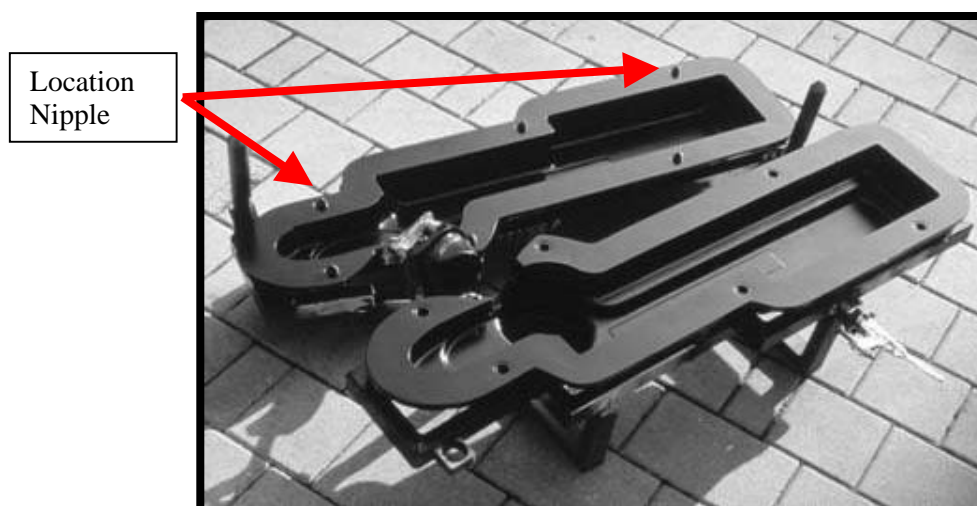


Figure 2.15 Black 'teflon' coated mould

Courtesy of Persico SpA

Coupled with PTFE's inherent softness, the reliance upon surface wetting and physical locking, without the strength of chemical bond formation, makes the surface coating inherently fragile. Indeed the word 'permanent' used in reference to these systems is somewhat of a misnomer. Even if the coating is treated most respectfully by the end-user, there comes a time when the whole preparation and attachment process has to be repeated. Repair to a damaged area of the coating usually requires an expert.

2.8.5 Hybrid Systems

Hybrid systems function in a manner, which could be described as 'functionally conventional'. The amount of reactivity in a hybrid system is typically much lower than that in a system described as fully 'reactive'. The presence of this lower reactivity does, however, ensure that any sites of functionality at the surface of the substrate can be used by the hybrid system, but it does not wholly rely upon this facet to bond the release system to the mould. Hybrid systems lend themselves better to providing attachment of the release system to substrates having a much lower degree of surface functionality.

The release system needs to possess sufficient adhesion to allow it to remain on the mould wall throughout the moulding cycle and provide release control during the cooling cycle. The amount of 'cling' will dictate the degree of semi-permanency achieved by the release system. The success of these so-called hybrid systems is a function of the skill employed in selection of the base polymer.

2.9 Mould Cooling

Although the mechanical properties of rotationally moulded parts are important, it is often the appearance of the moulded article that is the primary quality control parameter. If the moulding is warped or distorted or has the wrong dimensions then it is likely to be regarded as a reject, even though the physical properties are acceptable. It is very important therefore that moulders exercise control over the shape of the end product.

The nature of rotational moulding is such that the process is well suited to large, relatively thin wall parts and the cooling from the melt stage is unsymmetrical. These factors make it very difficult to avoid distortion of the end-products, particularly if they are made from a low modulus material such as polyethylene. The nature of the mould cooling has a major effect on the appearance of the moulded part, as well as its properties. Rotomoulding normally utilises unsymmetrical cooling (from the outside) and this can lead to distortion (warpage) of the moulded part. For this reason, the moulder is usually obliged to employ slow cooling of the outer surface of the mould until the point when the plastic has solidified. Cooling in still air causes the slowest cooling rate and is usually essential in the early stages of the cooling cycle. After this point, faster cooling methods can be used (Figures 2.16-2.20).

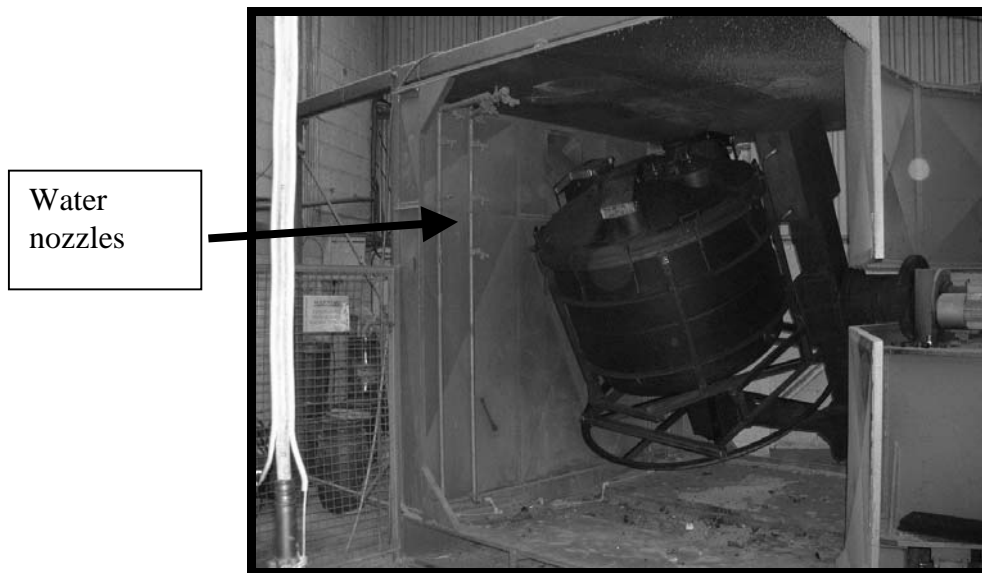


Figure 2.16 Tank mould in cooling bay
Courtesy of Clarehill Plastics Limited



Figure 2.17 Cooler bay doors open

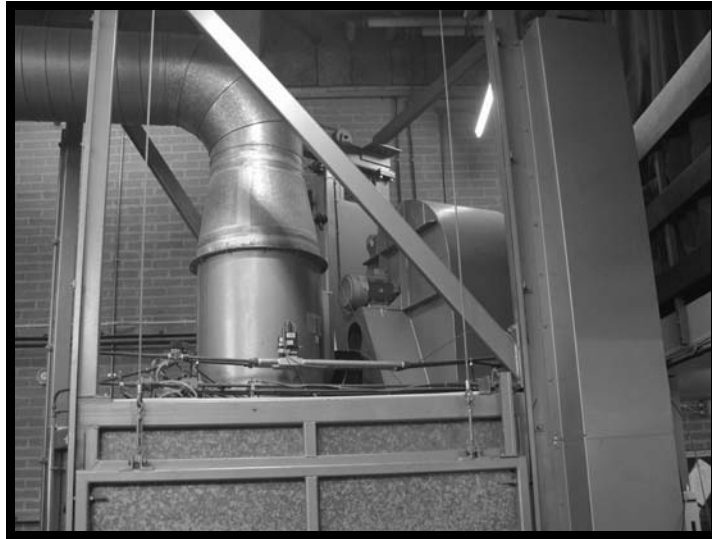


Figure 2.18 Cooler extraction detail

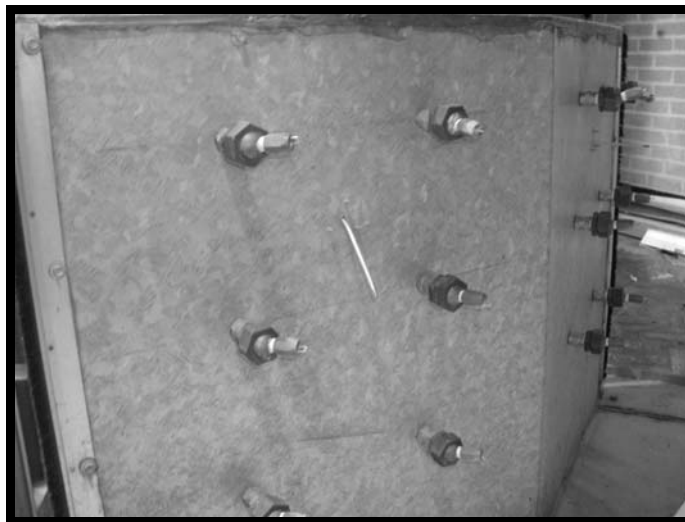


Figure 2.19 Water mist valves in cooler bay

The rate of cooling can be controlled by using varying degrees of still air, forced air, water mist and water spray. Sections 5.3–5.5 explain how the cooling rate of the mould affects the quality of the moulded part.

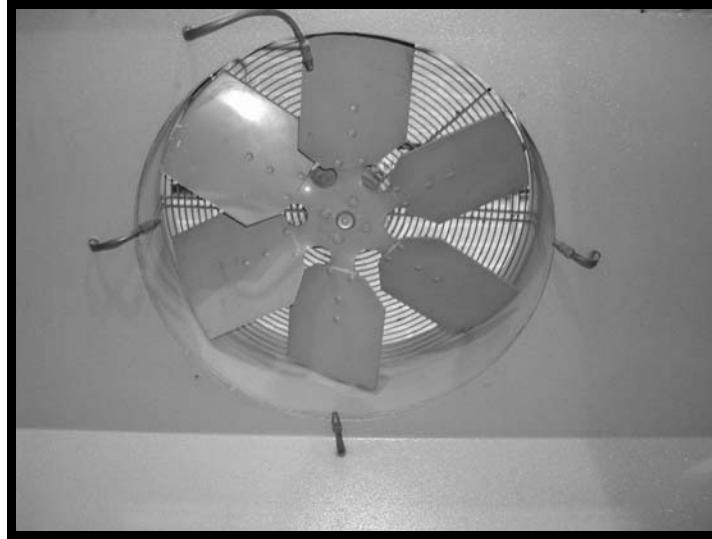


Figure 2.20 Water mist valves over cooling fan

2.10 Mould Ancillaries

There are a number of custom-built demoulding (Figure 2.21) or material filling (Figures 2.22 and 2.23) aids that the rotomoulder can employ.

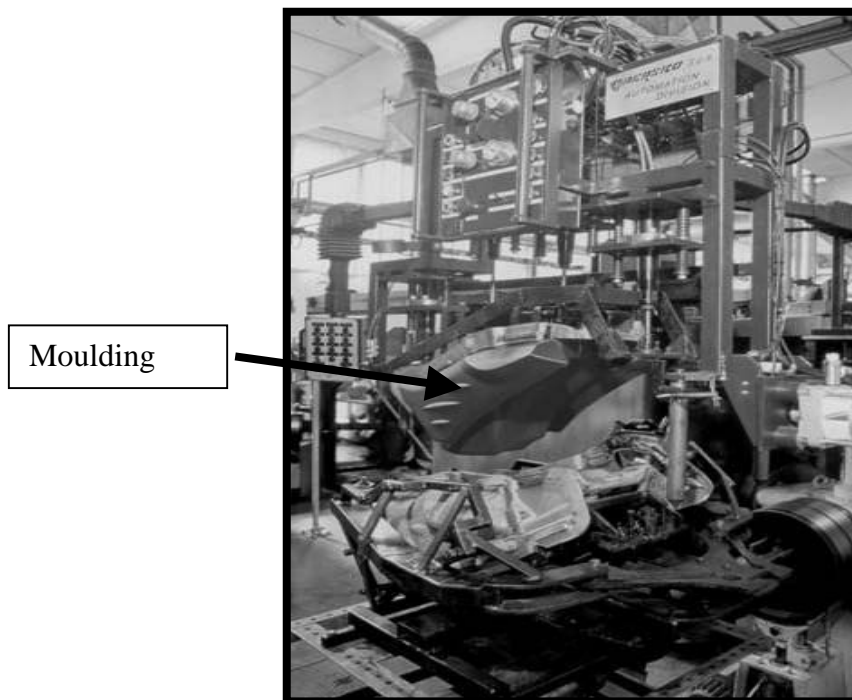


Figure 2.21 Automatic demoulding aid
Courtesy of Persico SpA



Figure 2.22 Automatic material dispenser
Courtesy of Persico SpA



Figure 2.23 Automatic material dispenser filling mould
Courtesy of Persico SpA

2.11 Moulding Aids

One particularly innovative moulding aid is the Mold In Graphic Systems[®] RMC³ or 'putty' (Figure 2.24). This pliable resin can be positioned into areas of a mould that powder has difficulty flowing into, effectively creating a solid area in the moulding.



Figure 2.24a Pliable RMC³
Courtesy of Mold In Graphic Systems[®]



Figure 2.24b Putty is pressed into corner recess
Courtesy of Mold In Graphic Systems[®]

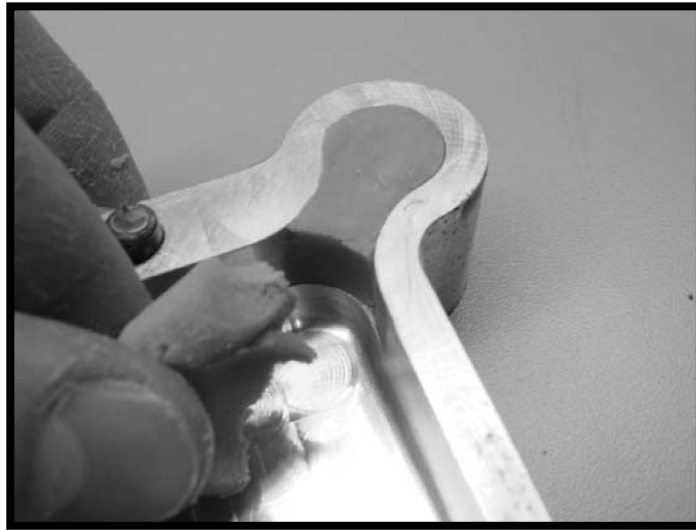


Figure 2.24c Putty is contoured to desired shape in mould
Courtesy of Mold In Graphic Systems®



Figure 2.24d Final moulding contains solid protrusion
Courtesy of Mold In Graphic Systems®

The material allows the production of hybrid solid/hollow parts and enables features such as solid external fasteners, handles, etc (Figure 2.25).

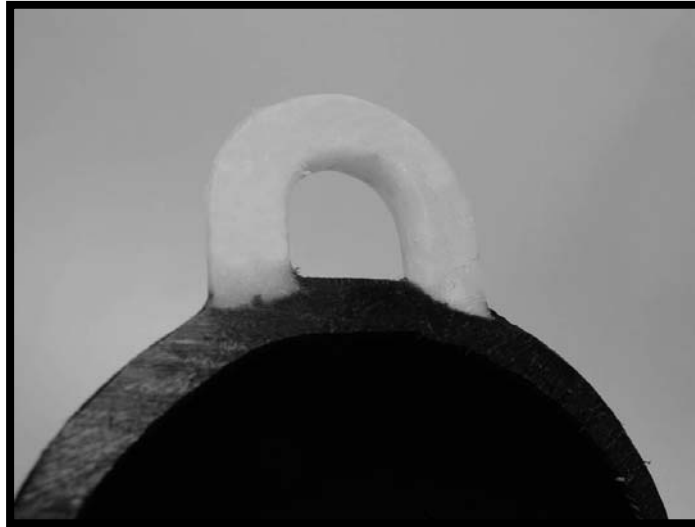
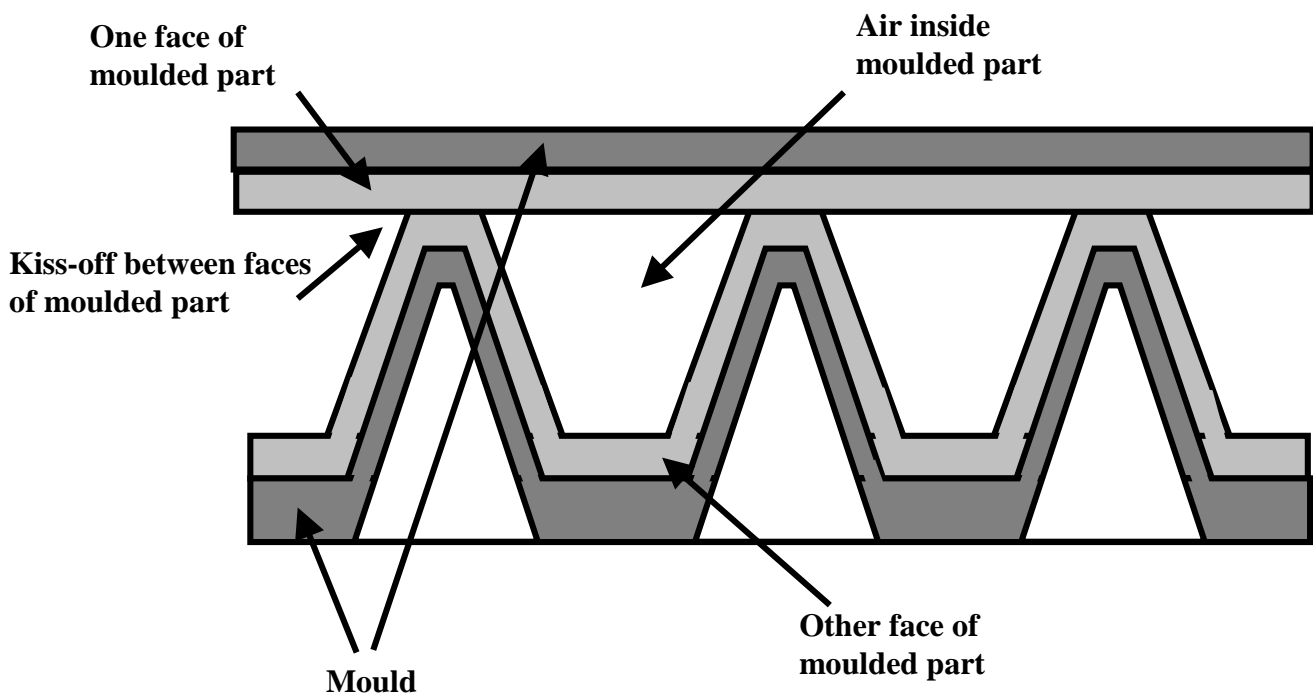


Figure 2.25 Example of rotomoulded part with solid handle protrusion
Courtesy of Mold In Graphic Systems®

Sharper corners, solid flanges and internal bosses are also possible with this material.

2.12 Kiss-Offs

Kiss-offs are used to provide rigidity in a rotationally moulded part. As the name suggests, they are a means of attaching opposite faces of the hollow part in order to provide better flexural stiffness (Figure 2.26). Shallow kiss-offs are made of highly conducting metal such as copper and may be attached to the mould surface as inserts. Large dimensioned kiss-offs are designed directly into the fabricated or cast mould.



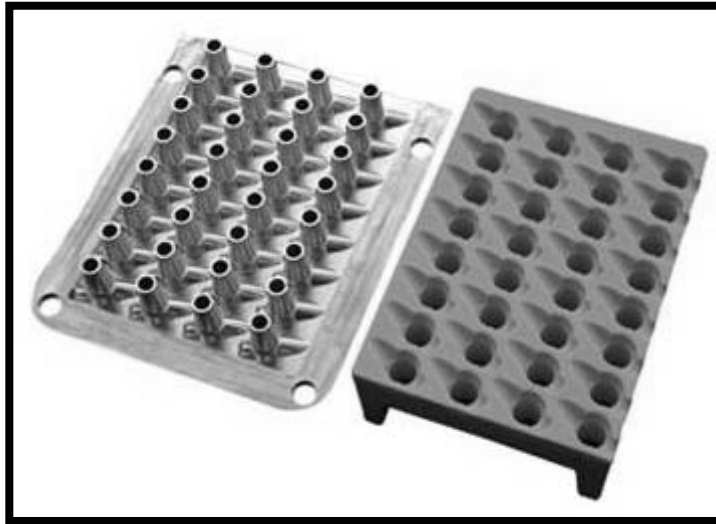


Figure 2.26 Kiss-Off feature in rotationally moulded part

2.13 Calculation of Charge Weight

A fundamental part of manufacturing a product by rotational moulding is relating the part wall thickness to the shot, or charge weight. In some cases the weight will be fixed to make the end product economically viable. The wall thickness may then have to be calculated in order to do a quick (or thorough) stress analysis to ensure that the end product will perform its function. In other cases the desired wall thickness will be known, perhaps from a finite element analysis, and the appropriate charge weight must be estimated to provide this thickness. If the mould has been designed using a CAD system or manufactured using a CNC-driven cutter, the surface area of the part will be known. From this, part wall thickness can be obtained and hence, an accurate charge weight determined.

If the end product has an irregular shape it is not easy to calculate accurately the desired weight or wall thickness. The moulder must then rely on experience or trial and error to get the correct charge of powder. This can be time consuming and wasteful of material so it is often worthwhile to make some attempt at estimating the amount of powder needed for a new moulding. Usually this involves simplifying the shape of the mould so that a quick approximation for shot weight can be made.

Except for scrapped parts or cut-out sections, there is no waste material in rotational moulding. All of the material that goes into the mould contributes to the shape of the end product. There may be some trimming afterwards but a fixed weight of material is charged to the mould to make the shape of the hollow part.

To get the charge weight for a desired wall thickness it is necessary to work out the volume of material in the end product and multiply this by the density of the plastic. The volume of the plastic is obtained by subtracting the volume of the air space inside the plastic part from the volume of the inside of the mould.

An alternative way to estimate the wall thickness is to take the volume of the part as the surface area of the inside of the mould multiplied by the wall thickness of the part.

The charge weight is then given by the following equation:

$$\begin{aligned} &\text{Weight of plastic} \\ &= \text{Surface area of moulding} \times \text{thickness of moulding} \times \text{density of plastic} \end{aligned}$$

This equation can then be rearranged to give the wall thickness. Formulae for the calculation of the volume and surface area of a variety of mould shapes are available from a number of sources. Simulation programs, such as RotoSim, can calculate accurately the required shot weight on the basis of a CAD drawing of the moulded part.

The RotoSim computer simulation package permits the shape of a moulded part to be loaded into the program and it will predict the wall thickness distribution in the rotomoulded part. The system is set up just like the rotational moulding machine by inputting the type of rotation (e.g., biaxial or rock and roll), the position of the mould on the plate of the machine, the rotational speeds, the oven temperature, the heating time, the type of cooling, the cooling time, etc. If some areas of the mould are shielded or receive extra heat, then this can also be input. The program will then predict the mould and internal air temperature profiles as well as the thickness of the part at every point on its surface. The software developed at Queens University, Belfast, runs in Windows on a PC. The speed of operation depends on the power of the computer used and the complexity of the moulded part but typically the simulation runs faster than the actual moulding time. Such a simulation package offers many advantages to moulders. Not only is it useful as a training package where all sorts of “What if...?” scenarios can be explored but it provides practical data on mould design and optimum machine set-up. Before metal has been cut or cast, it is possible to take an image of the shape of the part and use the simulation to decide what are the best speed ratios, what is the best position on the plate, what oven time is required, what areas of the shape are difficult to fill, etc. This information can then be used to finalise the design of the part and set up the moulding machine in the most efficient manner.

Chapter 3 – Rotational Moulding Machinery

3.1 Introduction

As described in Chapter 1, the basic principle of rotational moulding involves heating powdered (or liquid) plastic, and subsequently cooling it, inside a hollow shell-like mould. During the heating stage, the mould is rotated so that the melted plastic forms a coating on the inside surface of the mould. The rotating mould is then cooled so that the plastic solidifies to the desired shape and the moulded part is removed.

There are many methods that can be used to achieve the three essential requirements of the process – that is, (a) mould rotation, (b) heating and (c) cooling. Early types of rotational moulding machine involved the heating of the rotating mould by an open flame. The mould rotation usually involved a ‘rock and roll’ motion. This description was used because the mould rotated through 360° about one axis and was rocked backwards and forwards about the other axis. Few modern commercial rotational moulding machines involve direct flame heating of the mould but the rock and roll rotation mechanism is still used in some cases.

Most modern rotational mould machines involve full biaxial rotation about two perpendicular axes and use a hot air oven to heat the rotating metal mould. Other mould heating methods that are less common include electrical elements on the mould, infrared or microwave heating, or hot oil circulated in a jacket around the mould.

3.2 Types of Rotational Moulding Machines

As stated above, the common aspects of all rotational moulding machines are that the mould and its contents need to be rotated, heated and cooled. There also needs to be a convenient opportunity to remove the end product from the mould and put a fresh charge of plastic into the mould. Since rotationally moulded parts range in volume from 0.05 litres to more than 10,000 litres, generalization on machine types is difficult. Nevertheless, there are some basic types of commercial rotational moulding machines that are common across the industry. The various types of machines that are available are described below.

3.2.1 Carousel Machines

The carousel, turret or rotary machine was developed for long production runs of medium to moderately large parts. It is now one of the most common types of machine in the industry. The earliest machines had three arms, fixed at 120° apart, and driven from a single turret. One arm is at each of the stations - heating, cooling, servicing - at all times, as shown in Figure 3.1. Four-arm, fixed-arm, machines (with the arms 90° apart) are also available. Usually the fourth arm resides in an auxiliary cooling station when the other three are in heating, cooling, and servicing stations.

The carousel machine exemplifies the advantages of the rotational moulding process in that different materials within different moulds can be run on each arm. It is possible to change

the combinations of moulds on one arm or on the other arms at regular intervals so that there is great versatility in production schedules.



Figure 3.1 Fixed arm turret machine
Courtesy of Ferry Industries Inc.

A disadvantage of the *fixed* arm machines is related to the fact that all arms move together. Therefore for optimum use, the heating, cooling and servicing times have to be matched. If they are not, then the cycle time is dictated by the slowest event and time is wasted in the other stages. This disadvantage has been overcome to some extent with the development of the *independent* arm carousel machine (Figure 3.2). Although the arms cannot move past each other in an independent arm machine, if the heating stage is finished then that arm can move out of the oven and continue the mould rotation in ambient air whilst awaiting the arm in front to complete its cycle in the cooler.

Some independent arm machines have five designated stations, and can have two, three or four arms that sequence independently of one another. Extra versatility can be achieved in rotational moulding machines if there are fewer arms than stations. This allows the operator to designate the 'empty' stations as auxiliary oven stations, auxiliary cooling stations, and/or to separate the loading and unloading steps in the servicing stations.

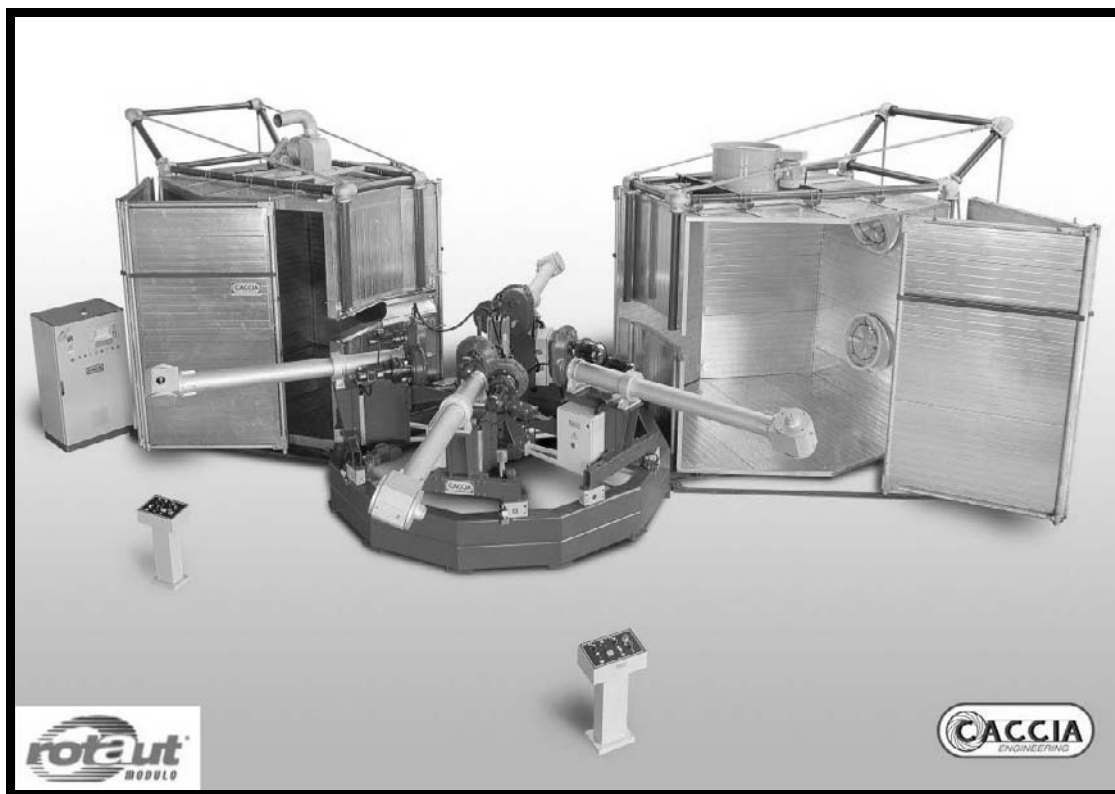


Figure 3.2 Independent arm carousel machine
Courtesy of Caccia Engineering SpA

3.2.2 Shuttle Machines

Shuttle machines were developed as an attempt to conserve floor space. There are many types of shuttle machine designs. In one type, the mould assembly, mounted on a rail carriage, is shuttled from the servicing/cooling station to the oven station, and back again to the servicing/cooling station, as shown in Figures 3.3 and 3.4. The efficiency of the shuttle machine is improved by using a dual-carriage design, whereby the oven is always occupied by the heating of a mould while the mould on the other carriage is being cooled or serviced. If the cooling/servicing time for the mould equals the heating time, then this system can approach the optimum in terms of maximum output rates. Since the scheduling of time in the oven is at the discretion of the operator, the dual-carriage machine is more versatile than the fixed-arm carousel type.

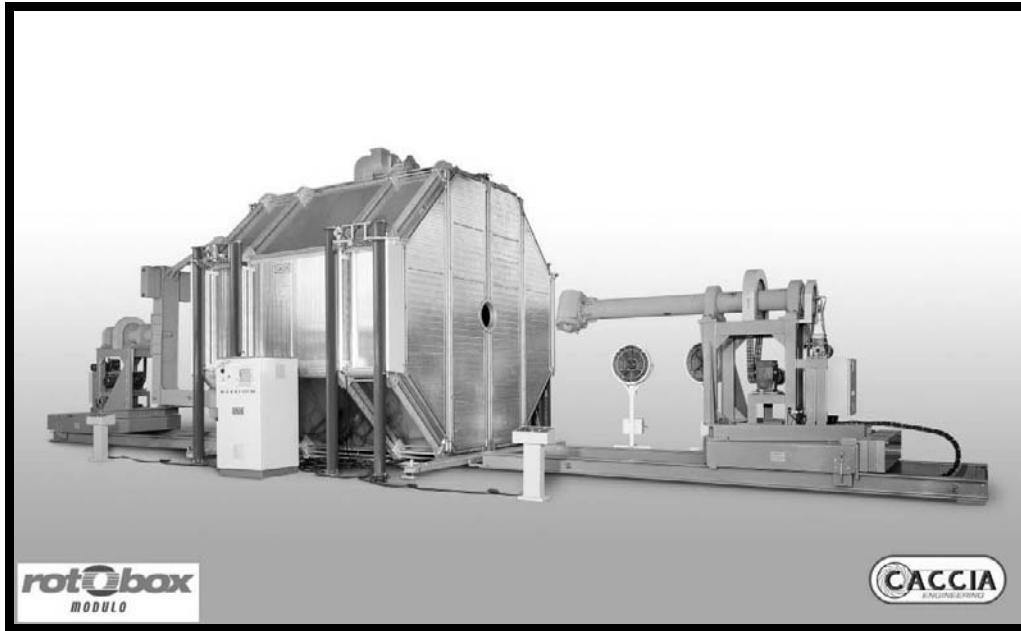


Figure 3.3 Two station shuttle machine
Courtesy of Caccia Engineering SpA



Figure 3.4 Two station shuttle machine with cooler bay doors
Courtesy of Ferry Industries Inc.

3.2.3 Clamshell Machines

This machine is characterized by an oven that closes in a ‘clamshell’ action over the mould as shown in Figures 3.5a and 3.5b. These machines have the attraction of a small floor footprint – Figure 3.6 illustrates 3 clamshell machines in series. The machine provides full biaxial rotation and has the advantage that the horizontal shaft can be supported at both

ends. The moulds are located on assemblies that are in turn mounted on turntables geared through the main shaft/axle. When the oven door is closed, the main axle rotates, turning the moulds in a ferris-wheel fashion and, through gearing, the turntables rotate the moulds about their axes. Heated air is circulated through the cabinet until the appropriate polymer temperature is achieved, then cooling occurs by cooled air and/or water mist.

At the completion of the cooling cycle, the cabinet door rises with a 'book' action, the moulds are opened, and the parts are removed. The moulds are then cleaned, inspected, and refilled with polymer and the next cycle begins. In some designs of clamshell machines, the moulds leave the oven chamber at the end of the heating phase so that cooling can take place externally. This makes the oven chamber free to receive another set of moulds whilst the previous set is being cooled and serviced.



Figure 3.5a Clamshell machine open
Courtesy of Ferry Industries Inc.



Figure 3.5b Clamshell machine closed
Courtesy of Ferry Industries Inc.



Figure 3.6 Clamshell machines in series
Courtesy of Sorcerer Machinery

3.2.4 Rock and Roll Machines

One of the earliest rotational moulding machine design concepts involved a rocking action about one axis ('rock') and a full 360° rotation about a perpendicular axis ('roll'). This is illustrated in Figure 3.7. For a long time it was thought that rock and roll machines were best suited to end-products that are approximately symmetrical about a central axis, such as cylindrical tanks, traffic cones and kayaks. In recent years there has been a renewed interest in rock and roll machines because they offer simplicity in design and have the major advantage that it is easier to get services to and from the rotating mould. It has also been found that, for the vast majority of mould shapes, the control over the wall thickness distribution can be just as good as that achieved on a biaxial rotation machine.

In a rock and roll machine, usually a single mould is mounted in the mould frame, the rotational speed is low (typically 3 rev/min), and the rocking angle is typically $\pm 35^\circ$. Direct open flame impingement is an effective method of heating sheet metal moulds and was widely used in the early rock and roll machines. In some parts of the world, this type of mould heating is still common.

The proximity of the gas jets to the metal mould is an important factor in mould heating. The gas jets should preferably be a fixed distance from the outside surface of the mould to avoid hot spots. Obviously this is easiest to achieve in cylindrical moulds that are rotated about their longitudinal axis. For moulds that do not have an axis of symmetry it is sometimes necessary to use cams so that the open flame can be kept equidistant from the mould surface. Where safety regulations prevent open flame heating, the rock and roll machines use a conventional type of hot air oven to heat the mould. The mould assembly moves in and out of the oven in a shuttle type design as described earlier.

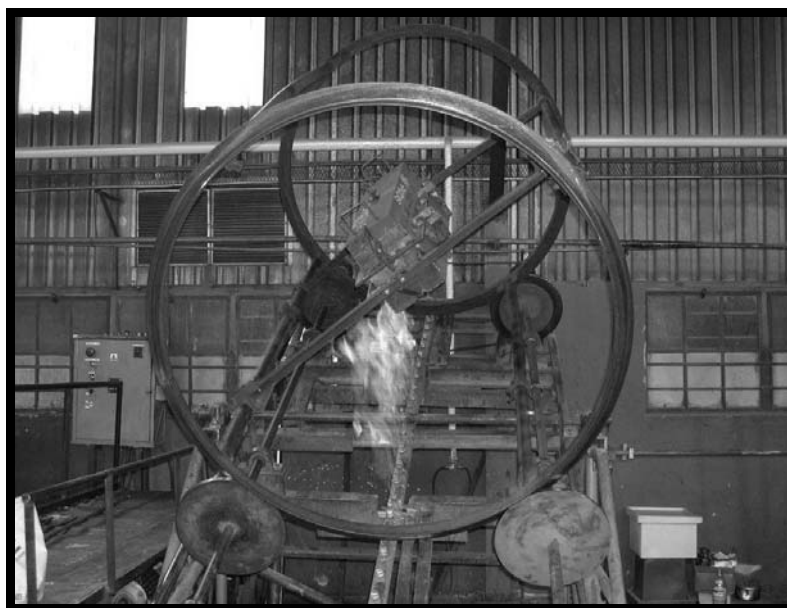


Figure 3.7 Open flame rock and roll machine
Courtesy of Pioneer Plastics

In the *rocking oven machine*, a hot air oven surrounds the mould, and the oven rocks with the mould as shown in Figure 3.8. The rocking oven must contain appropriate burner assemblies, ducting and blowers, as well as an adequate shroud. In some cases the mould assembly is mounted on a rail carriage, so that it can be moved from the oven chamber to the cooling area. Frequently the cooling area is also the servicing station. For smaller rocking oven machines, the oven can be shuttled, or crane-lifted, over the mould assembly. For larger machines, the oven is stationary and the mould assembly is moved into it through a single door. Figure 3.9 shows a number of rocking oven machines in series.

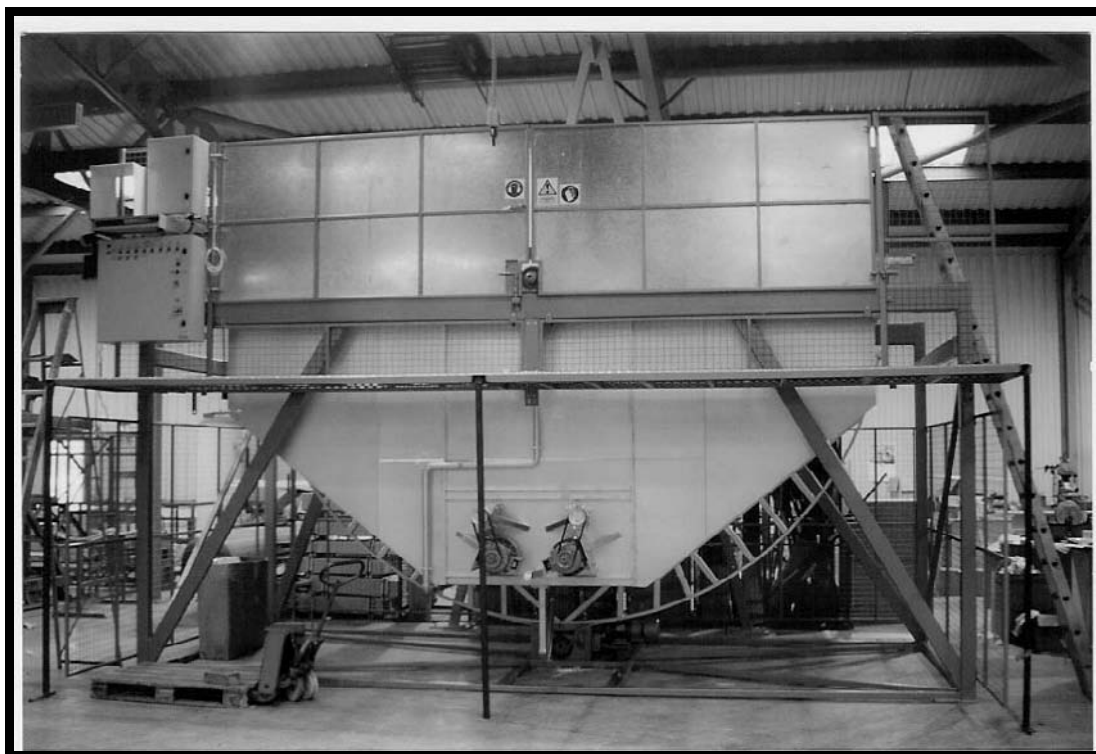


Figure 3.8 Rocking oven machine
Courtesy of Sorcerer Machinery

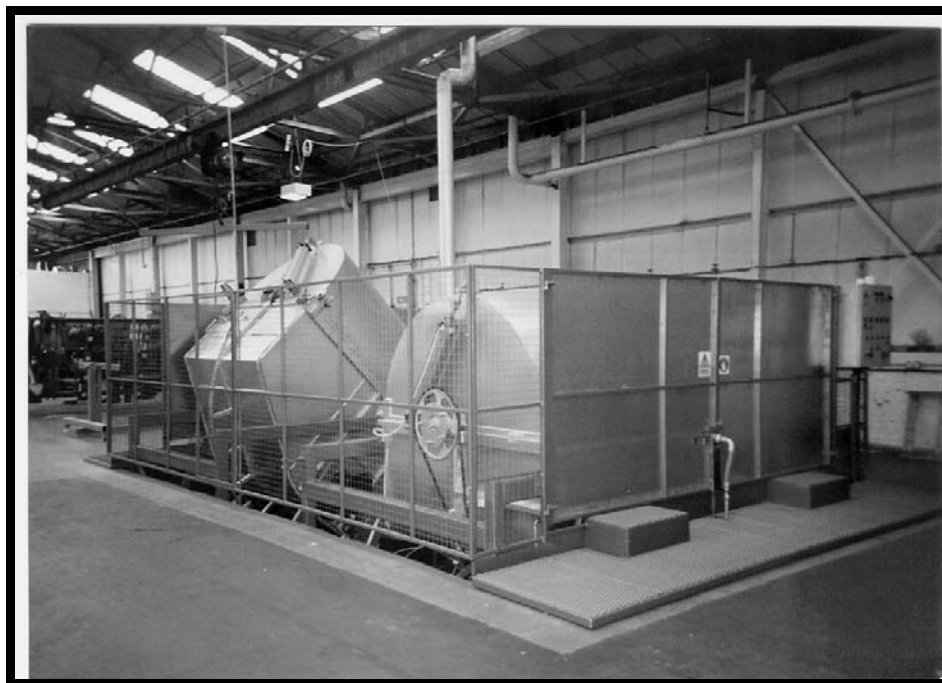


Figure 3.9 Rocking oven machines in series
Courtesy of Sorcerer Machinery

3.2.5 Other Types of Machines

Other types of mould heating involve the use of microwaves, induction heating, and infrared heating. These systems have been developed for specific applications, and can offer significant advantages in terms of faster, more efficient heating, but they are not in widespread use commercially.

Infrared machines offer high thermal efficiency, although it can be difficult to provide uniform heat to all areas of the mould. As well as the temperature being affected by the proximity of the heat source to the mould, support frames, brackets, spiders and machine arms can ‘shadow’ the mould from the heating elements. Infrared heating is normally used in a rocking oven type of machine design, and is best suited to parts that have an axis of symmetry.

Induction heating is an attractive concept for rotational moulding but if the mould wall varies in thickness, as is often the case in cast moulds and in the flange regions of sheet metal moulds, then the heat input from induction coils will be distorted causing non-uniform heating.

Direct conduction heating of a mould with a liquid (e.g., hot oil) is much more efficient than convection heating by air in an oven. This approach is being used commercially in a small number of specialised application areas – for example, with polycarbonate where high heating temperatures are needed. A problem with such machines is that it is difficult to avoid oil leaks in the rotating joints.

The most innovative types of rotational moulding machines to have emerged in recent years utilise electrically heated moulds in which a network of fine electrical conductors is

attached around the mould. In the original concept, the mould was made of a crosslinked reinforced plastic with embedded metal wires. The machine, illustrated in Figure 3.10, provides full biaxial rotation and the power supply to the heating elements is by means of slip rings in the rotating joints (Figure 3.11). Cooling is provided by blowing air through channels between the mould surface and the protective shell, as shown in Figure 3.12.

This machine concept has the advantage of direct heating of the mould and so it is very energy efficient. As the electrical machine does not use an oven, it also facilitates easy access to the mould for instrumentation, extra charges of material, etc. The disadvantages are that the moulds cannot easily be modified and cycle times are long since heating, cooling and servicing take place sequentially rather than in parallel as in shuttle or carousel machines. Another problem with the early designs of this type of machine was that the moulds were not very durable. Recent variants have involved infrared heating of metal moulds and these systems are more robust. The Leonardo machine (see Figure 3.13) takes direct electrical heating concept one step further and incorporates automatic mould filling and demoulding.

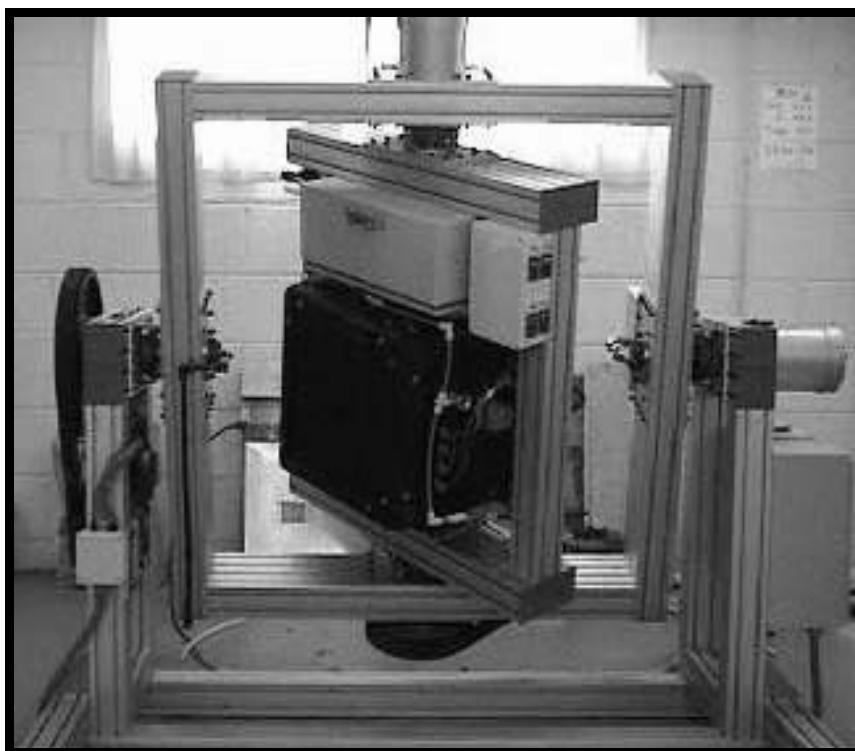


Figure 3.10 Direct electrical heating machine
Courtesy of PPA Teo



Figure 3.11 Slip rings

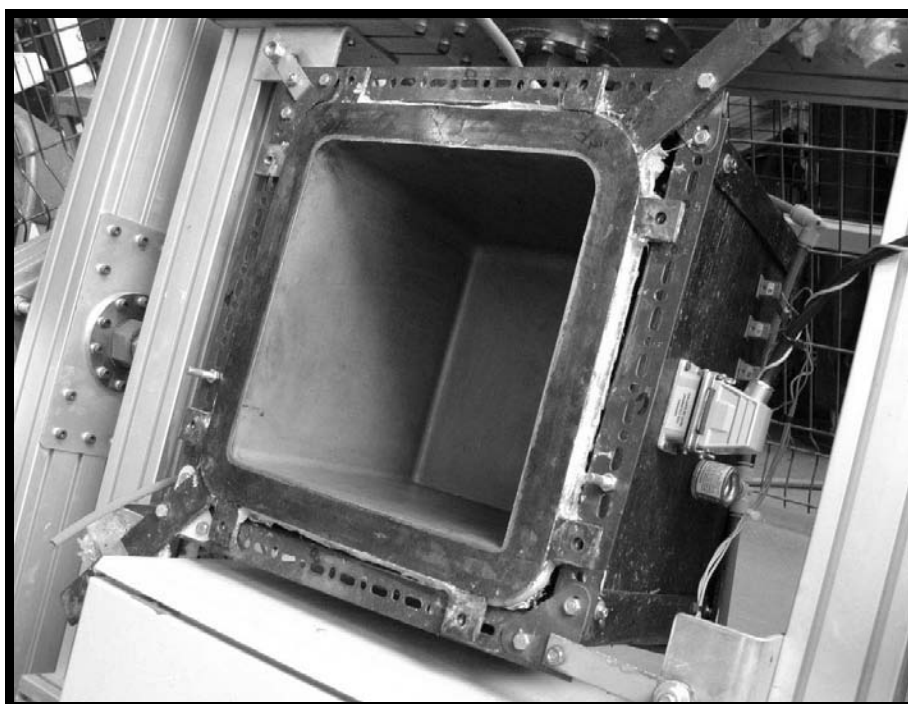


Figure 3.12 Mould opened on direct electrical heating machine



Figure 3.13 Leonardo automatic rotomoulding machine
Courtesy of Persico SpA

3.3 Mould Swing

The size, or capacity, of a commercial rotational moulding machine is specified in terms of two parameters. The first is the *maximum weight* of the mould or moulds that can be placed on the arm. The other parameter is the *mould swing*. These two parameters define the limits on the weight and size of mould that will fit on a particular machine.

The mould swing is linked to the size and shape of the space inside the oven and cooler. In the specification sheets, machine manufacturers provide an envelope inside which the mould must fit to ensure that it does not come into contact with the oven or cooler as it rotates. Examples of a ‘drop arm’ and a ‘straight arm’ are shown in Figure 3.14 and 3.15. Figure 3.16a illustrates the mould swing for an offset arm machine and Figure 3.16b illustrates the mould swing dimensions for a straight arm machine. To assess whether or not a mould will fit on a particular machine it is necessary to check if the mould height and longest diagonal dimension will fit inside the dotted lines.



Figure 3.14 A typical drop arm
Courtesy of Polivinil Rotomachinery SpA

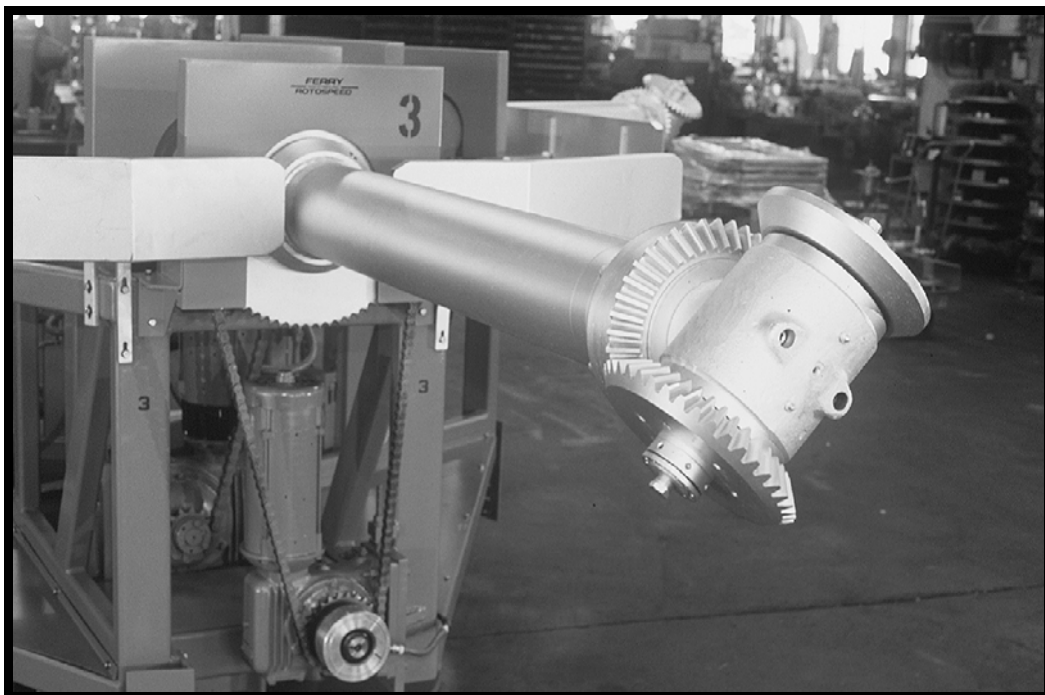


Figure 3.15 A typical straight arm
Courtesy of Ferry Industries Inc.

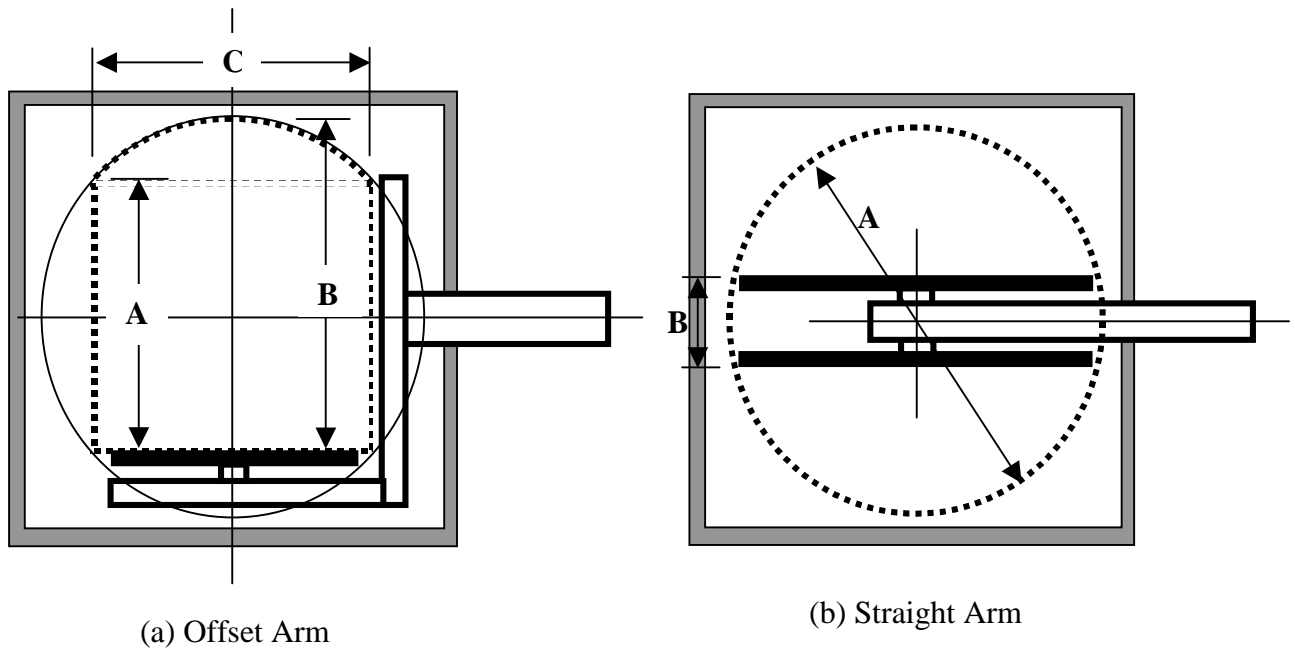


Figure 3.16 Mould swing diameters

3.4 Mould Speed

The rotational speed(s) of the mould is usually constant throughout the rotational moulding process from loading to unloading, and is monitored with tachometers. While the minor (plate/equatorial) and major (arm/polar) rotating speeds are usually set (nominally) by the operator, care must be taken to ensure that the speeds remain at the set values throughout the entire 360° paths followed by the mould. Improperly balanced mould spiders can cause non-constant rotational speeds during the cycle. Early machines had a fixed major-to-minor rotation ratio. Most modern machines allow independent changes to major and minor rotation speeds. This independence increases the versatility in moulding odd-shaped parts or complex spider assemblies. As new machine design concepts emerge it is likely that much more attention will be paid to strategic variations to the mould speeds throughout the cycle.

3.5 Speed Ratio

During rotational moulding, the speeds of rotation are slow and the plastic effectively resides in the bottom of the mould until it is picked up to form a coating on the inside of the mould surface. The thickness of the coating of the plastic on the mould wall depends on how regularly each point on the mould surface dips into the powder pool. The speed of rotation and, in a biaxial rotation machine, the ratio of the speeds about the two axes has a major influence on the thickness distribution of the plastic on the mould. For some moulded parts it is necessary to reverse the direction of rotation occasionally to ensure that all areas of the mould surface have access to the powder pool.

It is important to realise that it is the *actual* speeds of the arm and plate, and their ratio that are important. As the minor axis drive shaft is often inside the major axis drive shaft, the

minor axis speed reading on the moulding machine may be higher than the major (arm) speed. The *actual* (relative) speed of the minor axis is lower than the major (arm) speed because it is given by the difference between the machine readings for the minor and major axes. The speed ratio (arm/plate) is therefore often defined as

$$\text{Speed Ratio} = \frac{\text{MajorAxis}(rpm)}{\text{MinorAxis}(rpm) - \text{MajorAxis}(rpm)}$$

Thus if the minor axis speed reading on the machine is 15 rpm and the major axis speed is 12 rpm, then the Speed Ratio (arm/plate speeds) is 3:1. Table 3.1 gives typical values of speed ratios (arm:plate) that are recommended for different mould shapes.

Table 3.1 Recommended speed ratios for various mould shapes (adapted from recommendations by McNeill Akron Co.)	
Speed ratio	Shapes
8:1	Oblongs, straight tubes (mounted horizontally)
5:1	Ducts
3:1	Cubes, balls, rectangular boxes, most regular 3-D shapes
2:1	Rings, tires, mannequins, flat shapes
1:2	Parts that show thinning when run at 2:1
1:3	Flat rectangles, suitcase shapes
1:3	Curved ducts, pipe angles, parts that show thinning at 3:1
1:5	Vertically mounted cylinders

It is very important to recognise that the speed ratio, and rotation reversal if it is used, only affects material distribution during that part of the heating cycle when the plastic is being laid up against the mould wall. This occurs during the middle part of the oven stage (see Section 3.9) and so speeds, speed ratios and rotation reversals are important at this time. Once the plastic is in position against the mould wall it is usually too viscous to move by any significant amount. The rotational speeds and the speed ratio are less critical in the final stages of the process. Future machine designs that include the possibility of continuous rotational speed changes may use this fact more strategically. In some rock and roll machines it is common to stop the rocking motion and only maintain the mould rotation during the cooling stage.

3.6 Oven Air Flow Amplification

The efficiency with which the mould is heated in the oven depends on effective air flow around the mould surface. There are two practical issues that have an adverse influence on effective and uniform air flow across the entire mould assembly. Rotational moulding has traditionally long cycle times. As a result, moulders frequently tier mould assemblies in order to make more efficient use of the swept volume of the arm. Air circulation to the inner surfaces of these tiered assemblies is often impeded by outside moulds and the architecture of the spider supports. This can result in non-uniform heating and cooling of a particular mould.

Efficient energy transfer can also be impeded even when single moulds or single-tiered spiders are used. In some cases, vanes or baffles are welded to the mould surface or to the spider to help deflect the air flow. For deeper recesses, it is very difficult, if not impossible, to get high-velocity air to the bottom of the inner mould surfaces simply by baffling. Currently, a limited flow of high-velocity air, supplied through a hollow element in the arm, is fed to a venturi or air amplification device (air mover) as illustrated in Figure 3.17.

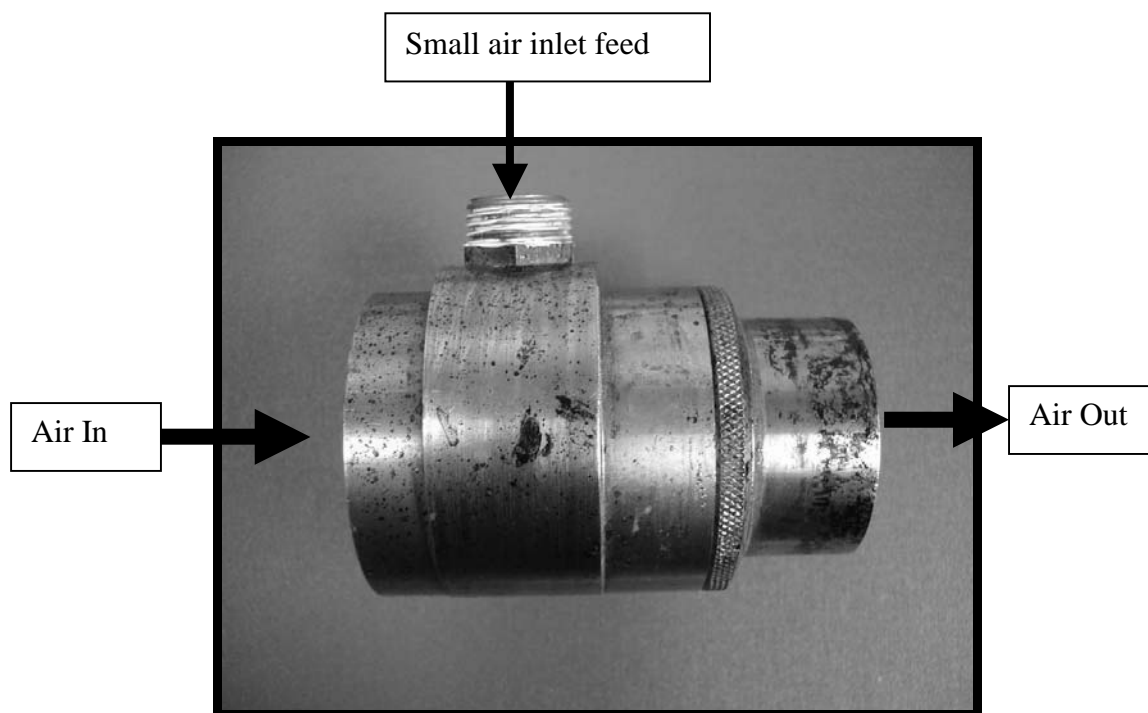


Figure 3.17 Example of a Venturi ('air mover')

As the high-velocity air flows into the throat of the venturi, it draws heated oven air into the inlet, and propels it against the mould surface, sometimes in a swirling motion to improve heat transfer as illustrated in Figure 3.18. Venturis can also be used to draw cooler air to some areas of the mould in the cooling bay.

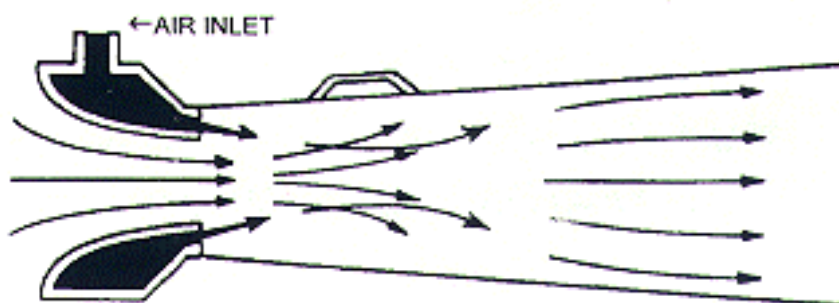


Figure 3.18 The Venturi principle

3.7 Cooling

Once the plastic has all melted and formed a coating against the mould inner surface, the plastic, the mould and the ancillary supporting structure must be cooled. The most popular cooling media are water and air. Most commercial rotational moulding machines are equipped with both, and many have options such as water spray, water mist/fog, etc. As discussed elsewhere (Section 2.9), sprayed water is an extremely effective way of reducing mould assembly temperature, but quenching may not always be desirable. As cooling normally occurs from the outside only, fast cooling results in an unsymmetrical structural formation across the part wall, which leads to warpage. Typically, sequential applications of still air, forced air, water mist or fog are used to alleviate warpage problems. On a carousel machine, if cooling does not control the rotational moulding cycle, cooling may be done gently using only room temperature air.

The typical water cooling station is a galvanized or stainless steel sheet metal box, with a floor having adequate drain holes. There are many types of water jetting or spraying nozzles. If drenching is needed, high volume flow 'shower heads' are mounted above the mould assembly. Fog or fine mist nozzles are usually mounted at the corners of the cooling chamber, to provide a suspended 'cloud' of moisture droplets with low settling velocity. This allows the mould assembly to pass through the cloud and leads to more uniform cooling. Fog and mist nozzles are recommended when the mould is relatively thin. Chemically treated and conditioned water is always recommended, to minimize scale build-up and rusting of steel parts on the mould assembly.

Air-moving fans are selected for high velocity, high volume flow. Positive ventilation is needed in the cooling station if the plastic gives off noxious fumes, such as hydrogen chloride from PVC. Although there is little need to rotate the mould when the plastic has solidified, to provide uniform cooling, the mould assembly is usually rotated in the cooling environment throughout the cooling cycle.

3.8 Developments in Machine Control

Since its inception, rotational moulding has been regarded as a low technology manufacturing method. Traditionally the quality of the moulded part has relied heavily on the skill and experience of the machine operator. The apparent simplicity of the process meant that it did not attract much attention from researchers or system developers. Or perhaps it was the complexity presented by the rotation of the mould that meant that process control experts did not give rotomoulding much attention. Whatever the reasons, the lack of accurate process control undoubtedly hampered rotomoulding from achieving its true potential.

Fortunately that situation is changing rapidly. As a result of detailed studies of what is going on inside the mould, the nature of rotational moulding is now well understood. And this is leading to major new developments in machine control. These major advances are being made primarily in the nature of the control. Instead of controlling the environment *outside* the mould, it is being realised by machine manufacturers that process control should be based on the conditions *inside* the mould.

Modern machine control systems are now based on the temperature of the air inside the mould and the temperature difference across the wall of the plastic. Serious attempts are also being made to monitor the pressure of the air inside the mould so that it also can be controlled. This leads to the concept of active, rather than passive, venting to ensure that the main function of the vent is being achieved.

The following sections outline the benefits to be gained by using the modern machine control methodologies.

3.9 Internal Air Temperature Measurement in Rotational Moulding

In the vast majority of cases, the rotational moulding process involves heating a powdered plastic in a rotating metal mould. Normally the heating is done in an oven and this is the situation that will be considered in detail, although the basic principles that are described below will apply to any heating method. For proper process control in rotational moulding it is important to record the time-dependent variations of the oven temperature, the mould temperature and the temperature of the air inside the mould. Typical graphs of these variables are illustrated in Figure 3.19. The shape of the internal temperature graph, in particular, is unique to rotational moulding and it can be used to provide very close control over the whole cycle.

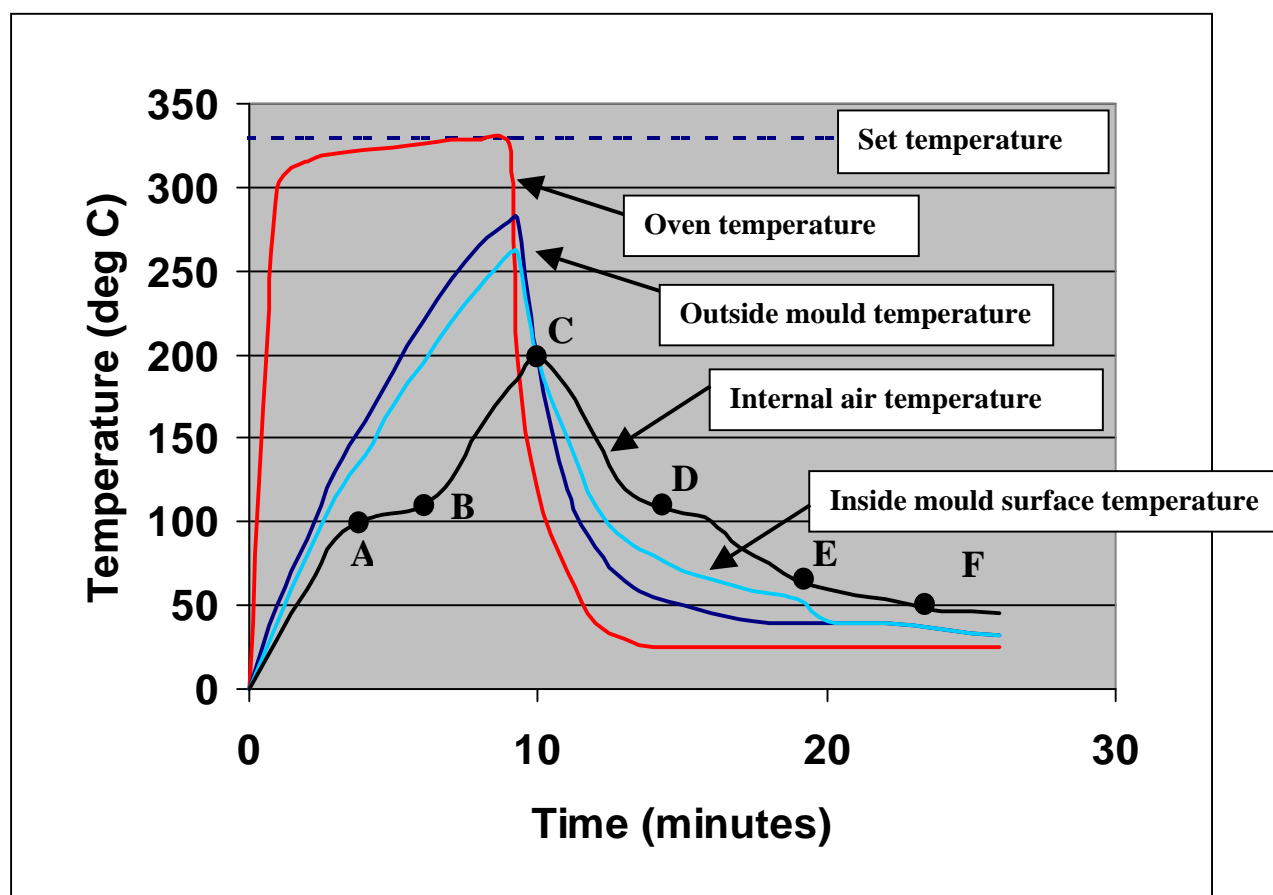


Figure 3.19 Typical temperature traces for a rotational moulding cycle

Let us consider the temperature traces in Figure 3.19 in detail. The set temperature for the oven is 330 °C (626 °F). When the cycle starts, the temperature of the air in the oven increases steadily towards the set temperature. It is several minutes before the temperatures of the mould, the plastic and the air inside the mould begin to increase in response to the increasing oven temperature. The lower line in Figure 3.19 is the temperature of the air inside the mould. The two lines above it are the temperatures of the outside surface and inside surface of the mould. As expected, in the oven the outer surface of the mould has the higher temperature and in the cooling chamber the outer surface of the mould is the cooler.

The temperature graph for the air inside the mould provides the most interesting information. Initially the temperature of the air inside the mould increases steadily. Up to Point A there is no powder sticking to the mould because the plastic has not reached its 'tacky' temperature. The rotational speeds of the mould about the two perpendicular axes are not critical during this period as the powder is simply tumbling about in the mould. If a graphic has been placed in the mould it is generally recommended to use slower speeds during this initial period to avoid scuffing it off the mould wall.

At Point A the plastic powder is sufficiently hot to start sticking to the mould. With polyethylene this stage is usually reached when the inner air temperature reaches a value of about 100 °C (212 °F). The rate of increase of the internal air temperature now slows because the melting of the plastic absorbs most of the heat being put into the system. This means that less heat is available to increase the temperature of the air inside the mould. The speeds of rotation, and their ratio, are very important at this stage because this is the period when the plastic coating is being formed on the inside of the mould. If the speed ratio is incorrect then the wall thickness distribution of the moulded part will not be correct.

The flat plateau on the internal air temperature graph continues for several minutes. By the time that Point B is reached, all the plastic powder has adhered to the mould wall and there is no longer loose powder tumbling about in the mould. A significant amount of the melting of the plastic has been completed and so the majority of the thermal energy being input to the system is once again directed to heat the internal air. At this point the internal air temperature starts to increase more rapidly again, at approximately the same rate as in region 0A. The plastic has now adhered to the inside wall of the mould. Close to the metal mould, the plastic powder will already have started to coalesce and densify. Towards the inner free surface the plastic will still be in the form of a loose powdery mass. During the region BC, the coalescence process is completed as the powder particles join together to form a uniform melt, which spreads from the mould wall towards the inner, free surface.

When the powder particles are laying up against the mould wall, they trap irregular pockets of gas as illustrated at Stage 1 in Figure 3.20. These pockets gradually transform into spheres (Stage 2) and over a period of time they diffuse out of the plastic. It should be noted that the pockets of gas ('bubbles') do not push their way through the melt because the molten plastic is too viscous to allow this to happen.

As a practical quality control measure, moulders will take a slice through the wall thickness of the moulded part and look for the presence of some bubbles towards the inner free surface. This is Stage 3 in Figure 3.20. This is regarded as the correct level of 'cooking' for the plastic. An even better moulding is obtained when the bubbles just disappear totally but of course if the moulder looks at a section that has no bubbles, there is

no way of knowing if the bubbles have just disappeared or perhaps had disappeared many minutes previously. Once the bubbles disappear, degradation processes very rapidly start to have an effect and so it is better to be under-cooked rather than over-cooked.

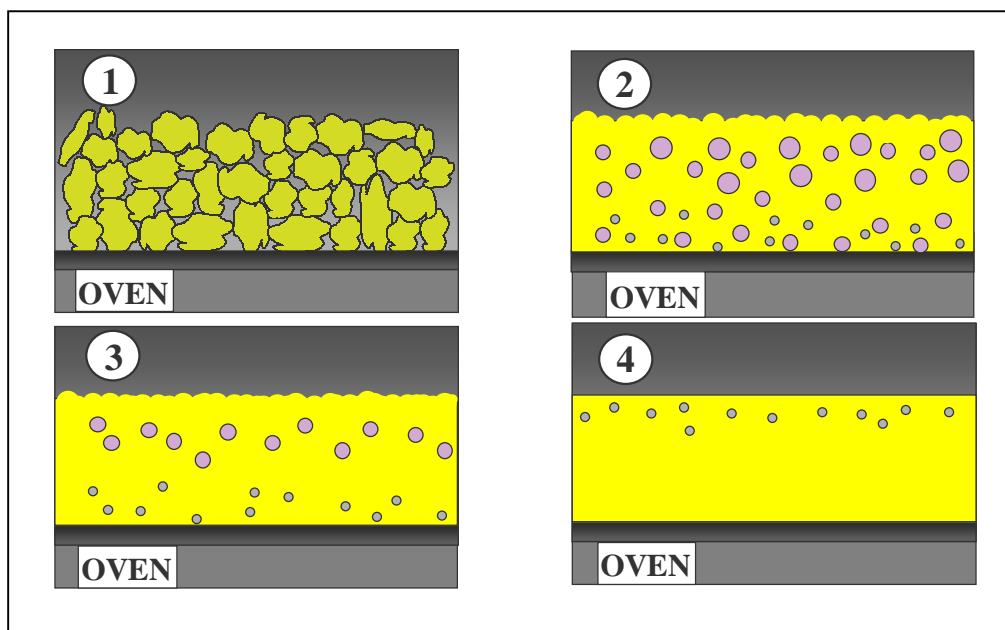


Figure 3.20 Bubble formation and removal in rotational moulding

The internal air temperature trace is very useful as a quality control check because extensive trials have shown that independent of any other machine variable, the bubbles will have just disappeared when the internal air temperature reaches a critical value. Typically for rotational moulding grades of polyethylene this is at about 200 °C (392 °F). Thus, by ensuring that this value of internal air temperature is always reached, the moulder is able to produce a good moulding every time.

At this point the mould can be taken out of the oven and the cooling stage begins. It should be noted in Figure 3.19 that it is common for the temperature of the internal air to continue rising after the mould comes out of the oven. This is particularly the case if the plastic part is thick. It is necessary to allow for this ‘overshoot’ when determining the optimum time in the oven.

Once cooling begins, the internal air temperature starts to decrease. The rate of decrease will depend on the type of cooling in addition to the part wall thickness and thickness of the mould material. Water-cooling causes a rapid drop in temperature whereas air-cooling causes a more gradual rate of decrease of temperature. During the initial period of cooling, the plastic attached to the mould wall is still molten. Its structure is being formed and the rate of cooling will have a major effect on the properties of the end product. The impact strength of the moulding and physical characteristics such as shrinkage and warpage are affected dramatically by the cooling rate.

During the initial phase of cooling, the internal air temperature decreases at an approximately constant rate, but at a certain point the slope of the internal air temperature trace changes markedly (Point D). This is associated with the solidification of the plastic.

As it solidifies and crystallizes, the plastic gives off heat which means that the internal air is not able to decrease in temperature as quickly as before. Once the plastic has become solid across the wall section of the moulded part, the internal air temperature starts to decrease again at a rate similar, but usually slower, than that occurring previously. As the plastic is now solid, the rate of cooling has less effect on the morphology of the plastic. Therefore fast cooling, using water, is permissible. The only thing that one has to be careful about is the unsymmetrical cooling across the wall thickness, if the mould is cooled from the outside only. This will tend to cause warpage, as discussed in more detail in Section 5.4.

The final important stage in the cycle is Point E. It may be seen in Figure 3.19 that this is characterised by a slight change in slope of the internal air temperature graph. This indicates that the plastic is separating from the mould wall and an insulating layer of air is forming between the plastic and the mould. At this point, the external cooling becomes less efficient and so the internal air temperature cannot decrease as quickly as before. It may be seen in Figure 3.19 that the temperatures of the inner and outer surfaces of the mould become equal after this point. Eventually the demoulding temperature, Point F, is reached and the part can be removed from the mould. It should be noted that the moulded part will cool more slowly in air than it will when it is inside the mould.

The next generation of commercial rotational moulding machines will almost certainly monitor and control the temperature of the air inside the mould. Existing machines can be retrofitted with control systems, which monitor the air temperature inside the mould using slip rings or radio transmission of data from the rotating mould. The Rotolog is the most common way of achieving this and is illustrated in Figure 3.21 The setting up of a Rotolog on a commercial machine is illustrated in the next section.



Figure 3.21 The Rotolog process control system
Courtesy of Ferry Industries Inc.

3.10 Preparation of Rotolog for Moulding Trials

The Rotolog unit consists of a transmitter unit, which rotates with the mould throughout the cycle, and a receiver that is connected to a computer at some convenient location away from the moulding machine (Figure 3.22). The transmitter unit has electronics that enable the temperature of the mould, the oven and, most importantly, the air inside the mould to be monitored in real time throughout the moulding cycle. The transmitter electronics are housed in an insulated container to protect them from the high temperatures in the oven.

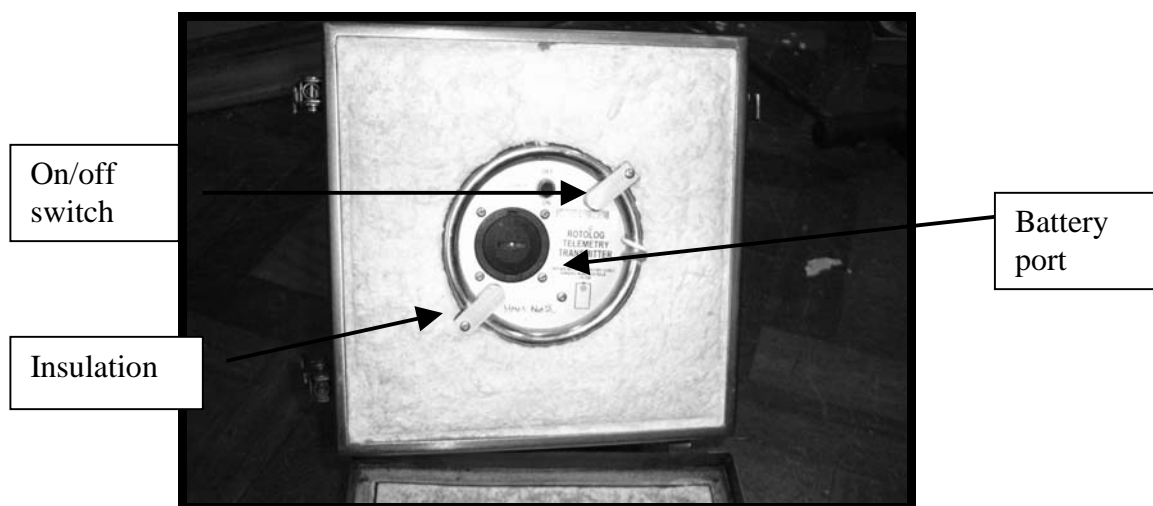


Figure 3.22 Rotolog with lid removed

The thermocouple connectors are housed at the back of the unit (Figure 3.23), inside a protective cover. The cover plate shields the thermocouple joints (Figure 3.24) when using a water spray. The transmitter aerial is also located at the back of the unit.



Figure 3.23 Rotolog on a mould



Figure 3.24 Rotolog showing thermocouple block

Attachment of the Rotolog is carried out via the fitting of the mounting plate to a suitable place on the mould. The position of the mounting plate and hence the Rotolog must be such that the unit does not (a) shield the mould from the oven hot air or cooler cold air or (b) prevent proper rotation of the arm or plate.

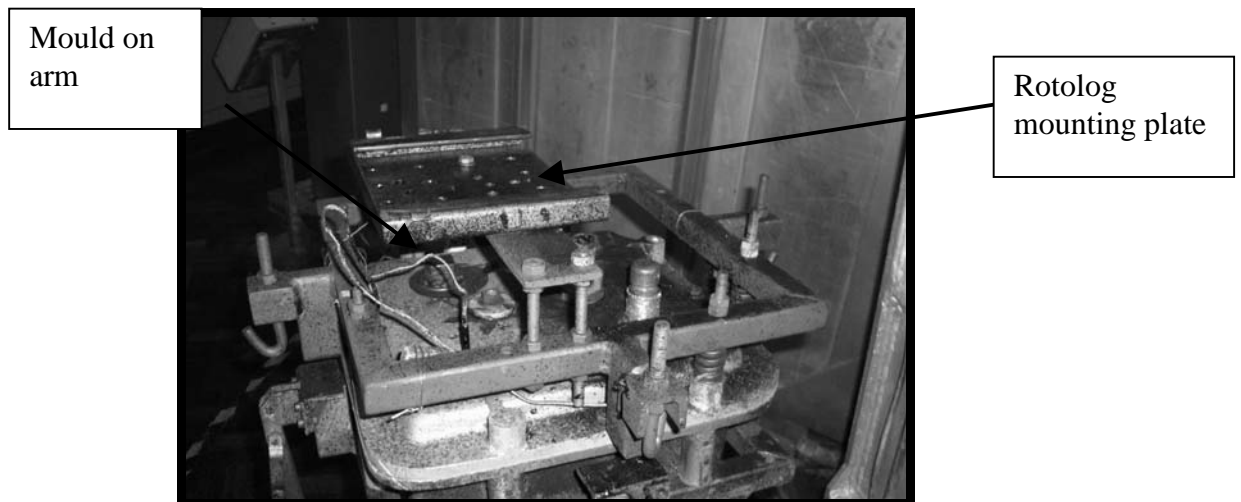


Figure 3.25 Mould with Rotolog mounting bracket

Guide rails on the base of the unit aid mounting of the Rotolog onto the arm of the machine and two toggle clamps are used to secure it in position (Figures 3.25-3.27). There is also a provision for a locking pin if required.



Figure 3.26 Rotolog being attached to mounting bracket



Figure 3.27 Lid being attached to Rotolog

The thermocouples are then connected to the thermocouple block. In normal operation it is recommended that a thermocouple extends down the breather or vent tube since the internal air temperature (IAT) information obtained is crucial in monitoring the cycle. A short thermocouple can also be used to record the temperature of the environment outside the mould (e.g., oven / sintering zone / cooler / demoulding area) (Figure 3.28).

Thermocouples
connected



Figure 3.28 Thermocouples being attached to Rotolog



Figure 3.29 Rotolog signal receiver

Double clicking the Rotolog icon on the PC begins the software enabling real time recording of temperatures (Figures 3.29 and 3.30).

Windows Rotolog
software started



Figure 3.30 Rotolog software on the computer screen

3.11 Monitoring Pressure Inside a Mould

There is extensive evidence from numerous research studies to show that it is desirable to have a positive pressure inside the mould during rotational moulding. This should occur after the plastic powder has melted and formed a loose structure on the inside surface of the mould. The net effect is to remove the bubbles physically from the melt and therefore the time in the heating environment does not need to be so long. This in turn leads to shorter cycle times and better mechanical properties (less thermal degradation).

If the pressure is maintained during the cooling cycle, this helps to keep the part against the mould wall until the pressure is released. If the latter is controlled on a temperature basis, rather than a time basis, then part shrinkage will be accurately controlled, warpage will be minimised and faster cycle times can be achieved. The latter benefit arises from the better heat conduction to the metal mould, compared with convective heat transfer to still air if the part separates from the mould. In both the heating and cooling parts of the cycle, the internal pressure does not need to be very high $\sim 2 \text{ lbf/in}^2$ (0.14 atmospheres or 13.8 kPa) is usually enough to produce the desired effects.

Despite the benefits of mould pressurisation, it is not widely understood or used in the rotational moulding industry. Moulders are quite rightly concerned about safety issues, and indeed the use of large moulds may rule out the possibility of internal pressure. Moulds must be designed to withstand the forces that are generated deliberately or unknowingly. A problem with current moulds is that even if one wanted to provide a controlled environment where a required positive pressure can be maintained, there are generally inadequacies in the parting line and the vent. Usually the parting line is not airtight, so that leaks can occur. Also, vents are normally not designed properly so that they are either restricted or blocked, leading to excessive pressure or partial vacuum inside the mould.

Despite the fact that moulders say they do not want to pressurise their moulds, in most cases there are pressures inside the mould, due to ineffective venting. Normally these pressures are not occurring in a controlled fashion and so do not create desirable effects. Therefore it is recommended that the pressure inside the mould should be monitored – this can subsequently lead to control of the pressure.

For accurate process control in rotational moulding it is highly desirable to be able to monitor the pressure inside the mould. It is difficult to generalise about how this can be done because there are so many different types of rotational moulding machines. On a 'rock and roll' or 'rocking oven' machine it is relatively easy to measure the mould temperature, the temperature of the air inside the mould and the pressure throughout the cycle. Figure 3.31 illustrates one convenient way to achieve this. A system such as this will give continuous feedback on both temperatures and pressures throughout the cycle.

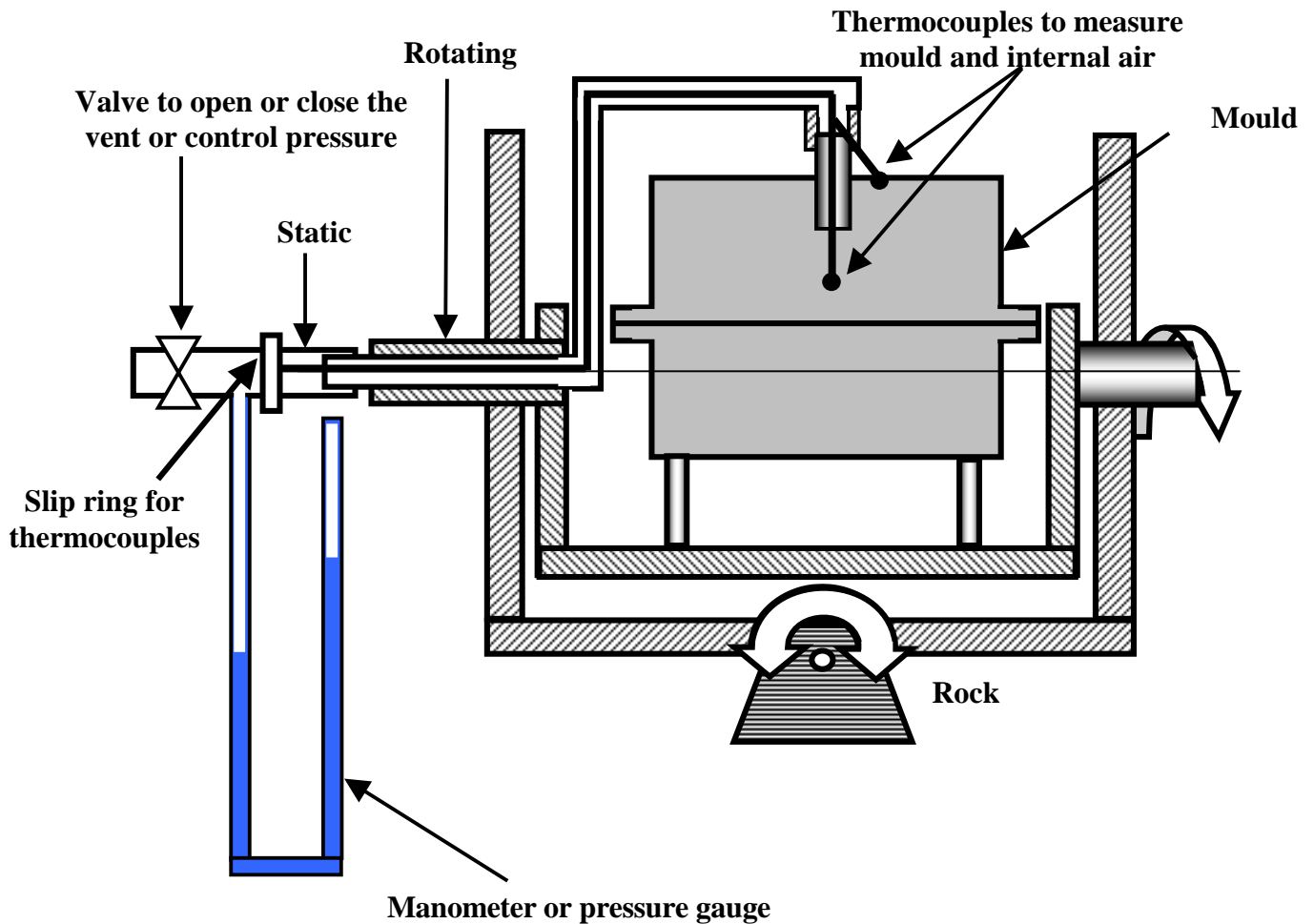


Figure 3.31 Pressure and temperature monitoring system on a rock and roll or rocking oven machine

In a biaxial machine, a bit more engineering ingenuity is needed but effects similar to those illustrated in Figure 3.31 can and have been achieved on full-scale biaxial rotational moulding machines. Figure 3.32 illustrates how the gas line through the arm of a biaxial, or rock and roll machine could be used as the conduit for both temperature and pressure measurements from inside the mould. Thus it may be possible to vent the mould or control the pressure in the mould using the gas line through the arm of the machine.

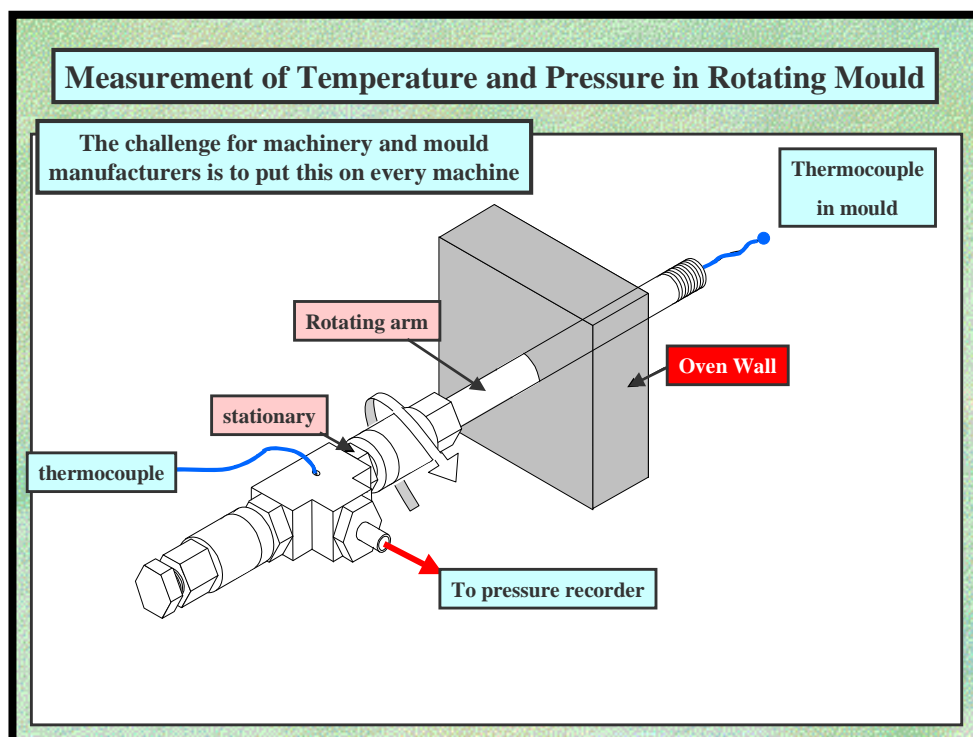


Figure 3.32 Pressure and temperature monitoring system using gas line on moulding machine

The sequence of photos (Figure 3.33 to Figure 3.41) illustrates a typical rotomoulding factory set-up for mould pressurisation and internal air temperature measurement.



Figure 3.33 Pressure regulators reduce factory air pressure from 120 psi to 10 psi
Courtesy of NOVA Chemicals

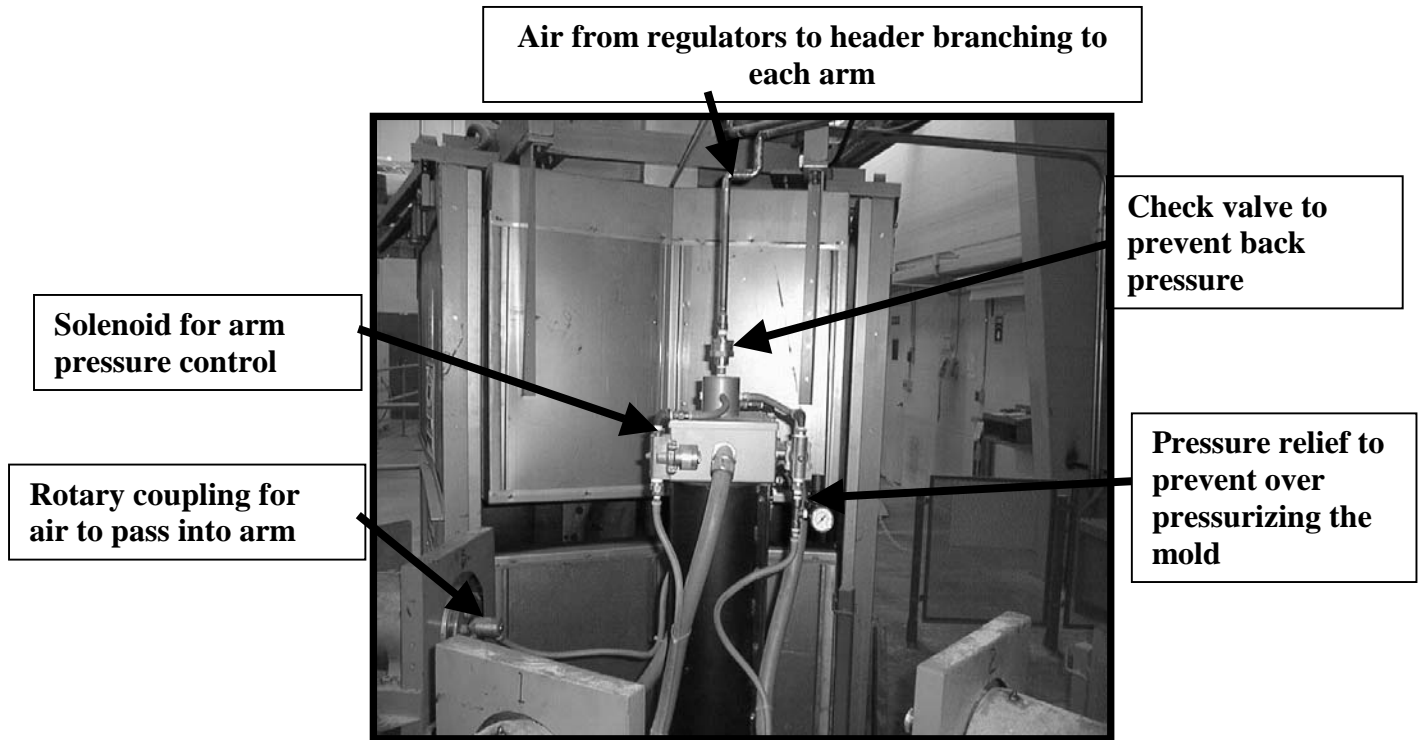


Figure 3.34 Air is fed to arms via check valve and solenoids



Figure 3.35 Air passed to rotary couplings

Air tube along the arm to bottom of mould (second rotating coupling)

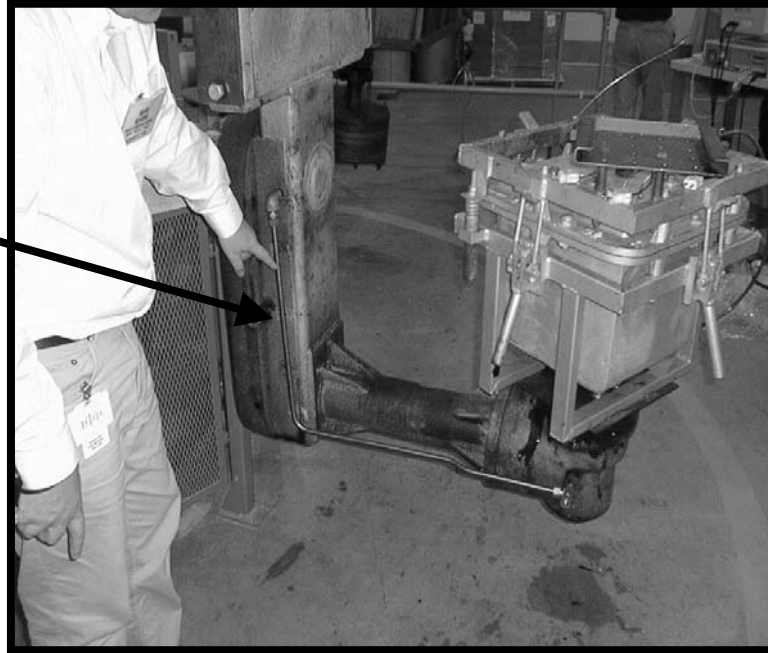


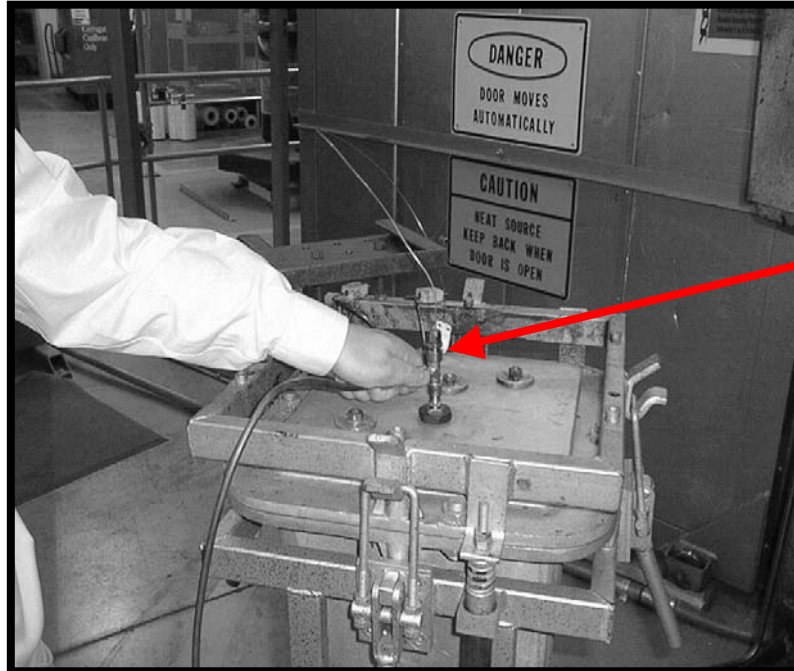
Figure 3.36 Air line to second rotary coupling at plate

Tube for air to go to the vent for pressurization



Coupling where air leaves the arm

Figure 3.37 Air line from second rotary coupling to mould



Coupling to vent
tube to allow air in
for pressurization

Figure 3.38 Air line attached to mould vent



Figure 3.39 Mould attachment for air line and thermocouple



Figure 3.40 Thermocouple extending through vent tube

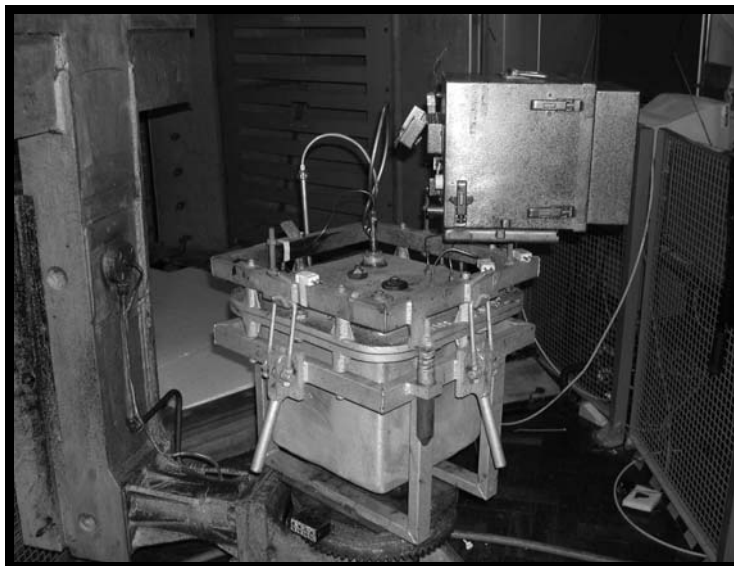


Figure 3.41 Mould with Rotolog and air line ready for oven

Bibliography

1. S. Scaccia, Future Trends in Rotational Molding, *Rotation*, 2002, **11**, 3, 38.
2. S. Scaccia, A Dream of the Future: A Challenge for Today, *Rotation*, 2000, **9**, 6, 48.
3. J. Stout, What's New in Rotational Molding and Tooling, *Rotation Buyers Guide*, 1999, 15.
4. Anon, *Venting*, Association of Rotational Molders, Oak Brook, Illinois, USA, 1999.
5. Anon, *Rotational Molding Equipment*, Association of Rotational Molders, Oakbrook, Illinois, USA, 1996.
6. Anon, *Slush Rotational Moulding*, AtoChem, France, 1987.
7. Anon, *Guide to Induction Heating Equipment*, The Electricity Council/British National Committee for Electroheat, London, 1984.
8. Anon, *Dielectric Heating for Industrial Purposes*, The Electricity Council/British National Committee for Electroheat, London, 1983.
9. B. Blaiklock, Practical Process Control for Rotomoulding, *Rotation*, 2002, **11**, 1, 18.
10. A.F. Bockmann, Rotational Moulding - Recent Developments in Machine Construction and Moulding Procedure, *Kunststoffe*, 1971, **61**, 7, 1.
11. T.A. Corlett, Rotomolding and CNC Routers: Making it Work, *Rotation*, 1999, **8**, 1, 74.
12. T.A. Corlett, CNC Routers Coming Soon to a Rotational Molding Shop Near You, *Rotation Buyers Guide*, 1999, 10.
13. W.H. Covington, Rotational Moulding Machines, in *Rotational Moulding of Plastics*, 2nd Edition, Ed., R.J. Crawford, Wiley, New York, 1996, 100.
14. H. Covington, Black Art or Technology? A Look at Equipment in the Rotational Molding Industry, *Rotation*, 2000, **9**, 6, 58.
15. J. Crouch, Multiple Passage Gas Supply System for Rotomoulding Machines, in *BPF Rotomoulding Conference*, Leicester, UK, 1995.
16. R. Hentrich, Rotational Molding Tools, *Mold Making Handbook for the Plastics Engineer*, Ed., K. Stoeckhert, Hanser, Munich, 1983, 148.
17. J.A. Jennings, High Intensity Mixers, *Rotation*, 1999, **8**, 5, 24.
18. J. Jennings, Powder Dispensing Systems, Accuracy for Profitability, *Rotation*, 2000, **9**, 3, 32.
19. C. MacKinnon, Venting in Rotational Moulding - Another Perspective, *Rotation*, 2000, **9**, 1, 40.
20. P. Nugent, Venting of Molds for Rotational Molding, in *20th Annual Spring ARM Meeting*, Orlando, Florida, 1996.
21. C. Persico, Leonardo - Automated Molding Opens a New Era, *Rotation*, 2002, **11**, 6, 36.
22. S. Scaccia, Developing Tooling Technologies, *Rotation*, 1999, **8**, 2, 60.

23. S. Scaccia, Cast Aluminium Moulds, in *Rotational Moulding of Plastics*, 2nd Edition, Ed., R.J. Crawford, Wiley, New York, 1996, 143.
24. S. Scaccia, Developments in Cast Aluminum Tooling, in *BPF Rotamoulding Conference*, Leicester, 1995.
25. S. Scaccia, Plaster Cast Aluminum Tooling - A Guided Tour, *Rotation*, 1994, **3**, 3, 32.
26. D. Schraegle, Trip Mold - New Tooling Technology for Rotational Molding, *Rotation*, 2001, **10**, 2, 36.
27. M. Spencer and M. Kearns, Intelligent Process Control for Rotational Molding, *Rotation*, 2001, **10**, 2, 44.
28. R. Syler, A Mold With a View, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
29. A. Wytkin, Composite Mold Upgrades Rotomolding Process Control, *Modern Plastics*, 1998, January, 2.
30. A. Wytkin, A New Rotational Moulding System - Composite Mould Technology, *Rotation*, 1997, **6**, 3, 30.
31. R.J. Crawford, The Importance of Venting in Rotational Moulding, *Rotation*, 1999, **8**, 5, 20.
32. R.J. Crawford, Active Venting in Rotational Moulding, *Rotation*, 2002, 11, 3, 32.
33. M. Wright and R.J. Crawford, Hot Air Convection Heating in Rotational Molding - The Cold Reality, *Rotation*, 2002, **11**, 6, 32.
34. M. Wright and R.J. Crawford, Effects of Machine Variables on Cycle Time During Rotational Molding - Part 1, *Rotation*, 2003, **12**, 2, 20.
35. M. Wright and R.J. Crawford, Effects of Machine Variables on Cycle Time During Rotational Molding - Part 2, *Rotation*, 2003, **12**, 3.
36. M. Wright, J.A.G. Spence and R.J. Crawford. An Analysis of Heating Efficiency in Rotational Moulding. in *SPE ANTEC*, Toronto, Canada, 1997.
37. D.I. Abufara, M.P. Kearns and R.J. Crawford, Control of Rotational Moulding Process Using Neural Network Techniques, in *SPE ANTEC*, New York, USA, 1999.
38. M. Beltran, M.P. Kearns and R.J. Crawford, Experimental Study of the Effect of Mould Material on Cycle Time during Rotational Moulding, *Rotation*, 2001, **10**, 6, 24.
39. R.J. Crawford and E.J. Wright, Thermal Effectiveness of Mould Materials, *Rotation*, 1998, **7**, 1, 17.

Chapter 4 – Materials for Rotational Moulding

4.1 Introduction

There are two main classes of plastics. About 80% of the millions of tons of plastics used in the world every year are ‘thermoplastic’ and the remaining 20% are ‘thermosetting’. Thermosetting polymers are those that undergo an irreversible change during moulding - as happens to an egg when it is boiled. Thermoplastics, on the other hand, can go through a continual cycle of softening when they are heated and solidifying when they are cooled – like candle wax. The vast majority of the plastics used in rotational moulding are thermoplastics, but some moulders use materials with thermosetting characteristics – for example, crosslinked polyethylene.

Polyethylene and polypropylene are thermoplastics that are part of the same *polyolefin* family. Along with polystyrene and polyvinyl chloride they are the most common thermoplastic polymers, and are frequently called the *commodity* plastics. *Engineering* plastics have higher performance criteria and are generally more expensive than commodity materials. Nylon, acrylonitrile-butadiene-styrene terpolymer (ABS) and polycarbonate are typical engineering plastics. *High-performance* plastics generally have properties superior to engineering plastics and are even more expensive. Fluoroethylene (FEP) and polyether etherketone (PEEK) are typical high-performance plastics.

Thermoplastics, by their nature, are amenable to reuse and recycling. Although their properties deteriorate each time they go through a cycle of heating and cooling, thermoplastics are relatively easy to work with during moulding, and waste material need not be totally discarded. At the end of its useful life, a thermoplastic part could be melted and moulded into a different shape. The only problems are the practical ones of ensuring that there are no contaminants in the plastic, and it is often necessary to replace fillers and additives that have been consumed during the earlier moulding process.

Thermosetting plastics are more difficult to re-use or recycle. Once the material has solidified into its desired shape, no amount of heating will cause it to revert to a form where it is mouldable. Excessive heating will cause the material to degrade and break down into a powdery ash. Sometimes it is possible to re-use the material in this form as a filler, but this is rarely an economical option.

An important subdivision within the thermoplastic group of materials is related to whether they have a *crystalline* (ordered) or an *amorphous* (random) structure. In practice, it is not possible for a plastic to have a totally crystalline structure. Some plastics, such as polyethylene and nylon, can achieve a high degree of crystallinity, but they are probably more accurately described as *partially crystalline* or *semi-crystalline*. Other plastics such as acrylic and polystyrene are always amorphous. The degree of crystallinity in those plastics capable of crystallising is very dependent on their thermal history and hence on the processing conditions used to produce the moulded article. In turn, the mechanical properties of the moulding are very sensitive to whether or not the plastic possesses crystallinity. These facts are very important for rotational moulders because the rate of the cooling has a major effect on the degree of crystallinity and hence on the properties of the moulded part.

In general, plastics have a higher density when they crystallise due to the closer packing of the molecules. The more crystalline the material, the more it will exhibit the following characteristics:

- Greater rigidity
- Greater strength
- Lower friction, hard wearing
- Greater hardness
- Greater resistance to environmental stress cracking
- Greater creep resistance
- Greater shrinkage
- Lower toughness

4.2 Typical Characteristics of Rotationally Moulded Plastics

The range of plastics now available to moulders is extensive. However, not all plastics can, as yet, be rotationally moulded successfully. There are some general criteria that plastics have to meet before they may be classed as being suitable for this processing technique. Firstly, they must be capable of being produced economically as a free flowing powder (or they should be conveniently available in liquid form). Secondly, as the plastic is heated, it should transform from the solid state to the molten state relatively quickly so as to avoid clumps being formed inside the rotating mould.

The plastic melt must also have the ability to coat the mould surface evenly, so as to produce a part of the desired wall thickness distribution. Generally this includes the ability to form a smooth inner surface, as there is no mould to define the contours of the free surface. However, the plastic melt must not be of low viscosity, or flow too freely in the melt form, because the rotational speeds are relatively slow and a low viscosity plastic would tend to flow to the bottom of the mould. It is also important that the thermal stability of the melt is such that it can withstand long times at elevated temperatures without degradation.

As with other processing methods for plastics, there is no ideal material for all applications. Hence, the designer must select the appropriate plastic and grade to suit the shape and performance specification of the end-product. Typical rotomoulding materials are discussed in the following sections.

4.3 Materials Used in Rotational Moulding

Currently polyethylene, in its many forms, represents about 90% of all polymers that are rotationally moulded. PVC plastisols are also widely used, and other materials such as polycarbonate, nylon, polypropylene, unsaturated polyesters, ABS, acetal, acrylics, cellulose, epoxies, fluorocarbons, phenolics, polybutylenes, polystyrenes, polyurethanes and silicones account for less than 3% of the market. This is summarised in Figure 4.1 and Table 4.1.

Table 4.1 Rotomouldability of plastics				
Resin Type	Mouldability	Impact strength	Characteristics	Remarks
ABS	Fair	Poor	Paintable, rigid	Univ. of Akron Report AMCP-706-312
ABS (suspension polymerized)	Good	Good	Paintable, rigid	Material from Daicel, Japan
Acetal copolymer	Fair	Good	Excellent stiffness, chemical resistance	Was used commercially
Acrylic	Unknown	Poor	Transparent	
Cellulosics	Fair/Poor	Fair	Translucent	
Ethylene butyl acetate (EBA)	Good	Good	Flexible	Available in powder
Epoxy	Fair	Poor	Used in statuary	Thick, heavy
Ethylene-vinyl acetate (EVA)	Good	Good	Flexibility, impact	
Fluoropolymers (PVDF, etc)	Good	Good	Excellent chemical resistance	Commercial applications as liners
Elastomers	Good	Good	Fuel resistant/flexibility	
Ionomers	Fair	Good	Impact strength	Some commercial use
Polyamide/ Nylon	Good	Good	Fuel resistance, higher temp	Successful commercial use
Polycarbonate	Good	Good	Transparent, toughness	Successful commercial use
Polyethylene	Very good	Good	Low cost	Most widely used
Polyethylene (crosslink)	Good	Good	Chemical resistance improved ESOR	Industry Standard
Conductive polyethylene	Good	Poor	Electrically Conductive	Black only
Polypropylene	Good	Poor	Stiffness, service temp	Commercial applications
Polyethersulfone (PES)	Fair	Poor	Low smoke, stiffness	R&D
Polyurethane (PU)	Good	Good	Tough, excellent wear resistance	Liquid, high potential
Polybutylene	Good	Good	Good low temperature impact	Commercially used
Polystyrene	Good	Poor	Rigid	Low shrinkage
Polyphenylene sulfide (PPS)	Good	Poor	Stiffness, dense smoke	R&D
Polysulfone	Good	Poor	High temperature	R&D
Polyether-ketone (PEK)	Fair	Poor	Rigid, high temperature	R&D
PEEK	Fair	Poor	Rigid, fire safety, high temperature	R&D
Polyether-ketoneketone(PEKK)	Fair	Fair	Rigid, fire safety, high temperature	R&D - expensive
Polyvinyl chloride (PVC)	Good	Good	From flexible to rigid, paintable, low cost	Industry standard
Styrene-acrylonitrile (SAN)	Poor	Poor	Rigid, transparent	
Silicone	Good	Good	Flexible, transparent	

Source: Information from Rotation, Spring 1994, reproduced with permission.

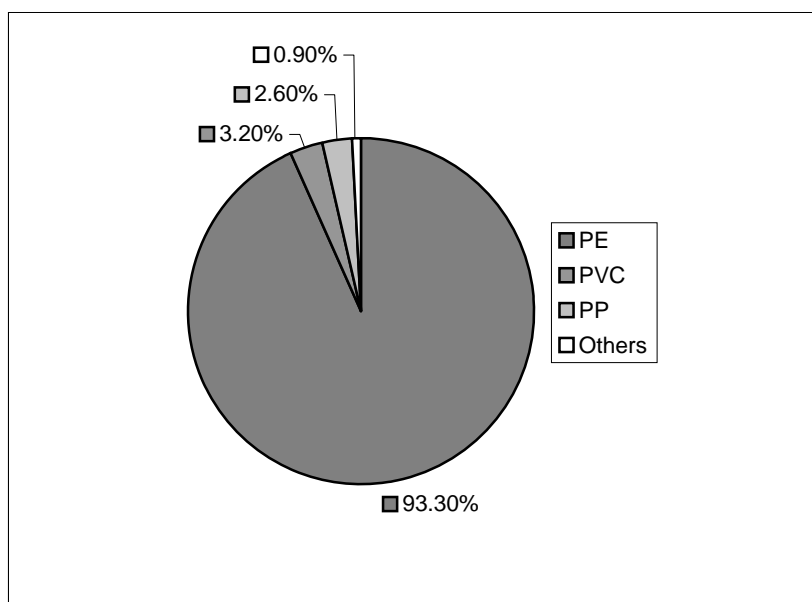


Figure 4.1 Typical usage of plastics in North American rotational moulding industry
Courtesy of Plastics Consulting Research Services

4.4 Polyethylene

Polyethylene (PE) dominates the rotational moulding industry. The most obvious reasons for this are the ability of PE to withstand the long time-temperature environment of the process, and its relatively low cost. Polyethylenes are generally resistant to water, vegetable oils, alkalis and most concentrated acids at room temperature. With the proper precautions they can be re-ground, re-pulverised and re-moulded. Polyethylene is compatible with a full range of pigments to produce coloured parts.

Polyethylene can be readily pulverised into a free-flowing powder at room temperature. The physical nature of the powder can have an important effect on the performance during moulding and the properties of the final product. Normally the powder particles vary from less than 150 microns to about 500 microns. The particle size distribution is very important as it can affect the way that the powder particles fuse together, which in turn affects the appearance of the moulded part.

Polyethylene is an easy flow material when it is in the melt form. This is quantified by the Melt Flow Index (MFI) value. The number quoted is the weight of material, in grams, which would flow through a standard orifice at a standard temperature in 10 minutes. An 'easy flow' grade of plastic will have a high MFI, which corresponds to a low viscosity. Rotational moulding grades of polyethylene usually have a MFI in the range 2-8. If intricate detail must be reproduced from the mould then a higher MFI is desirable. However, a higher MFI is associated with lower impact strength, stress crack resistance, chemical resistance and weatherability. These effects are summarised in Table 4.2.

Table 4.2 Property changes with increasing melt index	
Property	Change
Barrier properties	No trend
Bulk viscosity	Decreasing
Chemical resistance	Decreasing
Creep resistance	No trend
Ductility	Decreasing
Ease of flow	Increasing
Environmental stress cracking resistance (ESCR)	Decreasing
Flexural modulus	Decreasing
Hardness	No trend
Impact strength	Decreasing
Molecular weight	Decreasing
Stiffness	No trend
Tensile strength	Decreasing
Weatherability	Decreasing

Polyethylene is normally subdivided into one of the three categories shown in Table 4.3 depending on density.

Table 4.3 Density ranges of polyethylene	
Material	Density (kg/m³)
Low density polyethylene (LDPE)	915-929
Medium density polyethylene (MDPE)	930-939
High density polyethylene (HDPE)	940-965

In general, properties such as stiffness, shrinkage, chemical resistance and hardness increase as the density increases. Properties such as impact strength and stress crack resistance will decrease as the density increases. The fundamental differences between low and high density grades of polyethylene occur as a result of structural differences. In the high density grades, the molecular chains are essentially linear with few side branches so that the chains can pack closely together to provide more material per unit volume, i.e., a higher density. In low density grades there are many side branches so that the chains cannot pack closely together.

The fact that the chains in LDPE are further apart, and hence the forces of attraction between them are less strong, results in its characteristic properties, i.e., lower strength, lower stiffness (flexibility) and better ability to absorb impact (toughness). The development of linear low density grades of polyethylene (LLDPEs) resulted in a structure that is inherently stronger and stiffer than LDPE at the same density, whilst retaining toughness and stress crack resistance. This material has side branches, which keep its density low, but the branches are short and their occurrence can be well controlled. Due to

its excellent chemical resistance, LLDPE has proved to be very popular in the rotational moulding industry.

The general characteristics of the different types of rotomoulding materials are given next.

4.4.1 Low Density Polyethylene (LDPE)

This material has good flow behaviour and displays excellent resistance to chemicals. It is flexible and tough at low temperatures and has very good environmental stress cracking resistance (ESCR). A typical structure is shown in Figure 4.2.

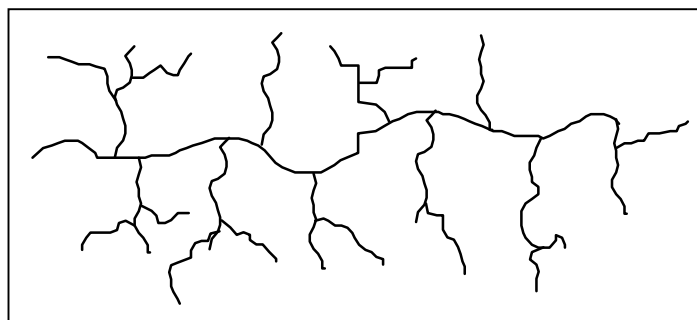


Figure 4.2 Typical chain branching in LDPE

4.4.2 High Density Polyethylene (HDPE)

This material is stronger and stiffer than LDPE but its impact strength is not so good at low temperatures. It is also prone to warpage due to high crystallinity. Structure is shown in Figure 4.3.

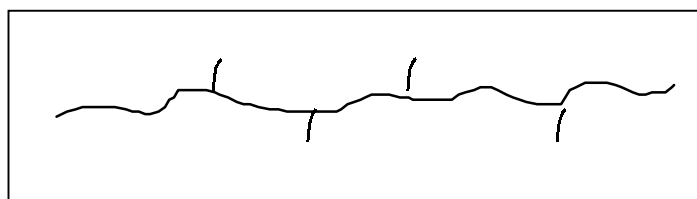


Figure 4.3 Low levels of chain branching, typical of HDPE and MDPE

4.4.3 Medium Density Polyethylene (MDPE)

This material exhibits characteristics between those of LDPE and HDPE.

4.4.4 Linear Low Density Polyethylene (LLDPE)

LLDPEs differ from HDPEs in the fact that they have many more relatively longer branches off the main molecular chain. This prevents the molecules from packing closely together as they do in the high density material. Linear low density polyethylene (LLDPE) materials have

more side branches than LDPEs but they are comparatively short (Figure 4.4). This has the advantage of improving the strength and stiffness of these materials, relative to LDPEs while retaining the excellent low temperature toughness.

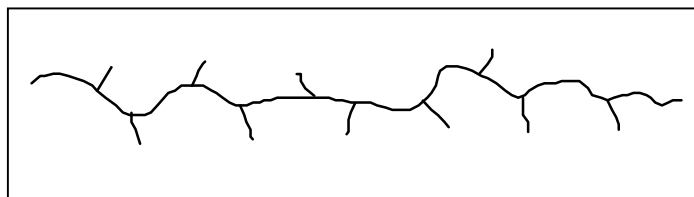


Figure 4.4 Branching typical of LLDPE

The general effects that density has on properties are summarised in Table 4.4.

Table 4.4 Property changes with increasing polyethylene density	
Property	Change
Barrier properties	Increasing
Chemical resistance	Increasing
Creep resistance	Increasing
Ductility	Decreasing
ESCR	Decreasing
Hardness	Increasing
Heat deflection	Increasing
Impact strength	Decreasing
Optical properties	Decreasing
Shrinkage	Increasing
Stiffness	Increasing
Tensile strength	Increasing
Weatherability	No trend

4.4.5 Metallocene Polyethylene

The next generation of polyethylenes are those based on metallocene catalysts. The different method used to create these polymers gives much greater control over the structure of the plastic. This means that processing characteristics and mechanical properties can be tailored much more precisely than ever before. Initial commercial grades are tougher and have better chemical resistance than LLDPE, and offer attractive characteristics for rotational moulders.

4.4.6 Ethylene-Vinyl Acetate (EVA)

The advantages of this material are softness, flexibility and good low temperature properties but its stress crack resistance is poor. It is typically used for products such as buoys and bollards (see Figure 4.5).



Figure 4.5 EVA traffic bollard
Courtesy of Rototek Limited

4.4.7 Ethylene-Butyl Acrylate (EBA)

The features of this material are softness, flexibility, good stress cracking resistance and toughness at low temperatures. It is used for crash barriers, buoys and road markers.

4.5 Polypropylene (PP)

In recent years, rotomouldable grades of polypropylene have become available. This material is much stiffer than HDPE and its density is lower (900 kg/m^3) than that of LDPE. A difficulty is that polypropylene has a ductile-brittle transition temperature close to room temperature. This means that the processing window for polypropylenes can be very small, and this makes them unattractive to many rotomoulders.

4.6 Polyamides (Nylons)

The nylon family of materials is becoming popular for rotational moulding due to their ease of flow and much greater strength, stiffness and toughness relative to polyethylene.

4.6.1 Nylon 6

The chemical resistance and low permeability of nylon 6 make it attractive for petrol tanks, etc. It is expensive in relation to polyethylene and also absorbs moisture, which affects its dimensions. Figure 4.6 illustrates an application.

4.6.2 Nylon 11 and Nylon 12

These two materials do not offer the same mechanical properties as nylon 6 but they do have better chemical resistance and lower moisture absorption.

4.6.3 Reaction Injection Moulding (RIM) Nylon

Reactive nylons in liquid form are used commercially in rotational moulding. These have the advantage that lower mould temperatures are used (approximately 120 °C). Also, there is no need for cooling because the material solidifies as a result of a chemical reaction.



Figure 4.6 Nylon roto-lined pipe
Courtesy of AtoFina

4.7 Amorphous Materials

4.7.1 Polyvinyl Chloride (PVC)

These materials are usually rotomoulded in the form of plastisols: however, powdered grades are available. The plastisols are dispersions of PVC in other compounding ingredients such as plasticisers, stabilisers, fillers and pigments. A major advantage of PVC is that it has a wide range of flexibilities depending on the ingredients of the plastisol (see Figure 4.8). This material is widely used to manufacture flexible toys. An application is shown in Figure 4.7.

4.7.2 Fluoropolymers

Materials such as polyvinylidene fluoride (PVDF) and ethylene-chlorotrifluoroethylene (ECTFE) can be rotomoulded. Although expensive they provide excellent chemical resistance and high temperature capability. They are currently used for chemical vessels or for protective linings.

4.8 Other Plastics

A number of other thermoplastics are rotationally moulded commercially. These include polycarbonate (see Figure 4.8) which offers excellent optical clarity, stiffness and toughness and is typically used for light globes. Thermoplastic polyesters and thermoplastic polyurethanes are also capable of being rotomoulded, and products include buoyancy aids and medical skeletons (see Figure 1.18). Other plastics which would come into the category of 'rotomouldable with difficulty' include ABS, acetal, acrylic, cellulose, epoxy, phenolics, polybutylene, polystyrene, SAN and silicone.



Figure 4.7 PVC exercise / fitness device



Figure 4.8 Rotomoulded polycarbonate part

4.9 Additives Used in Rotational Moulding Materials

The bulk properties of a polymer can often be altered considerably by the incorporation of additives. In general, additives should have the following features:

- (a) They should be efficient in their function.
- (b) They should be stable under processing conditions.
- (c) They should be stable under service conditions.
- (d) They should be non-toxic and not impart taste or odour.
- (e) They should be cheap.
- (f) They should not adversely affect the properties of the polymer.

The following sections consider some of the main additives used in rotomouldable plastics.

4.9.1 Fillers

The term filler is usually applied to solid additives incorporated into the polymer to modify its physical properties (Figure 4.9). Inert particulate fillers include materials such as calcium carbonates, china clay, talc and barium sulfate, which can improve modulus, hardness, tensile strength and heat deformation resistance. Normally the finer the particle size, the higher the value of these properties - at least up to an optimum loading of filler. Other factors affecting a filler's performance include particle shape, chemical nature, and any impurities such as grit. Fillers are also important from a commercial point of view, as they will substantially reduce the cost of the compound.



Figure 4.9 Calcium carbonate filler

Rubbery materials are often incorporated into rigid amorphous thermoplastics to improve their toughness. Examples include butadiene-acrylonitrile rubbers in PVC and ethylene-propylene rubbers in polypropylene. The incorporation of these rubbers improves the toughness of the final compound, and they are often referred to as 'impact modifiers'.

4.9.2 Plasticisers

Plasticisers are added to improve processability. Typically they lower the melt viscosity of the base polymer, and change the physical properties of the product, for example to increase softness and flexibility. Plasticisers are very widely used in PVC.

4.9.3 Lubricants

Lubricants promote the flow of the polymer in the melt but unlike plasticisers, they have little effect on the solid state properties.

4.9.4 Stabilisers

Stabilisers are used to reduce the degradation that may occur in plastics, when they are heated or oxidised during processing, or when they subjected to environmental effects during the service life of the moulded part.

4.9.5 Anti-Oxidants

Many rotomoulding grades of plastics contain anti-oxidants to protect the material during the long moulding cycles, and in subsequent use where high service temperatures may be encountered. Attack by oxygen during processing causes chain reactions to be initiated, which can lead to changes in chemical composition and reduction in properties of a plastic. Anti-oxidants diffuse into surface layers and are preferentially oxidised. They act by either terminating the destructive chain reaction, or preventing its initiation.

4.9.6 Ultraviolet Stabilisers

Exposure to ultraviolet (UV) light, particularly in an oxygen-containing atmosphere, can cause physical and chemical changes to occur in plastics. These result in effects such as discoloration, surface cracking, hardening and changes in electrical properties. Efficient melt compounding of carbon black into the polymer at concentrations of about 1.5% can improve the service life dramatically. However, carbon black cannot always be used, due to its high heat absorption and the aesthetic problems it presents. Hence, a number of other UV stabiliser systems are also available.

For example, ultraviolet absorbers (UVAs), are a form of light screen which absorb primarily in the UV range. The UV absorber then disposes of the absorbed energy by radiation, by conversion into heat or by chemical changes leading to stable products.

Quenching agents, although not in themselves powerful absorbers of UV light, react with activated polymer molecules to prevent oxidation occurring. Hindered amine light stabilisers (HALS), combine the roles of anti-oxidants and quenching agents. Highly stable polymeric forms of these have been developed and have proved very effective. Their combination with a UVA gives even better UV resistance in unpigmented parts.

4.9.7 Flame Retardants

Flame retardants function by one or more of four mechanisms:

- (a) They chemically interfere with the flame propagation mechanism, e.g., as in halogenated compounds.
- (b) They may produce large volumes of incombustible gases, which dilute the air supply, e.g., release of carbon dioxide gas.
- (c) They may react, decompose or react endothermically, thus absorbing heat, e.g., release of water vapour.
- (d) They may form an impervious fire-resistant coating preventing access of oxygen to the polymer, e.g., charring of the outer surface layers of a part.

The use of fire retardants in polymers is complex because in a serious fire, the effects of smoke inhalation and toxic combustion products can be as damaging as the fire itself.

4.9.8 Crosslinking Agents

Crosslinking agents can be substances which bridge two polymer molecules during crosslinking or substances which initiate a crosslinking reaction. Radiation crosslinking can be used with polyethylene, but this requires expensive equipment and extensive protective measures. Other chemical methods exist and although cheaper, they require close control.

4.9.9 Foaming Agents

Foamed plastic mouldings are becoming very common nowadays because they have a much better stiffness to weight ratio than solid mouldings. The technology is considered briefly here and is described in more detail in Section 5.7.

Blowing agents may be mixed with the polymer powder, but a more satisfactory result is achieved if the blowing agent is pre-compounded into the polymer. The foamed part is produced from the release of gases as the blowing agent breaks down. The polymer must be melted before the blowing agent gets activated, while the agent itself must be well dispersed to give uniform foaming in the melt. The foaming reaction can be exothermic which, when combined with the improved insulation properties of the foamed part, results in a considerably lower rate of cooling (i.e. longer cycle time) than that for an unfoamed part.

If the purpose of the foaming is to provide better thermal insulation then the use of polyurethane foam, introduced after rotomoulding of the PE part, gives the best results. A typical part is illustrated in Figure 4.10. Normally the PU foam does not adhere to the PE skin and so the mechanical properties (such as stiffness) are usually not enhanced by this type of foaming.



Figure 4.10 Polyurethane foam filled trolley

To improve the stiffness per unit weight, it is desirable to introduce PE foam inside the solid PE rotomoulded skin. This can be done in either a one shot or two shot process. Also, the PE foam may either partially, or totally, fill the void inside the solid PE part. In two shot foaming, the solid skin is formed first and at a pre-determined point during the oven cycle, a second charge of material (PE containing the foaming agent) is introduced. This is often done using a ‘drop box’ – an insulated container that sits alongside the mould. At the selected time the drop box discharges its contents into the mould (Figure 4.11).

Often in rotational moulding it is desirable to produce products made from multiple layers of different materials. An example of this is in the creation of high barrier fuel tanks with an outer layer of polyethylene and an inner layer of nylon. However, a more common use of this technology is in the creation of skin/foam sandwich structures (see Chapter 5.7). Figures 4.11a and 4.11b illustrate a ‘drop box’ used to create multilayer products. In the case of a foam sandwich structure, polyethylene powder is placed as normal in the mould whilst a polyethylene/blowing agent foam mix is added to the insulated drop box. At a specific stage during the heating period an air valve is activated and the polyethylene/blowing agent foam mix is dropped creating the foam core.

In a one shot foaming system, two materials are put into the mould at the beginning of the cycle. One is the normal PE, which will produce the solid skin. The other material is PE containing the blowing agent. There are a variety of propriety methods by which the two materials separate during the tumbling inside the rotating mould. The result is a solid skin and a foamed core as illustrated in Figure 4.12.



Figure 4.11a Drop box on mould



Figure 4.11b Drop box on mould, open showing valve position

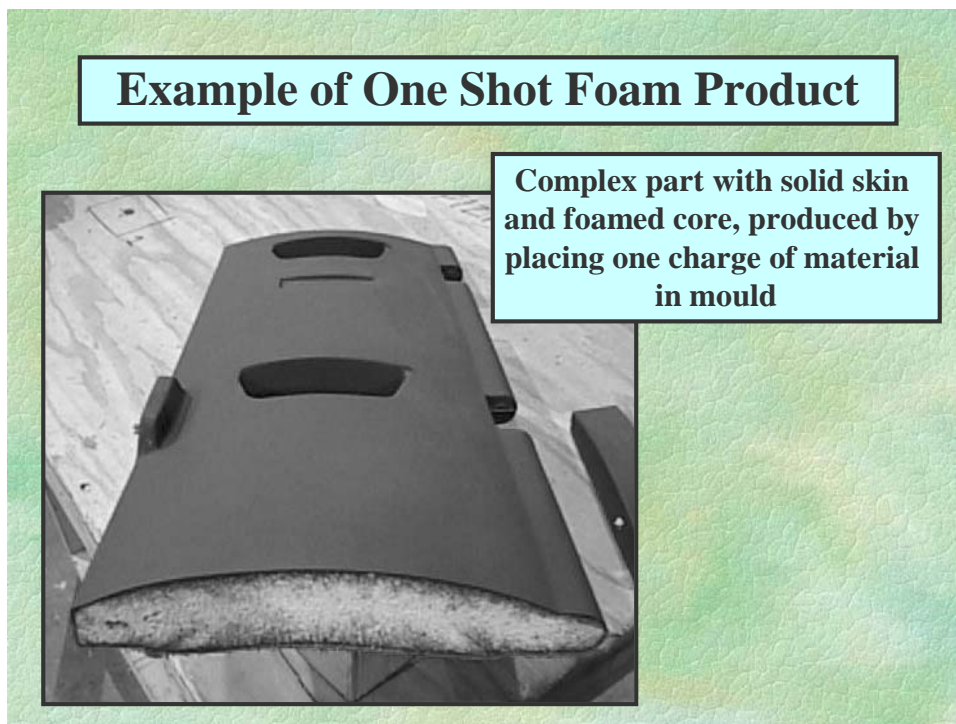


Figure 4.12 Foam PE door panel
Courtesy of ICO Polymers

4.9.10 Pigments

Coloured rotomouldings can be produced using pigments. These are very fine solid particles of organic/inorganic material (Figure 4.13), which not only impart colour to the plastic. It should also be recognised that pigments will have some effect on the physical properties of the moulded part, and so their concentration should be kept to a minimum. The pigment additive can also affect the way that the structure forms during solidification from the melt. This means that the amount of crystallinity that occurs, and hence the amount of shrinkage, can be different with different colours.

In rotomoulding, a number of methods are available for combining the pigment with the plastic – (a) dry mixing, (b) turbo/high speed mixing and (c) compounding. These are described in more detail in Section 4.16.



Figure 4.13 Powder pigments

4.10 Powders for Rotational Moulding – Grinding or Pulverising

4.10.1 Introduction

The polyethylene material used as the feedstock for rotational moulding is always in the form of powder or micropellets. The latter material form is a relatively recent development and although it has many attractive features, powder still accounts for over 95% of the polyethylene used in rotational moulding. Powder is produced by grinding or pulverisation, sometimes also called attrition.

Typical feed systems for the pellets (or granules) are shown in Figures 4.14 and 4.15. The basic stages in the grinding of polymers for rotational moulding are illustrated in Figures 4.16 and 4.17. Pellets are fed into the throat of the mill from a feed hopper by means of a vibratory feeder (or auger) at a uniform and controlled rate. As these pellets enter the mill, along with a flow of air, they pass between two metal cutting plates, each with a series of radial cutting teeth. Figures 4.18 and 4.19 show the construction of a vertical grinding head. Figures 4.20 and 4.21 show a horizontal grinding head and Figure 4.22 and 4.23 show a side view of the cutting teeth.



Figure 4.14 Hopper containing granules
Courtesy of Kingspan Environmental



Figure 4.15 Granule feed system

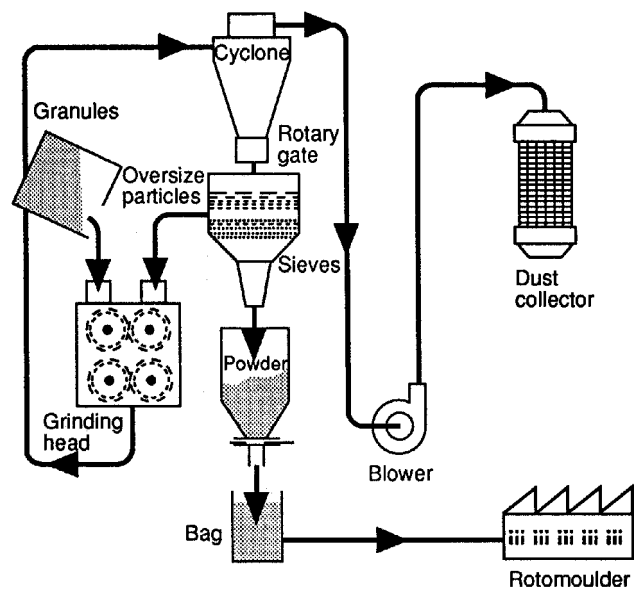


Figure 4.16 Stages in the grinding of powders for rotational moulding

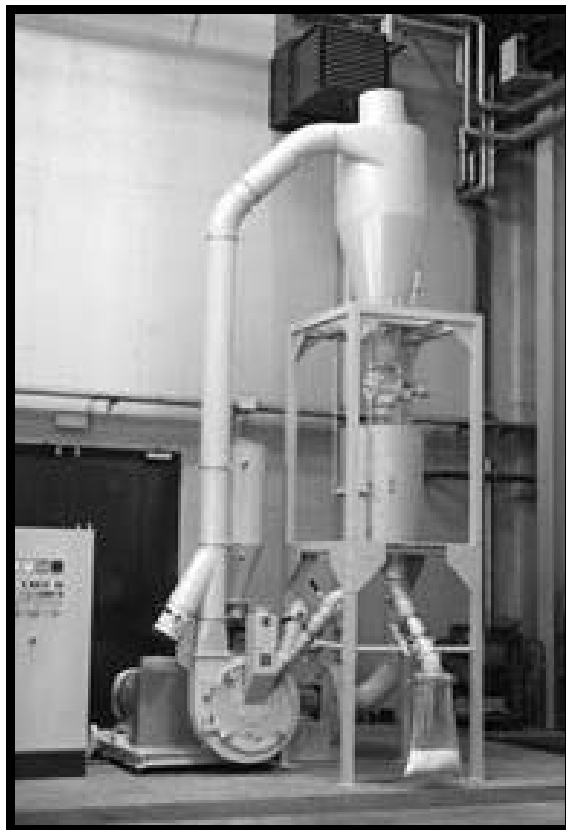


Figure 4.17 Typical grinding mill for polyethylene

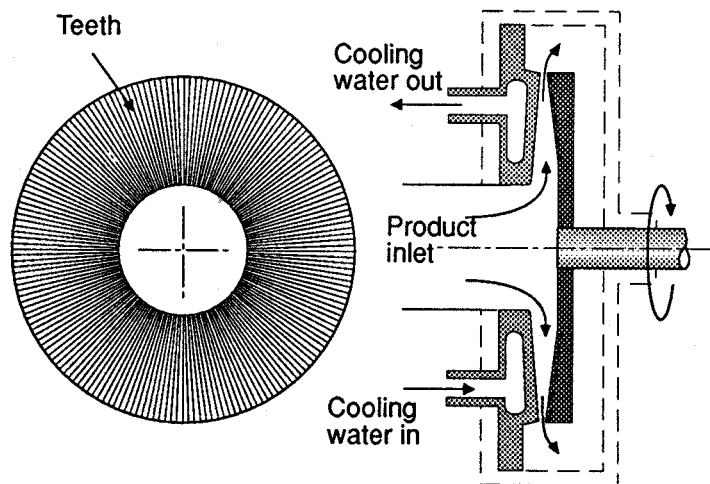


Figure 4.18 Typical vertical mill grinding plates for plastic powders

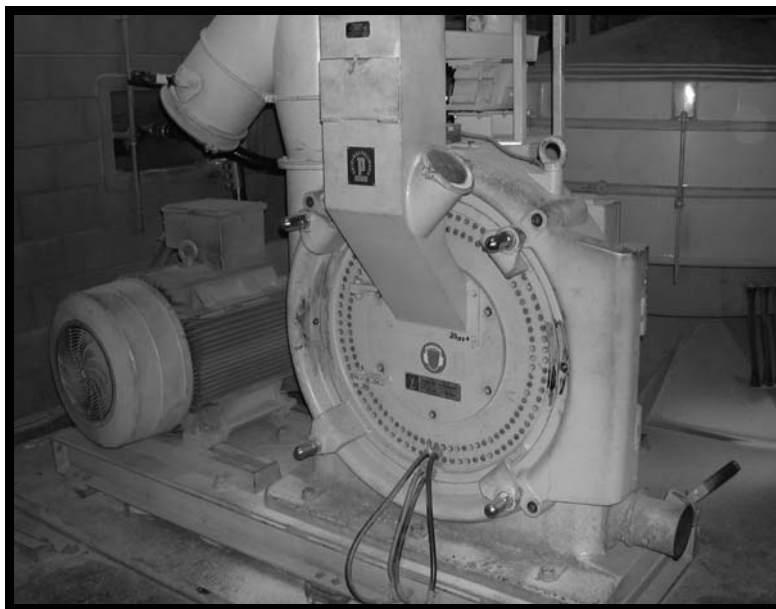


Figure 4.19 Vertical mill grinding head

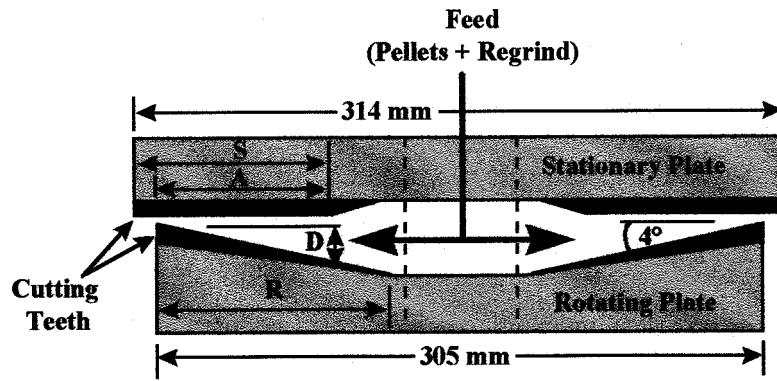


Figure 4.20 Typical horizontal grinding plates for rotational moulding powders



Figure 4.21 Horizontal grinding head



Figure 4.22 Grinding plate

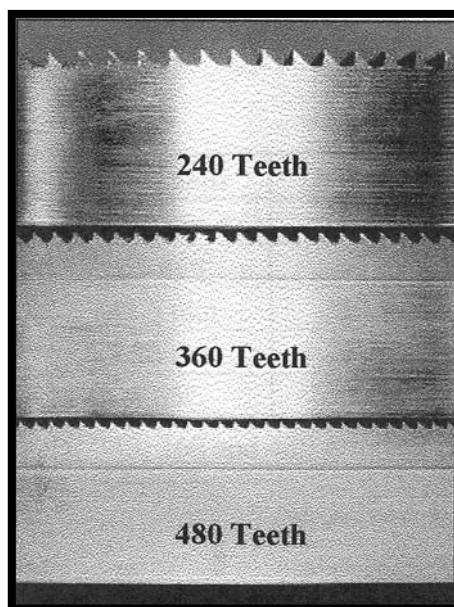


Figure 4.23 Side view of cutting plates with different numbers of teeth

The teeth on the rotating plate are cut at an angle (typically about 4°) so that the gap between the cutting edges of the two plates is narrower at the periphery. When the pellets enter the mill, the centrifugal effect forces them out between the cutting plates. Each pellet is slowly reduced in size as particles are shaved off it and it moves outwards into the narrowing gap between the two cutting faces. The particles remain between the plates until they are of a size that allows them to escape from the gap at the periphery.

In the grinding process, frictional heat increases the temperature of the metal cutting faces, as well as the individual polyethylene particles and the surrounding air. As a consequence, the temperature must be controlled so that it does not rise beyond the melting point of the polyethylene or to a critical softening temperature, prior to melting, when the particles begin to adhere to each other. This can cause blockages in the passage of new material entering the mill.

Once the particles exit the mill they go into an air stream, which carries them to a screening unit containing a number of sieves of a standard mesh size. Particles that pass through the screens are taken out of the system and collected as usable powder. Those particles that do not pass through are conveyed back to the mill and reground.

Industrial grinding machines may have two grinding mills in line. The gap size between the first two mill plates is relatively large compared to that for the second. The purpose of the first mill is to reduce the overall size of the particles going into the second mill. The gap size on the second mill is set so as to yield the desired particle size distribution. This improves efficiency, and allows for a higher production rate by decreasing the amount of regrind (oversize particles) that is returned to the mill.

4.11 Particle Size Distribution

In the rotational moulding industry, the particle size of powders is usually quantified in terms of the mesh size. This relates to the number of mesh openings per inch in the sieve used to grade the powder. Table 4.5 gives some of the mesh sizes defined in the British and American standards.

Table 4.5 ASTM E-11 US sieve sizes			
Tyler size (x 0.001 inch)	Sieve opening (x 0.001 inch)	Wire diameter (x 0.001 inch)	Particle size (microns)
35	16.5	11.4	420
60	9.8	7.1	250
80	7.0	5.2	177
100	5.9	4.3	149
115	4.9	3.6	125
150	4.1	3.0	105
170	3.5	2.5	88
200	2.9	2.1	74
250	2.5	1.7	63
325	1.7	1.2	44
400	1.5	1.0	37

A 35 mesh (500 μm) sieved powder has the typical particle size distribution that is suitable for rotational moulding. Although there have been few studies on the ideal particle size distribution, it is generally accepted that powders having a narrow size distribution under 500 microns offer the best compromise between grinding costs and the fusion characteristics of the plastic.

The preferred particle size distribution will provide good packing of the different particle sizes. This helps to reduce voids between particles, thereby minimizing surface porosity and the tendency to trap air bubbles in the melt. Very fine powders have a greater surface area-to-volume and so are more susceptible to thermal deterioration. Also, since fine powders tend to fluidise more readily and do not flow as well, heating cycle times can be extended. Problems with airborne dust during mould filling are also exacerbated by fine powders. Very coarse powders, on the other hand, lead to increased heating cycle times and irregular, matt outer surfaces with many pin-holes.



Figure 4.24 Typical sieve shaker used for rotational moulding powders

The particle size distribution of powders is measured according to ASTM test method D 1921. A set of nested, wire sieves, with mesh sizes ranging from about 35 mesh to 200 mesh is used for this determination. A sample of powder is taken, weighed, and placed in the top sieve. The shaker is covered and mounted in a device that rotates, shakes and vibrates, as shown in Figure 4.24. After a predetermined period of time, the sieves are separated and the amount of powder retained on each sieve is weighed. The powder that passes through the bottom sieve into the retaining tray is measured as well. The length of shaking time can affect the measured particle size distribution. Ten to fifteen minutes is considered sufficient for powders that have compact shape and no static charge build-up.

There is no absolute definition of the best particle size distribution (PSD) for rotational moulding. It is difficult to isolate the PSD from other variables and so suppliers and moulders have reported a variety of PSDs that give good results. Figure 4.25 shows a typical particle size distribution for polyethylene used successfully by rotomoulders.

4.12 Dry Flow

Powder dry flow properties are important during rotational moulding. They determine how well the powder tumbles in the mould, which affects heat transfer in the powder bed, and how the powder distributes itself over the mould surface. Dry flow depends mainly on particle size and particle shape. Since the particle size distribution for a 35 mesh powder tends not to vary greatly, it is the particle shape that has the greatest effect on dry flow. The presence of tails on powder particles reduces dry flow properties, leading to detrimental part properties such as bridging across narrow recesses in the mould and high void content within the part wall.

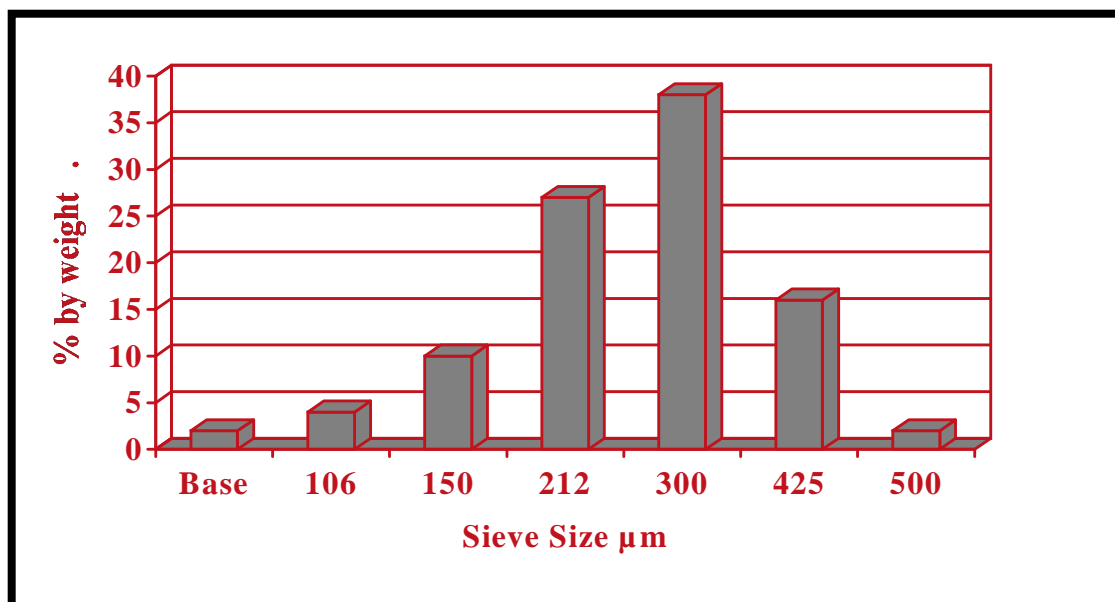


Figure 4.25 Typical particle size distributions for polyethylene used in rotational moulding

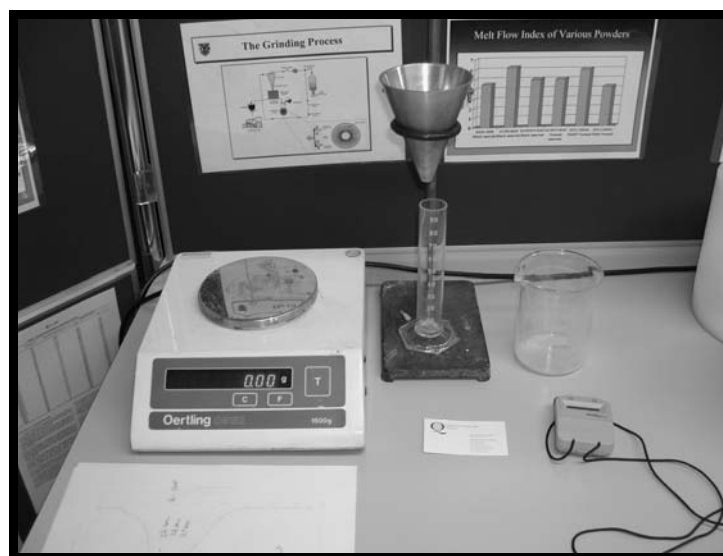


Figure 4.26 Equipment required for dry flow and bulk density analysis

The standard method for measuring the *dry flow* of a powder is described in ASTM D 1895-89. It is the time taken for 100 g of powder to flow through a standard funnel. The dry flow is quoted in seconds. The equipment used is shown in Figures 4.26 and 4.27. Note that the dimensions given are for guidance only – the accurate dimensions are given in the Standard. Great care is needed when carrying out tests on powders. To get reliable data it is very important to use consistent procedures and controlled ambient conditions.

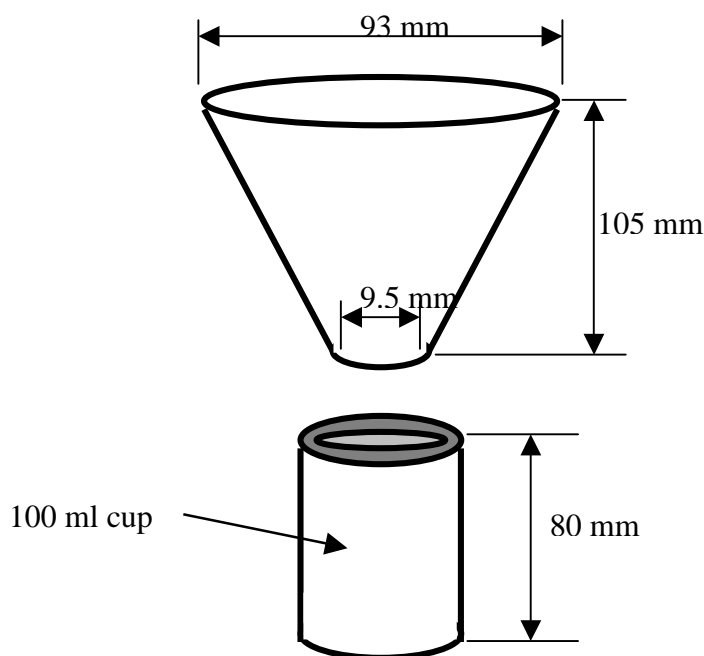


Figure 4.27 Dry flow and bulk density apparatus

4.13 Bulk Density

Bulk density is a measure of the efficiency with which the powder particles pack together. A good quality powder having 'clean' particles with no tails will have a high bulk density. Bulk density and dry flow are dependent on the particle shape, particle size and particle size distribution of the powder. These two properties are inversely related, in that an increase in the bulk density corresponds to a faster dry flow rate (see Figure 4.28).

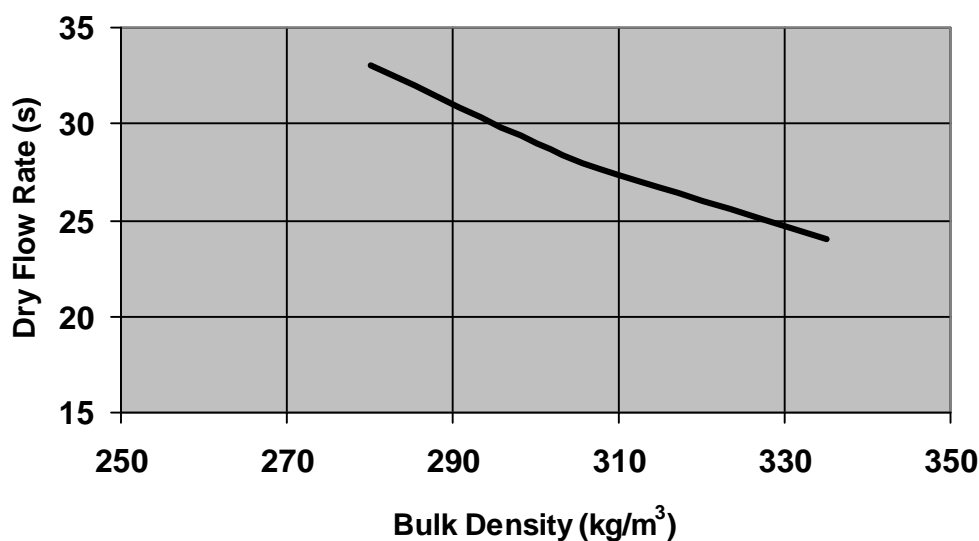


Figure 4.28 Variation of dry flow rate with bulk density for rotomoulding powders

4.14 Factors Affecting Powder Quality

There are many process variables and these will affect the nature of the powder in different ways and to varying degrees. Some of the main grinding variables are the:

- gap between the discs,
- feed rate of granules,
- system pressure,
- disc design,
- disc speed,
- choice and type of feeder,
- cooling efficiency,
- operating temperature,
- moisture control,
- air velocity,
- amount of recycle,
- type of auxiliary equipment used,
- amperage of the mill, and
- sieve aperture in the screen unit.

Research has shown that three of the main factors that affect grind quality are:

- (a) Gap size between the grinding plates
- (b) Number of teeth on the grinding plates
- (c) Grinding temperature (measured at the grinding head).

4.14.1 Gap Size

The size of the gap between the two grinding plates has a large effect on the particle shape, the particle size distribution of the powder and the efficiency of the process. Increasing the gap size produces more elongated particles and shifts the particle size distribution curve to the right, corresponding to an increase in the average particle size. Gap size also has an important influence on process efficiency. As the gap size increases, the percentage of oversize particles increases. These particles are returned to the grinding plates and hence the input of fresh granules from the feeder decreases. For continuity, the input from the feeder equals the output from the system and so the output decreases as the amount of recycled powder increases. Therefore, as the gap is increased, the output rate of useable powder decreases.

The dry flow and bulk density values have a small dependency on gap size. The fastest dry flow rates and highest bulk density values are found at a gap size of 0.35 mm, with a small decrease in both properties up to a gap size of 0.85 mm. Small improvements seen after 0.85 mm are attributed to the high percentage of large particles in the powder. It is apparent therefore that for any grinding system, there will be an optimum gap size based on a compromise between the desired particle size distribution, the dry flow, the bulk density and the maximum output rate.

4.14.2 Number of Mill Teeth

Varying the number of teeth on the grinding plates alters the particle size distribution. An increasing number of mill teeth cause an increasing amount of particle breakdown. With the reduced depth between the teeth, there is a decrease in average particle size and a shift in the PSD curve to the left (i.e., towards the smaller end of the spectrum).

The dry flow and bulk density properties improve as the number of mill teeth is reduced. This is attributed to the higher percentage of larger particles. Another important aspect of the grinding plates is the sharpness of the teeth. When the teeth get worn there tends to be a greater percentage of the smaller particles.

4.14.3 Grinding Temperature

Grinding temperature has a very significant effect on the quality of the powder. The effects on dry flow and bulk density are illustrated in Figure 4.29. It may be seen that the dry flow rate improves as the temperature of the powder increases. The time required for 100 g of powder to flow through a standard funnel reduced from 33 s to 24 s when the temperature at the grinding head increased from 95 °C to 104 °C. Powder ground below about 85 °C did not flow. The reduction in dry flow times at the higher grinding temperatures is associated with the smoothing of the particles at elevated temperatures.

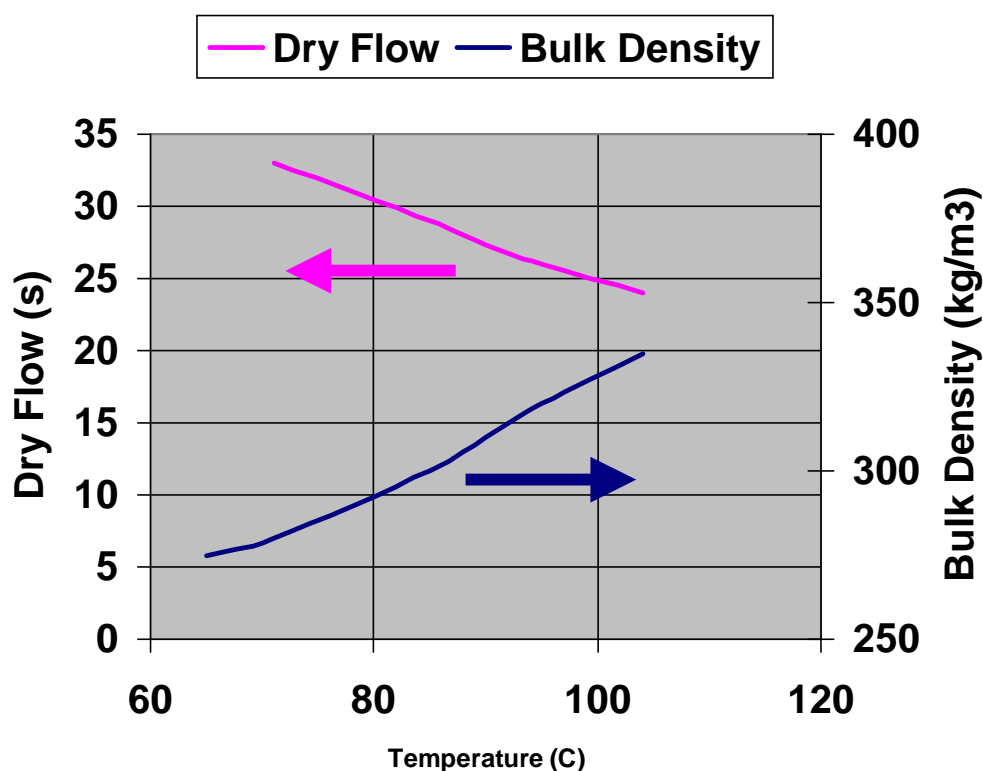


Figure 4.29 Effect of grinding temperature on bulk density and dry flow rate

The removal of tails and hairs from the particles results in an increase in the bulk density. The improvement in particle shape with increasing grinding temperature can be seen in

Figure 4.30. These micrographs show that the particles ground at the higher temperature (on the left) have smoother surfaces and fewer tails. These physical characteristics affect the amount of material that can be placed in the mould, and the flow of the powder when it is in the mould. When the tails are removed from the particles there is a reduced tendency for them to fuse together early and cause 'bridging' in narrow recesses in the mould.

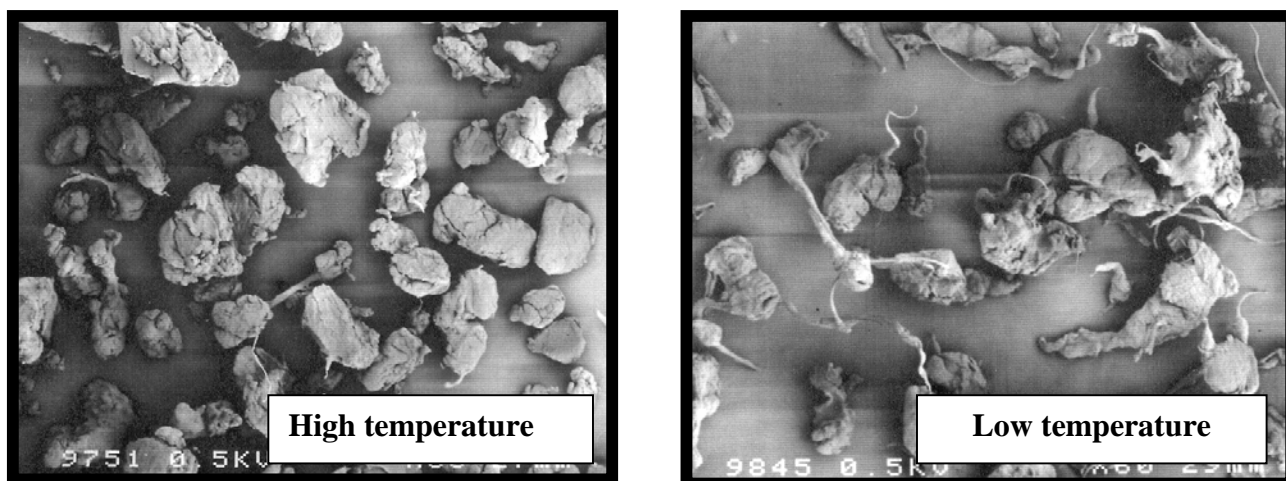


Figure 4.30 Effect of grinding temperature on particle shape

4.15 Micropelletising

Although powders dominate the rotational moulding industry, they suffer from a number of drawbacks. They are expensive to produce and are not amenable to regular colour changes. The production of consistent quality powder, in terms of particle shape and particle size distribution requires considerable skill on the part of the grinder. In addition, excessively dry environments lead to very high static charges when powders are dispensed to metal moulds.

Micropelletising is one way of overcoming some of these problems. Micropellets are manufactured in a similar fashion to conventional granules, except that the strand die openings are substantially smaller, with the truncated cylinder diameter being as small as 0.3-0.5 mm (0.012-0.02 inch) and a length of up to 0.6 mm (0.025 inch). Frequently the micropellets are lozenge or ovate in shape. Attractive features of micropellets are their very consistent quality and size. Since micropellets are extruded through fixed-diameter orifices, there is very little variation in particle size. Micropellets flow very easily compared to powders, which can be a problem in that they move very quickly over the mould surface. This can make it difficult to reproduce some surface details. Sometimes micropellets are mixed with powders to facilitate filling out of difficult areas of a mould. Molding conditions, such as the rotational speeds and speed ratios, often have to be altered to allow for the fast flow properties of micropellets.

4.16 Colouring of Plastics for Rotational Moulding

As with all plastics moulding technologies, the rotomoulded end product often needs to be coloured. There are a number of ways of achieving this but pigmenting the plastic, prior to or during moulding is still the best method of colouring rotomoulded parts. The pigment can be added as the granules/pellets are being produced by the extruder, and thus the resulting powder will be of the desired colour. This is called *compounding* and generally produces the best results. The pigment is thoroughly mixed with the polymer and the properties of the moulded part will be better than those produced by any other colouring method. The disadvantages are that the powder is more expensive to produce and the moulder needs to keep good control over stocks of the required colours.

An alternative is to *dry blend* the pigment with the powder. Some preliminary mixing may take place outside the mould (as illustrated in Figure 4.31) and the natural tumbling action that occurs during rotational moulding ensures good mixing in the mould. This is an attractive option to moulders because it is only necessary to purchase unpigmented material and this facilitates economies of scale and removes the need for tight stock controls on different colours. The disadvantage is that the pigment is not homogenised with the polymer nearly so well as in compounding. As a result, the properties of the end product are not so good and are very sensitive to the amount of pigment used. As the pigment is not intimately bound to the polymer, it can also leave deposits on the mould called plate-out or staining.

To improve the dry blending of pigments into polymers, *high speed mixers* or *turbo blenders* can be used. These combine the pigment and the polymer at modestly high temperatures in a paddle-type mixer (see Figures 4.32-4.34). The powdered pigment particles become bonded or fused to the softened surface of the plastic particles and the resulting material can be rotomoulded in the normal way. The output material from the high speed mixer is very clean to handle and does not transfer the pigment to the mould. The properties of the resulting moulding are still not as good as from compounded material but material handling is much cleaner. Currently developments are taking place to impart colour to the plastic powder as it emerges from the grinder or pulveriser. This may give a more economical means of rapid colour change and offer some of the advantages of high speed blending.

The vast majority of the pigments used in rotational moulding are in powder form but in recent years the use of liquid pigments is becoming popular. These can be economic and potentially offer the convenience of dry mixing with the properties of compounded material. However, in most cases the formulations still have to be perfected for rotational moulding.

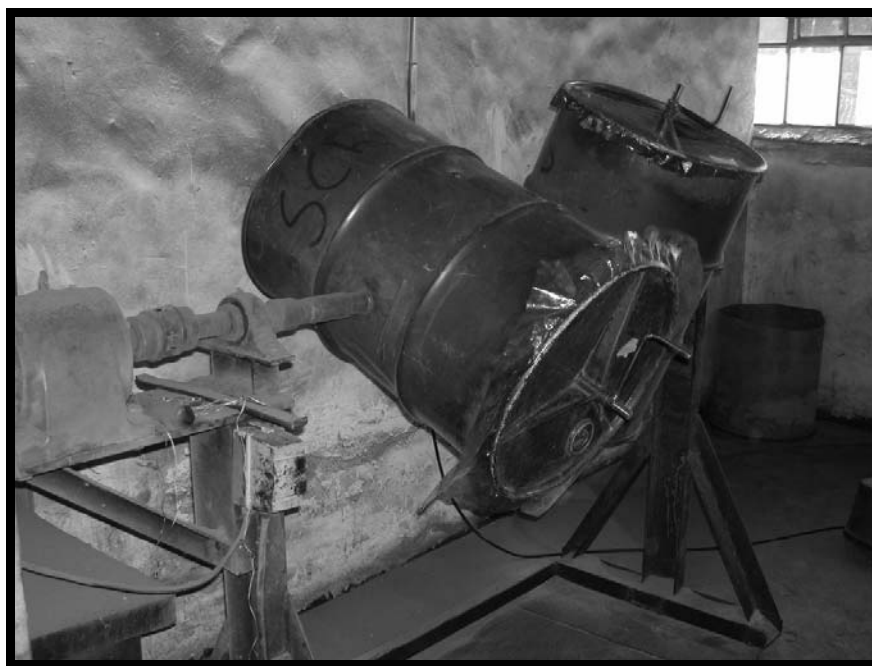


Figure 4.31 Typical tumble/dry blender
Courtesy of Atlas Plastics Pty



Figure 4.32 Typical high speed blender



Figure 4.33 Blender barrel

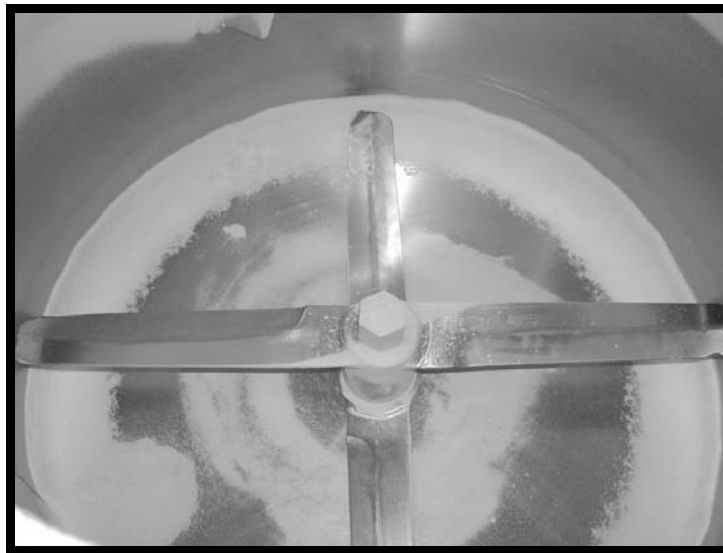


Figure 4.34 Blender blades

If the production volumes warrant it, pigments should be compounded with the polymer prior to grinding because this gives the best mechanical properties in the moulded part (see Figure 4.35). Also, if the pigment concentration must be in excess of 0.2% (wt), for colour intensity, it must be melt-blended with the polymer. Melt compounding provides the best blending and homogenisation of the pigment and the plastic.

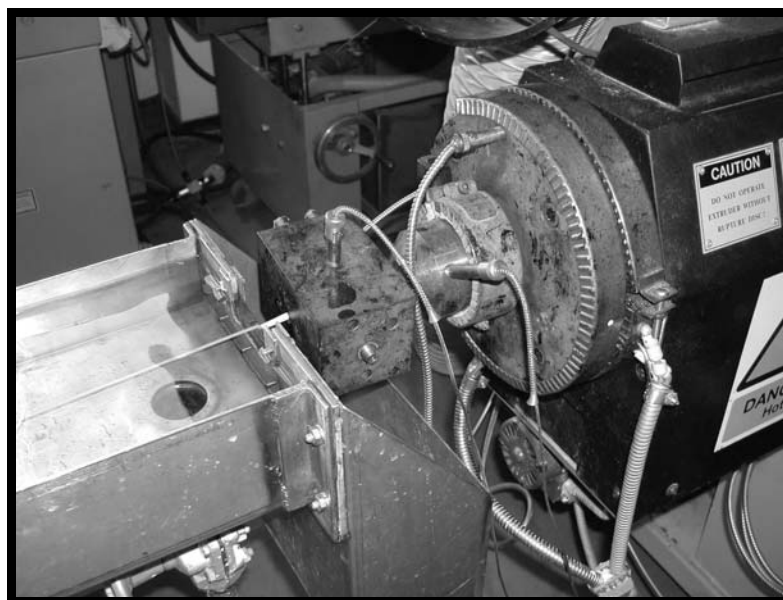


Figure 4.35 Compounding line

4.17 Types of Pigments

There are about 200 pigments available to the plastics processing industry but only about 30 of these are suitable for rotational moulding. The long time at elevated temperature eliminates many organic pigments. Since many rotationally moulded parts are used outdoors, the UV resistance must be high and this eliminates some other pigments. For the higher temperature engineering resins, such as nylon and polycarbonate, the number of available pigments is very restricted and most of the important colours must be compounded.

There are several classes of pigments. Pigments containing heavy metals such as lead, cadmium, and chromium, yield very intense colours and are relatively inexpensive but legislation restricts their use. They cannot be used in toys, FDA products, sporting goods or recreational equipment. Other inorganic pigments based on tin, iron and zinc are not restricted but do not have bright colours. Cadmium pigments are historically one of the most widely used pigment groups in rotational moulding. Their heat stability and outdoor light stability are excellent. They offer a broad range of very clean and bright colours and they can be used at levels that do not affect the impact properties of the resin.

Organic pigments fall into two primary categories: azo type pigments and polycyclic pigments. The majority of all organic pigments (> 65%) are the azo type pigments and their colour range follows very closely to that of the cadmiums, mainly yellow to red. The polycyclic pigments consist of almost everything else with the quinacridones (red and magenta) and the phthalocyanines (blue and green) being the most important for rotational moulding. Carbon black is also an important organic pigment but does not fall into either category.

In general, organic pigments are strong, bright, clean, and translucent with reasonable heat and outdoor light stability. However, they are difficult to disperse, they are expensive and they can shift in colour over a range of processing temperatures. Some cause warpage problems, some will bleed, and because of their small particle size, static problems are more apparent.

Fluorescent additives are expensive and tend to fade. As a result, they are used with inorganic pigments to minimize the fading effect. Fluorescents have very high static charges and will migrate during rotation in the oven to yield non-uniform coloration. Many pigments are polymer-specific. For example, due to its higher crystallinity, natural (or unpigmented) HDPE has a higher opacity than LLDPE.

Adhesion of pigment on the inner mould surface, can be a problem when using dry blended pigments. The condition of the mould surface is very important. One way of minimising the effect is to use a baked-on, professionally applied permanent or semi-permanent mould release such as FEP fluoropolymer or siloxane. When there are problems with inconsistent colour, it is recommended that for most pigments, including TiO_2 and carbon black, the oven temperature should be reduced and the time in the oven increased. Streaking is more apparent with glossy moulds and glossy surfaced parts than with matte finished moulds and parts.

Rotationally moulded parts can have special effects such as granite, marble, and sparkle. Mixtures of different sized melt-blended powders yield the best results. For sparkle, metallised polyethylene terephthalate (PET) flake is recommended. Metal flake such as coated aluminium should not be used, since it may oxidize explosively in the oven. Low concentrations of mica, at 5% to 15% or so, will also yield a sparkle surface. Photochromic and thermochromic effects can be achieved with certain pigments but at a very high cost. Pearlescents are somewhat successful but the dosage must be low to minimize impact property loss. The preferred way of achieving a look of high pearlescence is to increase the wall thickness. Representative pigment types are given in Table 4.6.

Table 4.6 Types of pigment	
Organic pigments (complex chemicals)	Inorganic pigments
Green and blue phthalocyanines	Red, yellow and orange cadmiums (HM)
Red, yellow and orange azos	Yellow and orange chromes (HM)
Purple and violet quinacridones	Titanium dioxide white
Carbon black	Brown and black iron oxides
	Ultramarine blue sodium silicates
	Blue cobalt (HM)
	Ochre, yellow and brown titanates
Note: HM = heavy metal	

Bibliography

1. J. Aasen, How PE Foam can Increase Your Design Possibilities and Profits, *Rotation*, 2001, **10**, 5, 36.
2. R. Al Zubi, Why Some Rotomolded Tanks are Black in Color, *Rotation*, 2001, **10**, 3, 18.
3. Anon, Micropellets - An Alternative Rotomolding Product Form, *Rotation*, 1995, **4**, 4, 9.
4. W.D. Arendt, J. Lang and B.E. Stanhope, New Benzoate Plasticizer Blends for Rotational Molding Plastics, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
5. E. Boersch, Plasma-Modified Polyolefin Powders for Rotational Moulding, in *Designing Your Future*, Auckland, New Zealand, 1999.
6. E. Boersch, Plasma-Modified Polyolefin Powders for Rotational Molding, *Rotation*, 1998, **7**, 4, 18.
7. E. Boudreaux, R.K. Krishnaswamy and J. Ratzlaff, D. Measurement of Peroxide Content of Crosslinkable Polyethylene by DSC, in *SPE ANTEC*, San Francisco, USA, 2002.
8. L. Carrino, G. Moroni and W. Polini, Cold Plasma Technology for Surface Treatment, *MacPlas*, 1999, Summer, 69.
9. J.W. Cowburn, Rotational Moulding of Hytrel Polyester Elastomer, in *International Conference of Rotational Moulders*, Jersey, 1978.
10. S. Dority, *et al.* Can Color be Consistent in Rotational Molding, in *ARM Fall Meeting*, Vienna, Austria, 1996.
11. S. Dority and H. Howard, Color for Rotational Molding: The Challenges, *Plastics Engineering*, 1998, **54**, February, 25.
12. S. Dority and H. Howard, Color for Rotational Molding - The Challenges We Face, in *SPE ANTEC*, Toronto, Canada, 1997.
13. W.E. Foster, Need a Tough Rotomolded Part? Now You can Rotomold Polycarbonate, *Plastics Technology*, 1970, November, 47.
14. J.C. Garcia, A. Marcilla and M. Beltran, The Effect of Adding Processed PVC on the Rheology of PVC Plastics, *Polymer*, 1998, **39**, 11, 2261.
15. J.C. Garcia, M. Beltran and A. Marcilla, Rheology: A Useful Tool to Assess the Processing of Commercial PVC Plastics, *Rotation*, 1998, **7**, 1, 26.
16. G.A. Gordon, Assessing the Cure State of Rotationally Molded Parts with Large-Time Bandwidth Ultrasonic Spectroscopy, Penn State University, 1998.
17. B.A. Graham, Rotational Molding of Metallocene Polypropylenes, in *ARM Fall Conference*, Cleveland, USA, 1999.
18. B. Graham, Environmental Stress Cracking Resistance of Rotationally Molded Polyethylene, *Rotation*, 1994, **3**, 2, 16.
19. S.A. Guillen-Castellanos, *et al.*, Effect of Processing History on the Sintering of Ethylene Copolymers, *Int. Polymer Processing*, 2003, **18**, 1, 87.

20. S.A. Guillén-Castellanos and C.T. Bellehumeur, The Sintering Behavior of Ethylene/Olefin Copolymers Powders, in *SPE ANTEC*, San Francisco, USA, 2002.
21. A. Gupta and U. Stadler, Influence of Stabilisers in Rotational Molding, in 22nd Annual Conference, Association of Rotational Molders, Oak Brook, Illinois, USA, 1997.
22. E.M. Harkin-Jones, Rotational Moulding of Reactive Plastics, in Mechanical and Manufacturing Engineering, The Queen's University of Belfast, Belfast, 1992.
23. E.H. Harkin-Jones, Rotational Moulding of Liquid Polymers, *Rotation*, 1994, **3**, 3, 22.
24. E. Harkin-Jones and R.J. Crawford, Rotational Moulding of Liquid Polymers, in *Rotational Moulding of Plastics*, 2nd Edition, Ed., R.J. Crawford, Wiley, New York, 1996, 243.
25. R.L. Heck, An Introduction to Chemical Blowing Agents and Their Use in Rotational Molding, in *ARM Fall Meeting*, 1978.
26. N. Henwood, New Materials for Rotomoulding, *Rotation*, 2003, **12**, 1, 32.
27. L. Johnson and E. Mincey, Post-Mold Graphics: The New Way to Decorate, *Rotation*, 1997, **5**, 2, 47.
28. R.T. Johnston, Modelling Peroxide Crosslinking in Polyolefins, in *SPE ANTEC*, San Francisco, USA, 2002.
29. M.P. Kearns, New Developments in Filler Materials, in *ARM Fall Conference*, Cleveland, USA, 1999.
30. K.B. Kinghorn, Developing ABS Materials for Rotational Molding, in *ARM Fall Conference*, Cleveland, USA, 1999.
31. J. Kjellqvist, R. Sylvest and K. Brunner, A New Material for Rotational Moulding Produced by INSITE Technology, in *BPF Rotamoulding Conference*, Leicester, UK, 1995.
32. R.I. Kliene, Rotational Moulding of Polyethylene, in *Rotational Moulding of Plastics*, 2nd Edition, Ed., R.J. Crawford, Wiley, New York, 1996, 32.
33. G. Liu, C.L. Park and J.A. Lefas, Production of Low Density LLDPE Foams in Rotational Molding, *Polym. Eng. Sci.*, 1998, **38**, 12, 1997.
34. G. Liu, C.B. Park and J.A. Lefas, Rotational Molding of Low-Density LLDPE Foams, in *Intelligent Processing of Polymeric Materials*, Ed., J.-M. Marchal, ASME, NY, 1997, MD-Vol. 79, 33.
35. D. Loti and R. Howerter, New Crosslinkable Metallocene-Based Resin for Rotational Molding, *Rotation*, 1999, **8**, 5, 28.
36. S.-J. Lui, A Study of Sintering Behaviour of Polyethylene, *Rotation*, 1996, **5**, 4, 20.
37. M. Majurey, Creep and Long-Term Lifetime for a Rotationally Moulded LLDPE Storage Tank, *Materials Australia*, 1997, May/June, 26.
38. A. Marcilla, *et al.*, Rotomolding of PVC Plastisol Foams, *Rotation*, 2002, **11**, 4, 26.
39. D. Martin, Suitability of Polyurethanes for Rotational Moulding, in *Designing Your Future*, Auckland, New Zealand, 1999.

40. J.M. McDaid, The Grinding of PE Powders for Use in Rotational Moulding, in *Mechanical and Manufacturing Engineering*, The Queen's University of Belfast, Belfast, 1998.
41. J.M. McDonagh, Rotational Casting of Acetal Copolymer, in *Society of Plastics Engineers*, 1969.
42. W.A. Miller, Rotomolding and Rotolining with E-CTFE, in *SPE ANTEC*, 1969.
43. G. Mills, Polypropylene for Rotomolding, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
44. B. Muller, *et al.*, The ABC of Rotational Molding PVC, in *20th Annual Spring ARM Meeting*, Orlando, Florida, 1996.
45. B. Muller, Carbon Black Interactions with UV Absorbers, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
46. J. Moser and G.J. Rensch, Designed Experiment Used to Characterise Shrinkage of Nylon Resin for Rotomolding, *Rotation*, 1994, **3**, 3, 26.
47. G. Park, F. Liu and J.A. Lefas, Rotomolding of Low-Density, Fine-Cell LLDPE Foams, in *PPS Conference*, North America Meeting, 1998.
48. R. Pop-Iliev and C. Park, Single Step Rotational Foam Molding of Skin Surrounded PE Foams, in *SPE ANTEC*, San Francisco, USA, 2002.
49. R. Pop-Iliev, *et al.*, Comparison of Dry Blending-Based and Melt Compounding-Based Rotomolding Techniques for LLDPE Foams, in *SPE ANTEC*, New York, 1999.
50. R. Pop-Iliev, *et al.*, Rotational Foam Molding of Polyethylene and Polypropylene, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
51. L. Pick and E. Harkin-Jones, An Investigation of the Impact Behaviour of Rotomoulded PE's over a Wide Temperature Range, in *SPE ANTEC*, San Francisco, USA, 2002.
52. E. Rabinovitz, and Z. Rigbi, Rotational Reaction Molding of Polyurethane, *Plast. Rubb. Proc. and Appl.*, 1985, **5**, 365.
53. R.L. Rees, What is Right for my Parts - Crosslinkable HDPE, in *ARM Fall Meeting*, Dallas, USA, 1995.
54. B. Rijksman, Expanding Our Future with One Shot Foams, in *Designing Our Future*, Auckland, New Zealand, 1999.
55. R. Saffert, PVC Powder Slush Molding of Car Dash Boards, in *3rd Annual PPS Meeting*, Stuttgart, Germany, 1987.
56. T. Smit and W. de Bruin, The Production of High Quality Powders for Rotational Molding, *Rotation*, 1996, **5**, 1, 10.
57. T.J. Stuft and J. Strebel, How Grinder Variables Affect Bulk Density and Flow Properties of Polyethylene Powders, *Plastics Engineering*, 1997, **53**, August, 29.
58. A. Tanaka, Rotational Molding of ABS Resin, *Japan Plastics*, 1974, **25**, 1, 16.
59. E. Takács, J. Vlachopoulos and C. Rosenbusch, Foaming with Microspheres in Rotational Molding, in *SPE ANTEC*, San Francisco, USA, 2002.
60. E. Takacs, C. Bellehumeur and J. Vlachopoulos, Differences in Rotomouldability of Polyethylene Micropellets and Powders, *Rotation*, 1996, **5**, 3, 17.

61. E. Takacs, J. Vlachopoloulos and S.J. Lipsteuer, Foamable Micropellets and Blended Forms of Polyethylene for Rotational Molding, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
62. T.S. Valera, *et al.* The Effect of Phyllitte as a Filler for PVC Plasticsols, in *SPE ANTEC*, San Francisco, USA, 2002.
63. J. Vlachopoulos, *et al.*, Polymer Rheology and its Role in Rotational Molding, *Rotation*, 1999, **8**, 6, 22.
64. J. Vlachopoulos, C.T. Bellehumeur and M. Kontopoulou, The Role of Rheology in Rotomolding, in *Proc. 12th Int. Congress on Rheology*, Quebec, 1996.
65. E. Voldner and R.D. Swain, Pigments Based on Heavy Metals, *Rotation*, 1999, **8**, 1, 55.
66. E. Voldner and R.D. Swain, Cadmium Pigments in Rotational Molding, *Rotation*, 1998, **7**, 4, 64.
67. E. Voldner, Crosslinked Polyethylene Scrap Can Be Recycled, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
68. E. Voldner, Understanding Recycling in Rotational Molding: Part 3, *Rotation*, 1993, **2**, 4, 26.
69. E. Voldner, Understanding Recycling in Rotational Molding: Part 2, *Rotation*, 1993, **2**, 3, 32.
70. E. Voldner, Understanding Recycling in Rotational Molding: Part 1, *Rotation*, 1993, **2**, 2, 36.
71. W. Wang and M. Kontopoulou, Rotational Molding of Polyolefin Plastomers and TPO's, in *SPE ANTEC*, San Francisco, USA, 2002.
72. R.D. Whitman, How to Make integral Skin Urethane Foams, *Plastics Technology*, 1970, February, 42.
73. S. Bickerton and R.J. Crawford, Investigations into Rotational Moulding of Short Fibre Reinforced Thermoset Resins, in *SPE ANTEC*, Dallas, USA, 2001.
74. N. Corrigan, E. Harkin-Jones and R.J. Crawford, Rotational Molding of a Dicyclopentadiene Reactive Liquid Polymer, in *SPE ANTEC*, San Francisco, USA, 2002.
75. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effect of Pigmentation on the Microstructure and Properties of Rotationally Moulded Polyethylene, in *PPS Conference*, New York, USA, 1997.
76. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Relationship Between the Microstructure and Properties of Rotationally Moulded Plastics, in *SPE ANTEC*, 1998.
77. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effect of Pigmentation on the Microstructure and Properties of Rotationally Moulded Polyethylene, *J. Mat. Sci.*, 1998, **33**, 4869.
78. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effects of Nucleating Additives on the Mechanical Properties of Plastics, in *18th Conference of the Prague Chemical Society*, Prague, Czech Republic, 1998.

79. E. Harkin-Jones and R.J. Crawford, Rotational Moulding of Liquid Polymers, *Proc Instn Mech Engrs*, Part B, *J. Eng. Man.*, 1996, **210**, 437.
80. E. Harkin-Jones and R.J. Crawford, Rotational Moulding of Liquid Plastics Systems: An Assessment of Material Mouldability, *Advances in Polymer Technology*, 1996, **15**, 1, 71.
81. E. Harkin-Jones and R.J. Crawford, The Processing of Reactive Liquid Polymers by Rotational Moulding, in *PPS Conference*, Singapore, 1996.
82. E. Harkin-Jones and R.J. Crawford, Mechanical Properties of Rotationally Moulded NYRIM, *Polymer Eng. Sci.*, 1996, **36**, 5, 615.
83. E.J. Harkin-Jones and R.J. Crawford, Guidelines for the Rotational Moulding of Liquid Polymers, in *SPE ANTEC*, Atlanta, USA, 1998.
84. M.P. Kearns, *et al.*, The Use of Hollow Microspheres in Rotationally Moulded Plastic Parts - Part 1, *Rotation*, 2000, **9**, 1, 20.
85. M.P. Kearns, *et al.*, The Use of Hollow Microspheres in Rotationally Moulded Plastic Parts - Part 2, *Rotation*, 2000, **9**, 2, 20.
86. M.P. Kearns, *et al.*, The Use of Hollow Microspheres in Rotationally Moulded Plastic Parts - Part 3, *Rotation*, 2000, **9**, 3, 22.
87. M.P. Kearns and R.J. Crawford, The Use of Chemical Blowing Agents in the Rotational Moulding of Plastics, in *Blowing Agents and Foaming Processes*, Heidelberg, Germany, Rapra Technology, Shrewsbury, UK, 2002.
88. M.P. Kearns, *et al.*, Development of Rotationally Molded Products for Fuel Gas Containment, *Rotation*, 2002, **11**, 4, 40.
89. J. McDaid and R.J. Crawford, The Grinding of Polyethylene Powders for Use in Rotational Moulding, in *SPE ANTEC*, Atlanta, USA, 1998.
90. J. McDaid and R.J. Crawford, The Grinding of PE for Use in Rotational Moulding, *Rotation*, 1997, **6**, 1, 27.
91. G.W.G. McDowell, *et al.*, Preliminary Investigation into the Use of Wood Fibres as a Filler in Rotationally Moulded PE, in *SPE ANTEC*, Dallas, USA, 2001.
92. A. Tcharkhtchi, *et al.*, Rotomoulding of Polyethylene Filled with Mica, *Materiaux et Techniques*, 2001, **89**, 9, 37.
93. J.P. Van Hooijdonk, *et al.*, Influence of Processing Parameters on the Properties of PP for Rotational Moulding, in *SPE ANTEC*, Dallas, USA, 2001.
94. J.P. Van Hooijdonk, *et al.*, Influence of Processing Conditions on the Properties of PP for Rotational Moulding, *Rotation*, 2001, **10**, 3, 28.
95. B.G. Wisley and R.J. Crawford, Physical Properties of Laminates made from LLDPE and XLPE by Rotational Moulding, *Rotation*, 1996, **5**, 2, 17.
96. Wang Xin, *et al.*, Rotational Moulding of Metallocene Polyethylenes, *Plastics, Rubber and Composites*, 2000, **29**, 7, 340.

Chapter 5 – Quality Control in Rotational Moulding

5.1 Introduction

A moulded plastic part must satisfy the customer's requirements in terms of functionality, longevity, aesthetics and economics. In all 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 rotomoulded 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 the Chapter.

It is apparent from the preceding chapters that rotational moulding has characteristics that make it uniquely different from any other moulding method. 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 significant 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 Wall Thickness Distribution

Rotational moulding is a single-surface moulding process. In this regard it is similar to thermoforming and blow moulding. This means that the mould can only affect the quality of one 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 a mould. As a result, wall thickness *tolerance* is never as good as 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 5.1).

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, run-of-the-mill parts such as tanks and outdoor toys, the wall thickness variation in rotomoulded parts is typically $\pm 20\%$. For certain products, such as medical facemasks and optical parts, a variation of $\pm 10\%$ 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 rotational speeds, etc. If the plastic part separates from the mould wall, then the air gap between the plastic and the mould means that the moulder has lost control of the cooling rate of the plastic. 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.

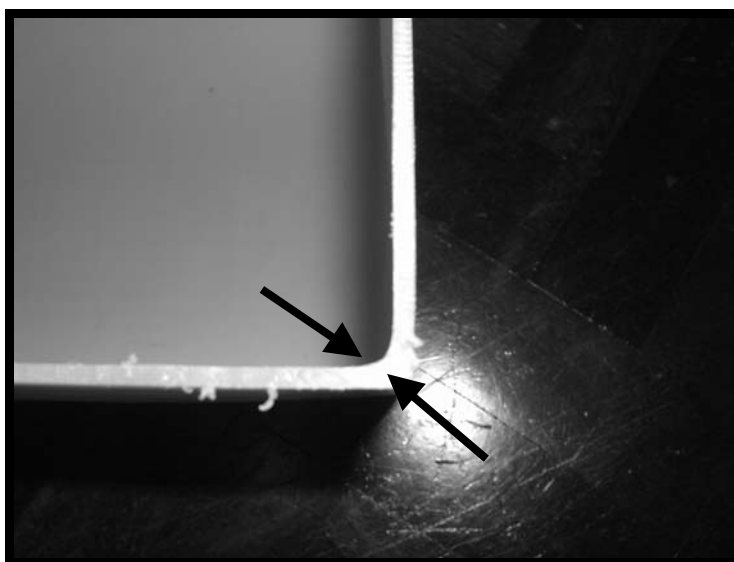


Figure 5.1 Cross-section showing greater thickness in corner of rotomoulded part

In modern control systems for rotational moulding, steps are being 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 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 5.1 Typical wall thickness ranges for rotationally moulded plastics			
Polymer	Minimum wall thickness range (mm)	Typical wall thickness (mm)	Maximum wall thickness (mm)
LLDPE	0.5	1.5–25	75
HDPE	0.75	1.5–25	50
PVC	0.2	1.5–10	10
Nylon 6	1.5	2.5–20	40
PC	1.25	1.5–10	10
EVA	0.5	1.5–20	20
PP	0.5	1.5–25	25

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 kept 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 3.9). 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, 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 or 3.9, 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 factor that affects the wall thickness distribution of the plastic is the uniformity of heat transfer to the mould and uniformity of the mould 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 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 5.2).



Figure 5.2 Tank with shielding on lid
Courtesy of Clarehill Plastics Limited

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 crucial to recognise, however, 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.

5.3 Shrinkage

Plastics, like all materials, shrink (i.e., get smaller) when they cool. Crystalline polymers such as polyethylene, polypropylene and nylon exhibit up to five times the shrinkage of amorphous polymers such as polycarbonate. 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.

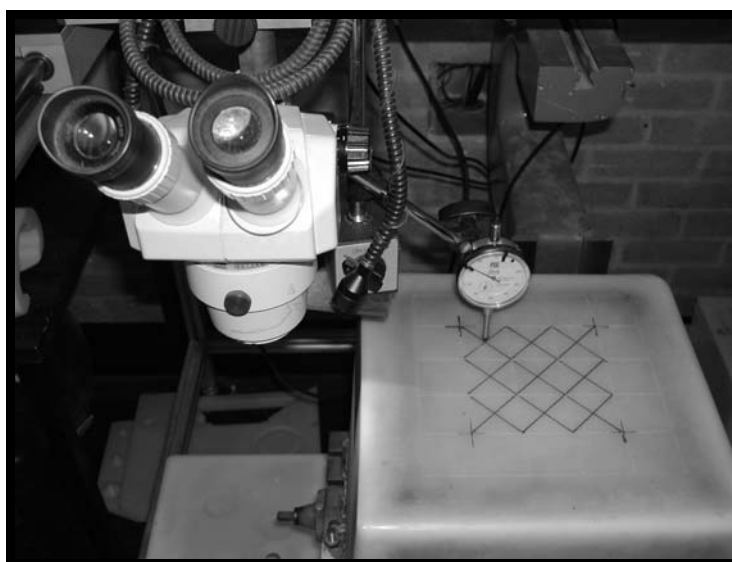


Figure 5.3 Dial gauge and microscope attachment for determining shrinkage

5.3.1 Shrinkage Guidelines

Plastics increase in density and therefore decrease in volume as they cool. Figure 5.3 shows equipment that can be used to measure shrinkage of a grid etched on to a rotomoulded part. 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 5.2 Linear shrinkage values for rotationally moulded polymers		
Polymer	Shrinkage range (%)	Recommended (%)
LDPE	1.6–3.0	3.0
HDPE	3.0–3.5	3.5
PP	1.5–2.2	2.2
PVC	0.8–2.5	1.5
PC	0.6–0.8	0.8
Nylon 6	1.5–3.0	3.0

5.3.2 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, etc. 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.

5.3.2.1 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 5.4 shows experimental evidence to link shrinkage with release temperature for a selection of pigmented and natural grades of polyethylene.

The various lines in Figure 5.4 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 regard 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.

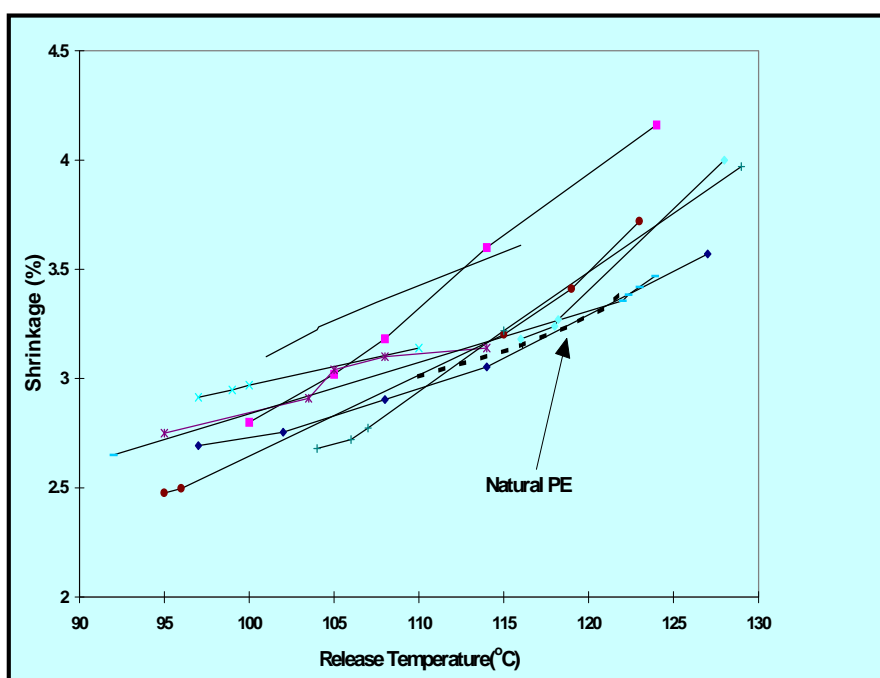


Figure 5.4 Effect of release temperature on shrinkage of rotationally moulded polyethylene with different types of pigment

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.

5.3.2.2 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 (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. In order 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 or, as is more likely, below atmospheric during the cooling phase. In the latter case this 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.

5.4 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 externally applied or be readily apparent. Quite often there are internal stresses set up as the structure of the material forms 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 measure of the nonuniformity 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		
Plastic	Commercial (%)	Precision (%)
Polyethylene	2.0	2.0
Nylon	0.5	0.3
Polypropylene	2.0	1.0
PVC plastisol	2.0	1.0
Polycarbonate	0.5	0.3

While flat surfaces on plastic parts are appealing, 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. 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, very smooth or glossy surfaces will accentuate distortion, whereas a certain degree of warpage can be accommodated if the surface texture is engraved, etched, or speckled.

5.4.1 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 5.5 shows the warpage caused by different cooling rates in aluminium and steel moulds. It is evident that water quenching is considerably worse than cooling using still

air, which reflects the experience of moulders. Also, steel moulds cause greater warpage than aluminium moulds due to the greater heat transfer from the thinner steel mould.

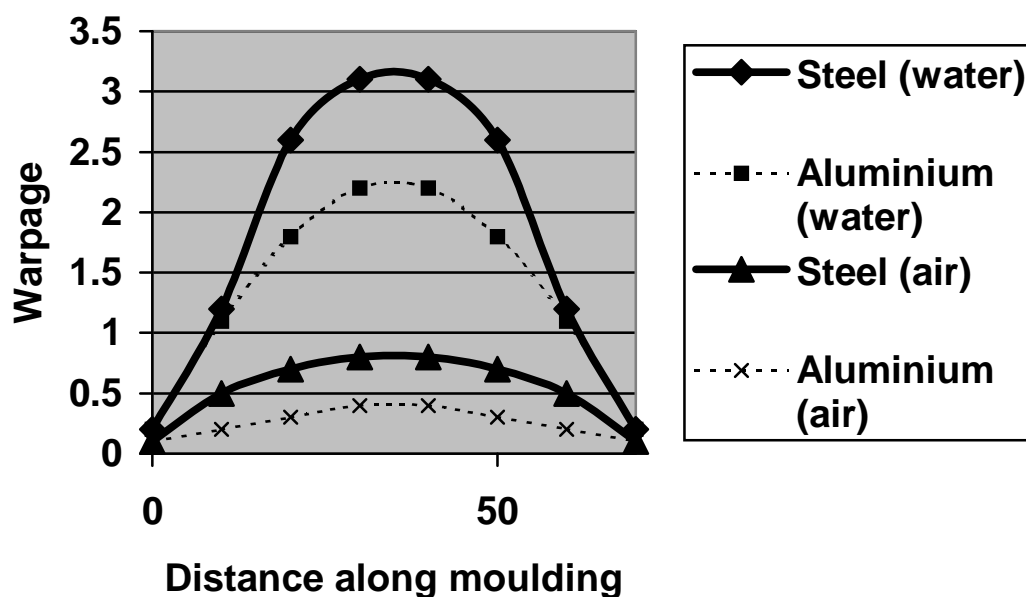


Figure 5.5 Warpage as a function of cooling method and mould material
(From C.H. Chen, J.L. White and Y. Ohta, A fundamental experimental study of the mechanisms of warpage and shrinkage of PE in rotational molding, *Int. Polym. Proc.*, 1991, **6**, 3, 212)

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 rate. If the cooling rates were balanced across the wall thickness of the part (see Figure 5.6) 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 the moulding because the heat transfer rate by conduction from the plastic to the metal mould is greater than the heat transfer rate by convection from the plastic to the gas inside the mould. The situation is improved if a cooling gas is circulated inside the mould, but very cold gas needs to be continuously fed inside the mould to create anything like the desired effect.

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.

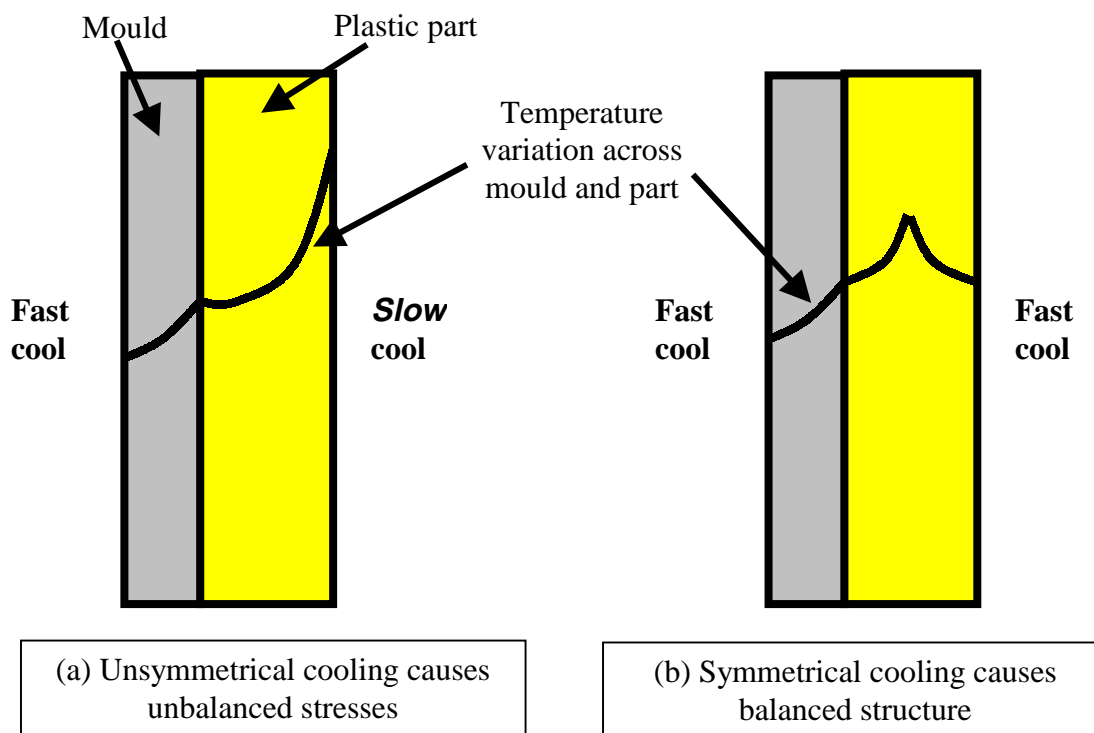


Figure 5.6 Effect of internal cooling on the structure of a rotationally moulded plastic part

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.

5.5 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, it is the moulder, rather than the mould designer, who 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 5.7. If there is differential shrinkage this will lead to warpage, and if the warpage is restrained by jiggling, for example, then residual stresses will be set up in the plastic. This is illustrated in Figure 5.8.

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 5.9, if it is available. If the restricted strain (shrinkage) is greater, then the residual stress will be proportionally higher, as shown in Figure 5.9.

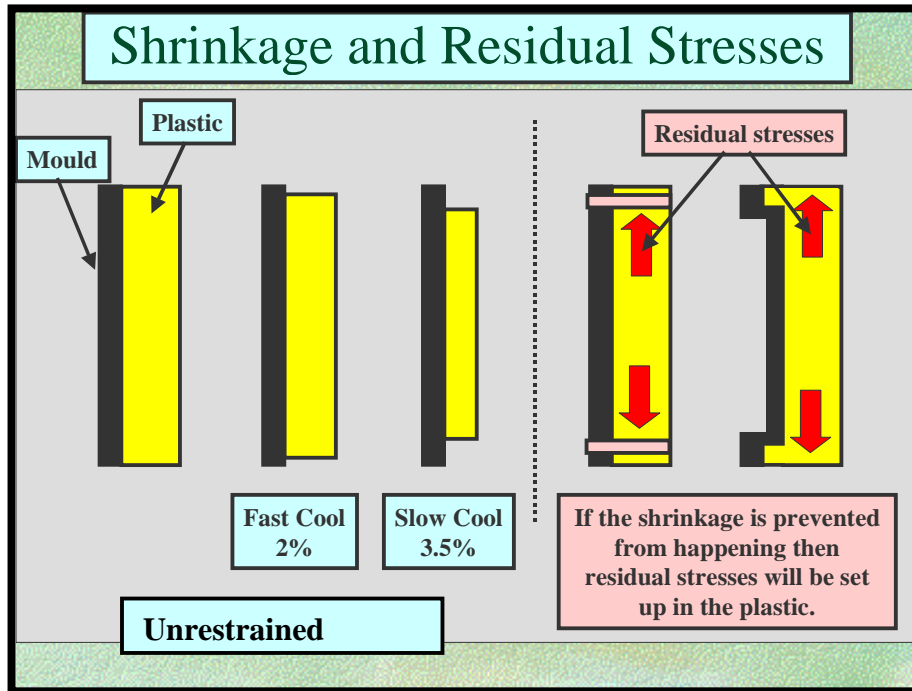


Figure 5.7 Relationship between shrinkage and residual stress

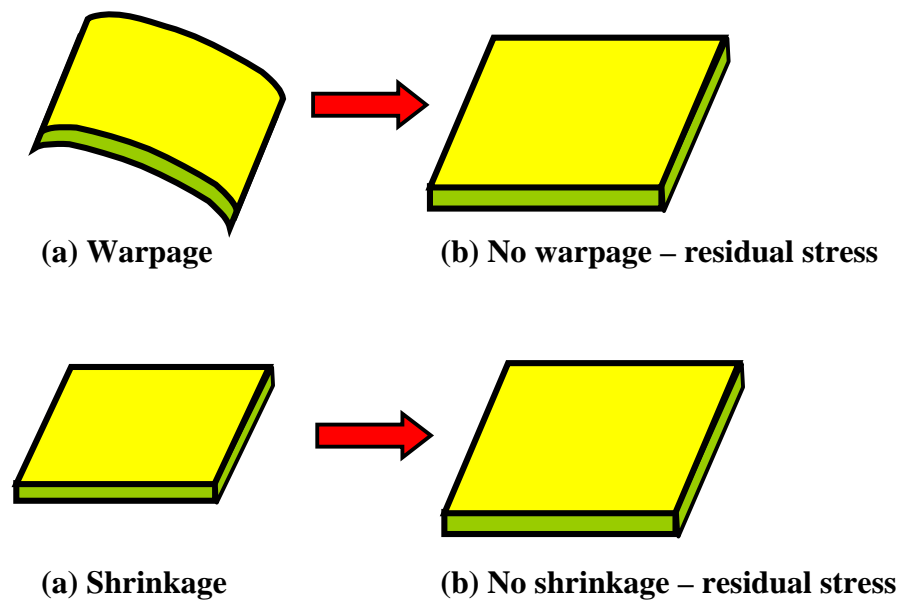


Figure 5.8 Linkages between warpage, shrinkage and residual stress

It should be noted that it follows from the above 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 (see Figure 5.9).

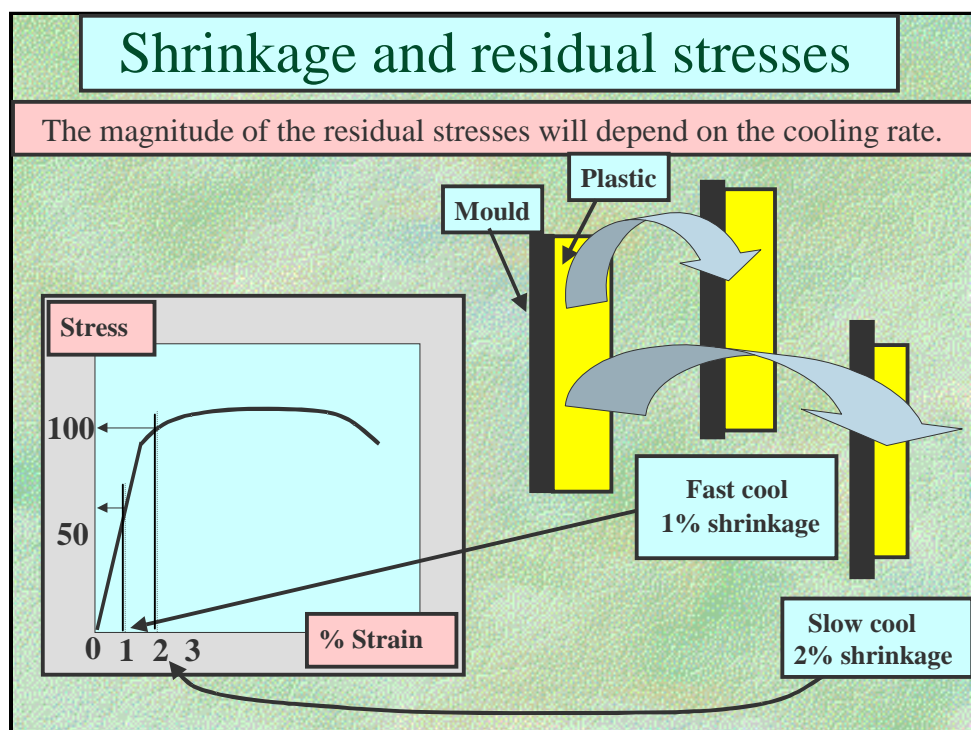


Figure 5.9 Shrinkage and residual stress

5.5.1 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/m^2 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/m^2 , as illustrated in Figure 5.10, then in service it would only be possible to apply an external stress of 80 MN/m^2 before the part would break. Therefore, as far as the user is concerned, the strength of the material has been reduced from 110 MN/m^2 to 80 MN/m^2 . A similar argument can be applied to impact strength, so that residual stresses are highly detrimental to the performance of the plastic.

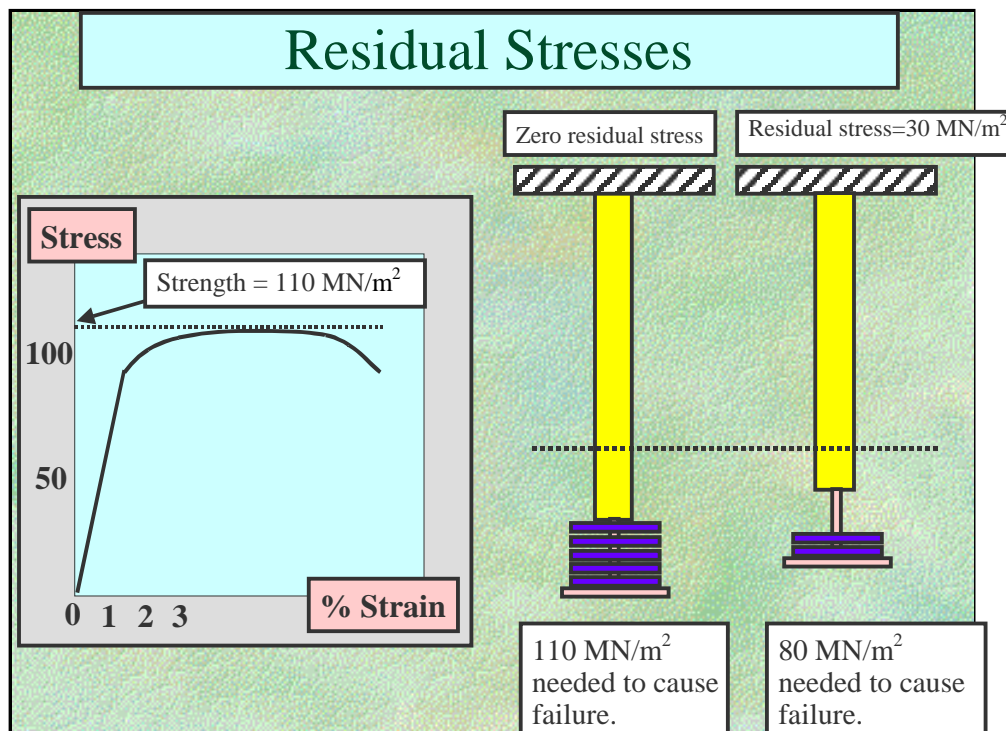


Figure 5.10 Effect of residual stress on the strength of a plastic

5.5.2 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, etc., 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, some time 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 increases because this leads to a further decrease in modulus.

Probably the most severe effect of moulded-in stresses is environmental stress cracking. Environmental stress cracking (ESC) usually refers specifically to a phenomenon observed in polyethylene. It is the tendency for polyethylene parts to fail prematurely in the presence of detergents, oils, and other active environments. 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.

5.5.3 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. Cooling rates are a particularly effective tool. 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.

5.6 Surface Decoration

As plastics can be brilliantly coloured by mixing a pigment with the plastic, rotationally moulded parts are usually used without further surface colouring or decoration. In certain instances, 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, polycarbonate and polystyrene. On the other hand, polyolefins are not receptive to paints and so chemical etching, flame treating or other methods of surface activation are necessary prior to painting of materials such as LLDPE, PP and EVA, as well as many nylons.

5.6.1 Painting

In general it is very difficult to paint polyethylene unless the surface is treated after moulding. There are some new grades of polyethylene that have been treated as a powder

so as to make the moulded surface receptive to paint. 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 5.11 and 5.12). In certain instances, 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 1 m² or so, the technique allows extremely fine details to be transferred.



Figure 5.11 Paint sprayed onto moulded part
Courtesy of Mold In Graphic Systems®



Figure 5.12 Final flame treatment
Courtesy of Mold In Graphic Systems®

5.6.2 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.

5.6.3 Adhesives

Adhesive-backed decals can be used to decorate moulded plastics. The most popular adhesive is the 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 PSAs designed specifically for this application, but surface preparation of the polymer is critical to provide the desired adhesion.

5.6.4 In-Mould Decoration

In-mould decoration has become very popular in the rotomoulding industry. The in-mould transfer consists of the decorative logo 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 5.13). 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 5.14–5.15). Care must be taken during the early stages of rotation to prevent the dry powder from scuffing or lifting the decoration.

Another in mould decoration system available is Mold In Graphic Systems® Color-In System. This technique employs a spray ‘paint’ and enables multiple colours to be integrated into rotomoulded parts. Since this system embeds itself directly into the resin surface, the new custom design is permanent and resistant to attack by chemicals, solvents or extreme weather conditions.

Figures 5.16-5.18 illustrate the use of Mold In Graphic Systems® Color-In System spray on graphics in rotomoulding.



Figure 5.13 Graphic applied to inside of mould prior to moulding
Courtesy of Mold In Graphic Systems®



Figure 5.14 Graphic in place following demoulding
Courtesy of Mold In Graphic Systems®

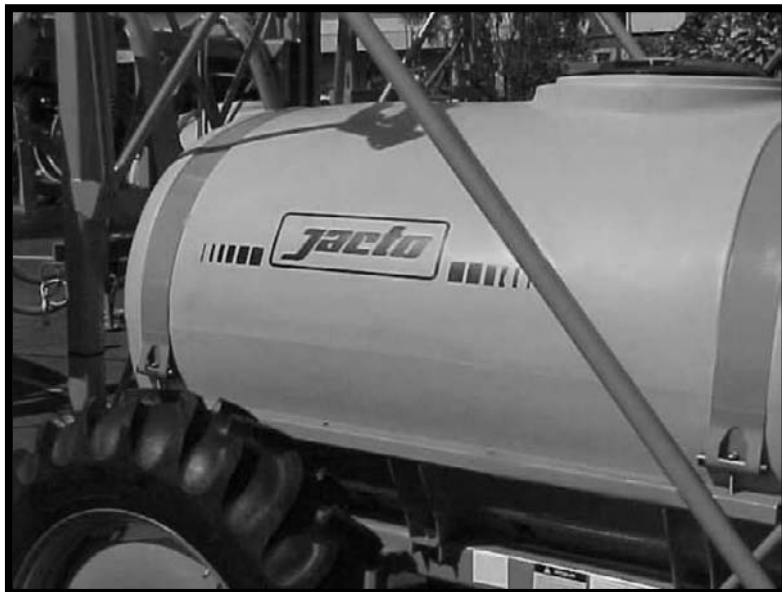


Figure 5.15 Graphic on final moulded part
Courtesy of Mold In Graphic Systems®



Figure 5.16 In mould colour spray
Courtesy of Mold In Graphic Systems®



Figure 5.17 PE powder placed in mould
Courtesy of Mold In Graphic Systems®

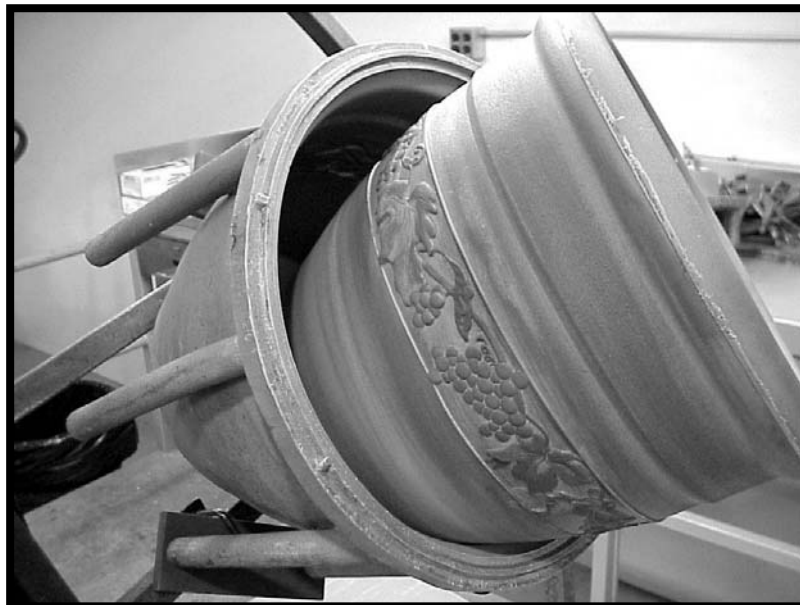


Figure 5.18 Moulding produced with multiple colours
Courtesy of Mold In Graphic Systems®

5.6.5 Post Moulding Decoration

Transfers, similar to those described for in-mould use, have also been developed so that they can be applied to the moulded part (see Figures 5.19 and 5.20). This can reduce scrap rates because in-mould transfers can get damaged, or may not properly adhere to the plastic, during moulding. The mould-on transfers are unique to rotomoulding and become part of the surface of the moulded plastic, thus making them durable and almost impossible to remove.



Figure 5.19 Transfer applied to moulding surface
Courtesy of Mold In Graphic Systems®



Figure 5.20 Flame treatment of moulding surface
Courtesy of Mold In Graphic Systems®

5.7 Foaming in Rotational Moulding

The use of foamed materials in rotationally moulded parts is becoming very common (Figure 5.21). In some cases the foam is used to improve the thermal insulation properties of the part and in such cases, polyurethane foam is injected as a secondary operation or polyethylene foam is added during moulding. In other cases the foam is included to improve the stiffness per unit weight of the part. If this is the objective then it is very important that there is a strong bond between the solid outer skin and the foamed inner layer. Otherwise the desired mechanical stiffening is not achieved. For this reason, if mechanical stiffening is the objective then polyethylene foam is usually preferred to polyurethane foam because the latter does not bond easily to polyethylene and extra surface treatment steps are needed to provide the necessary adhesion.

In rotational moulding two types of foam can be made: single layer foam and multi-layer foam.

- (1) The single layer foam can be achieved by blending the required amount of blowing agent into the polyethylene and rotomoulding using standard processing conditions. Above a specific activation temperature the blowing agent thermally degrades to release gases, which produce a foamed part.



Figure 5.21 Typical foam filled rotomoulded parts
Courtesy of ICO Polymers

- (2) The multi-layer foam system consists of a hard outer polyethylene skin and a core of foamed polyethylene. The foamed inner layer adds rigidity, increases structural strength and reduces raw material costs. The amount of resin needed per part produced can be reduced by as much as 50%. In some cases the whole interior of the moulding may be foamed, so that effectively a sandwich type structure is produced, i.e., a foamed core between solid skins. The foamed core may be introduced during the moulding process either by simply adding the core material via vent tubes (two-step/manually), using a 'drop-box' mechanism or alternatively by using a 'one-step' foaming material.

In the two-step process the solid outer skin material and foamable inner core are added sequentially. This can be carried out either manually or automatically through the use of a 'drop box'. In the manual case, the foamable polymer mix is added via vent tubes once the outer solid skin has just formed and involves removing the mould from the oven during the heating stage. Storing the foamable polymer powder in an insulated container or 'drop box' attached to the mould is an alternative method and negates the need to remove the mould from the oven. Following the initial lay up of the solid outer polymer skin in the mould, an air activated valve on the drop box can be operated at the desired time, dropping the foamable polymer into the rotating mould.

The one-step (or one-shot) foaming method involves the addition of two types of materials to the mould, one of which contains a chemical blowing agent. The materials are chosen in such a way as to promote the formation of a solid unfoamed skin prior to the foaming of the second material. One technique uses the polyethylene/blowing agent mix in a polyethylene film bag that is placed in the mould with the outer skin material. Once the outer skin material has been deposited on the inner mould surface and the mould temperature continues to increase, the polyethylene bag melts and releases the polyethylene/blowing agent mix which eventually foams and completely fills the cavity creating a sandwich structure. Another popular method utilises the polyethylene/blowing agent compounded as a pellet. The granules/pellets are sufficiently large to prevent them from foaming too soon and rupturing through the solid polyethylene skin.

At present there is no ideal system that works with every mould geometry and therefore complex mouldings with sharp radii can cause problems in the distribution of the foam. Process optimisation is also required in choosing correct mould rotation speeds/ratios as well as ensuring uniform part cooling. Cooling too rapidly (e.g., using water) and improper mould venting can destroy the foam structure. Figure 5.22 shows a typical Rotolog internal air temperature trace for a moulding produced using one-shot foam, and Figure 5.23 shows the cross-section of a foamed part.

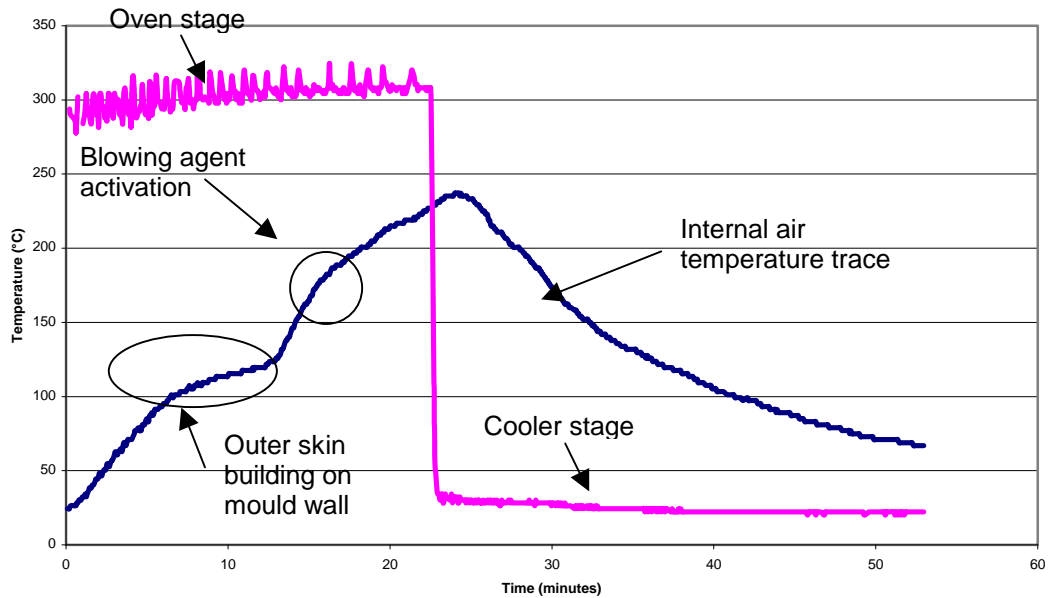


Figure 5.22 Internal air temperature trace for skin/foam moulding

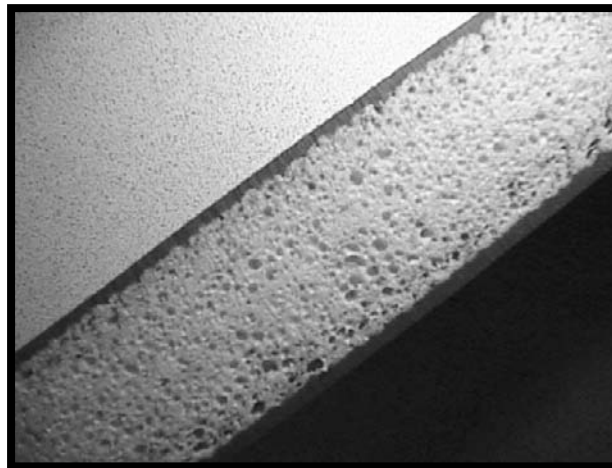


Figure 5.23 Cross-section through foamed rotomoulded part

5.7.1 Chemical Blowing Agent Technology

There are two categories of chemical blowing agents (CBAs):

- Exothermic CBAs, that give off heat while they decompose, and
- Endothermic CBAs, that take up heat while they decompose.

CBAs decomposes relatively rapidly at a very specific temperature. For example, azodicarbonamide (AZ), the most popular exothermic CBA, decomposes completely over the temperature range of 195-215 °C (380-420 °F). About 35% (wt) of the decomposition

product is a mixture of nitrogen (65%), carbon monoxide (31.5%) and carbon dioxide (3.5%). Sodium bicarbonate (NaHCO_3) is the most popular endothermic blowing agent, decomposing in a temperature range of 100-140 °C or 210-285 °F and generating carbon dioxide and water vapour.

The amount of gas generated by the decomposition of a blowing agent is typically given in cm^3/g of blowing agent at standard temperature and pressure. As examples, AZ generates 220 cm^3/g of blowing agent and NaHCO_3 generates about 135 cm^3/g of blowing agent. Common blowing agents are detailed in Table 5.3.

Table 5.3 Common chemical blowing agents				
Chemical blowing agent	Decomposition temperature (°C)	Gas yield (cm^3/g)	Type	Typical polymers
Azodicarbonamide (AZ)	195-215	220	Exothermic	EVA, HDPE, LLDPE, LDPE, PP, thermoplastic elastomer, PVC
4,4'-Oxybisbenzene sulfonyl hydrazide (OBSH)	160	125	Exothermic	HDPE, PVC
Sodium bicarbonate (NaHCO_3)	100-140	135	Endothermic	LDPE, EVA, PVC, thermoplastic elastomer

It is important to realize that a CBA can only be effective when the polymer is densified into a liquid layer before the CBA decomposes.

5.7.2 Design of Foamed Sections

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 5.24. 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 5.25). 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.

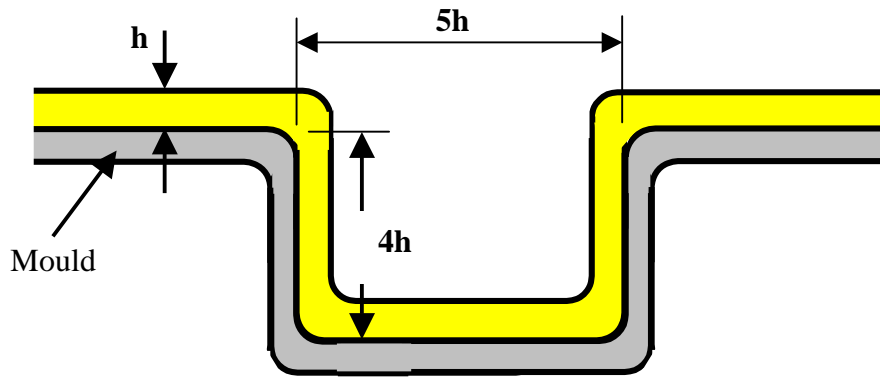


Figure 5.24 Typical dimensions of stiffening corrugations in rotationally moulded parts

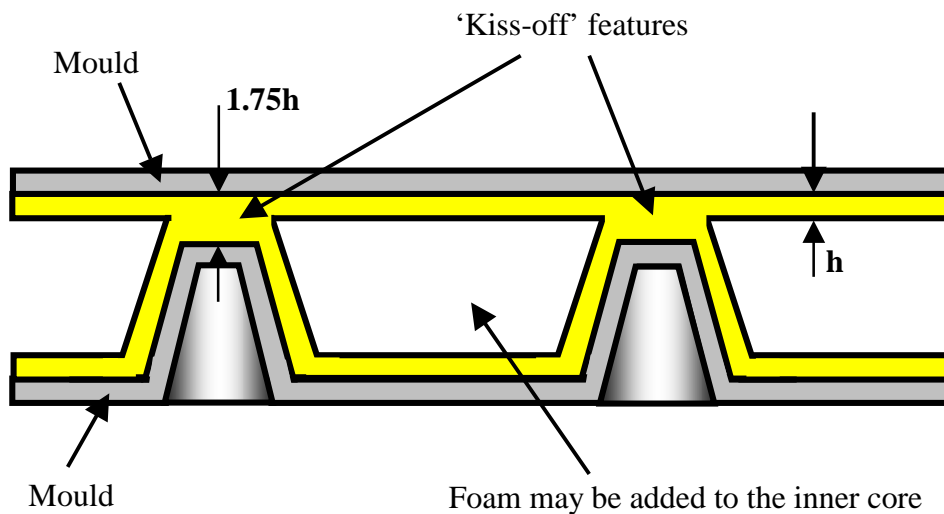


Figure 5.25 'Kiss-off' stiffening features in rotationally moulded parts

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. 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 5.26 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.

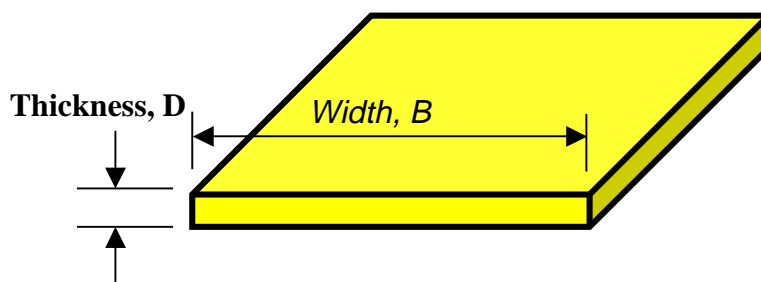
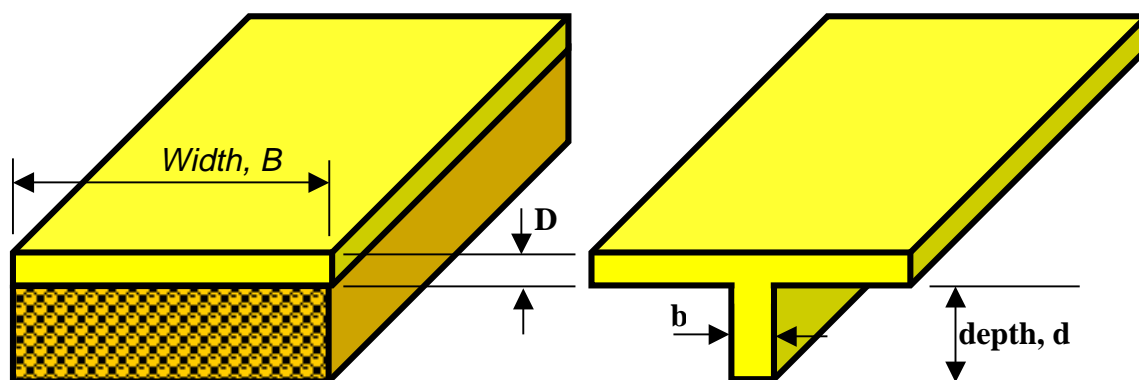


Figure 5.26 Factors used to calculate stiffness of solid rotomoulded part

5.7.3 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 5.27.



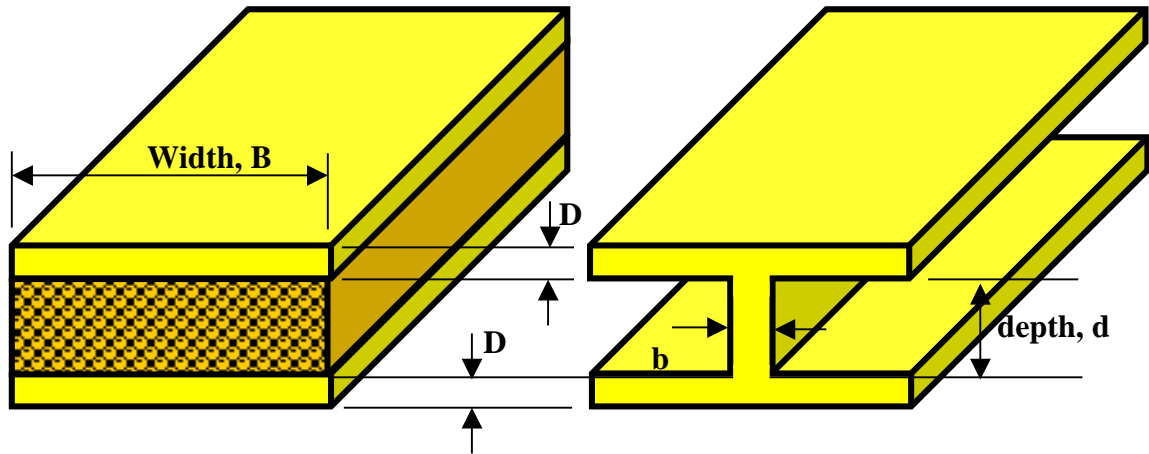
(a) Solid/foam cross-section

(b) Equivalent solid cross-section

Figure 5.27 Illustration that foam effectively acts as a rib

5.7.4 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 5.28). 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.



(a) Solid/foam/solid cross-section

(b) Equivalent solid cross-section

Figure 5.28 Foam effectively acts as a rib in sandwich cross-section

Bibliography

1. D. Ramazzotti, Rotational Molding, in *Plastic Product Design Handbook*, Ed., E. Miller, Dekker, New York, 1983, 75-104.
2. G.A. Gordon, Assessing the Cure State of Rotationally Molded Parts with Large-Time Bandwidth Ultrasonic Spectroscopy, Penn State University, 1998.
3. B. Graham, Environmental Stress Cracking Resistance of Rotationally Molded Polyethylene, *Rotation*, 1994, **3**, 2, 16.
4. M. Majurey, Creep and Long-Term Lifetime for a Rotationally Moulded LLDPE Storage Tank, *Materials Australia*, 1997, May/June, 26.
5. E. Rabinovitz, and Z. Rigbi, Rotational Reaction Molding of Polyurethane, *Plast. Rubb. Proc. and Appl.*, 1985, **5**, 365.
6. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Relationship Between the Microstructure and Properties of Rotationally Moulded Plastics, in *SPE ANTEC*, 1998.
7. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effects of Nucleating Additives on the Mechanical Properties of Plastics, in *18th Conference of the Prague Chemical Society*, Prague, Czech Republic, 1998.
8. B.G. Wisley and R.J. Crawford, Physical Properties of Laminates made from LLDPE and XLPE by Rotational Moulding, *Rotation*, 1996, **5**, 2, 17.
9. N. Callan, *et al.*, Effects of Cooling Rate on the Mechanical Properties of Rotationally Moulded Polyethylene Parts, in *SPE ANTEC*, San Francisco, USA, 2002.
10. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Influence of the Processing Parameters and Nucleating Additives on the Microstructure and Properties of Rotationally Moulded Polypropylene, in *ESAFORM Conference on Material Forming*, Sophia Antipolis, 1998.
11. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Prediction of Degradation of Polyethylene During Rotational Moulding, in *SPE ANTEC*, New York, USA, 1999.
12. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effect of Internal Pressure on the Microstructure and Properties of Rotationally Moulded Polyethylene, in *ESAFORM Conference*, Guimaraes, Portugal, 1999.
13. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Quality Control of Rotationally Moulded Polyethylene Using Reflected Light Microscope, *Rotation*, 1999, **8**, 2.
14. C. Cramez, M.J. Oliveira and R.J. Crawford, Prediction of Degradation of Polyethylene During Rotational Molding, in *SPE ANTEC*, Florida, USA, 2000.
15. M.C. Cramez, *et al.*, Rotationally Moulded PE: Structural Characterisation by X-Rays and Microhardness, *Advances in Polymer Technology*, 2001, **20**, 2, 116.
16. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Effect of Nucleating Agents and Cooling Rate on the Microstructure and Properties of Rotationally Molded Polypropylene, *J. Mat. Sci.*, 2001, **36**, 9, 2151.
17. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Optimisation of Rotational Moulding of Polyethylene by Predicting Antioxidant Consumption, *Polymer Degradation and Stability*, 2002, **75**, 321.

18. M.C. Cramez, M.J. Oliveira and R.J. Crawford, Optimization of the Rotational Moulding Process for Polyolefins, *Proc I. Mech E., Part B*, 2003, **217**, 323.
19. R.J. Crawford and J.A. Scott, The Formation and Removal of Gas Bubbles in a Rotational Moulding Grade of PE, *Plastics and Rubber Processing and Application*, 1987, **7**, 2, 85.
20. R.J. Crawford and P.J. Nugent, A New Process Control System for Rotational Moulding, *Plast., Rubber and Composites: Proc. and Appl.*, 1992, **17**, 1, 23.
21. R.J. Crawford and P.J. Nugent, Impact Strength of Rotationally Moulded Polyethylene Articles, *Plast. Rubber and Composites: Proc. and Applic.*, 1992, **17**, 1, 33.
22. R.J. Crawford and A.G. Spence, Formation and Removal of Gas Bubbles from Rotomoulded Products, in *9th Annual PPS Conference*, Manchester, UK, 1993.
23. R.J. Crawford and J.A. Scott, Optimising the Stiffness of Rotationally Moulded Products, *Rotation*, 1994, **3**, 4, 20.
24. R.J. Crawford, Causes and Cures of Problems During Rotomoulding, *Rotation*, 1994, **3**, 2, 10.
25. R.J. Crawford, Design of Stiffeners in Rotationally Moulded Products, *Rotation*, 1996, **5**, 3, 12.
26. R.J. Crawford, A.G. Spence and C. Silva, Effects of Pigmentation on the Impact Strength of Rotationally Moulded PE, in *SPE ANTEC*, Indianapolis, USA, 1996.
27. R.J. Crawford and A.G. Spence, Cycle Time Reduction and Shrinkage/Warpage Control in Rotational Moulding, in *PPS Conference*, Singapore, 1996.
28. R.J. Crawford, Reducing Cycle Times in Rotational Moulding-A Challenge, in *SPE ANTEC*, Atlanta, 1998.
29. R.J. Crawford and K.O. Walls, Shrinkage and Warpage of Rotationally Moulded Parts, in *SPE RETEC on Rotational Moulding*, Cleveland, Ohio, USA, 1999.
30. R.J. Crawford, M.P. Kearns and S. Murphy, Practical Ways to Reduce Cycle Times in Rotational Moulding, *Rotation*, 1999, **8**, 3, 24.
31. R.J. Crawford, Design of Stiffening Features in Rotationally Moulded Plastic Parts, in *SPE ANTEC*, Florida, USA, 2000.
32. R.J. Crawford, Warpage of Rotationally Moulded Parts, *Rotation*, 2000, **9**, 1, 36.
33. R.J. Crawford, Shrinkage of Rotationally Moulded Parts, *Rotation*, 2000, **9**, 2, 38.
34. R.J. Crawford, Residual Stress in Rotationally Moulded Parts, *Rotation*, 2000, **9**, 3, 36.
35. R.J. Crawford, *et al.*, Sensitivity of Cycle Time to Processing Conditions in Rotational Moulding, in *PPS Australasia Conf.*, Taiwan, 2002.
36. J. Godinho, A. Cunha and R.J. Crawford, Property Variations Across the Wall Thickness of Rotationally Moulded PE Products, in *SPE ANTEC*, Indianapolis, USA, 1996.
37. J. Godinho, A. Cunha and R.J. Crawford, Property Variations in PE Articles Produced by a Variety of Moulding Methods, in *SPE ANTEC*, Toronto, Canada, 1997.
38. J. Godinho, R.J. Crawford and A.M. Cunha, Mechanical Properties and Structure Development in LMDPE Using Different Moulding Techniques, in *ESAFORM*, Sophia Antipolis, France, 1998.

39. J.S. Godinho, A. Cunha and R.J. Crawford, Prediction of the Mechanical Properties of Rotationally Moulded Articles, *Rotation*, 1998, **7**, 3, 18.
40. J. Godinho, A. Cunha and R.J. Crawford, Prediction of the Mechanical Properties of PE Parts Produced by Different Moulding Methods, *Proc I. Mech E., Part L*, 2002, **216**, 1.
41. J.A. Martins, *et al.*, Prediction of Spherulite Size in Rotationally Moulded Polypropylene, *J. Macromolecular Sci.*, 2001.
42. L.G. Olson, *et al.*, Rotational Molding of Plastics: Comparison of Simulation Results for an Axisymmetric Mold, *Polymer Engineering & Science*, 2000.
43. A.G. Spence and R.J. Crawford, Mould Pressurisation Removes Bubbles and Improves Quality of Rotationally Moulded Products, *Rotation*, 1995, **4**, 2, 16.
44. A.G. Spence and R.J. Crawford, An Investigation of the Occurrence of Gas Bubbles in Rotationally Moulded Products, *Rotation*, 1995, **4**, 2, 9.
45. A.G. Spence and R.J. Crawford, Simulated Bubble Removal Under Pressurised Rotational Moulding Conditions, *Rotation*, 1995, **4**, 3, 17.
46. A.S. Spence and R.J. Crawford, The Effect of Processing Variables on the Formation and Removal of Bubbles in Rotationally Molded Products, *Polymer Engineering and Science*, 1996, **36**, 7, 993.
47. A.G. Spence and R.J. Crawford, Removal of Pin-holes and Bubbles from Rotationally Moulded Products, *Proc Instn Mech Engrs, Part B, J. Eng. Man.*, 1996, **210**, 521.
48. A.G. Spence and R.J. Crawford, Pin-holes and Bubbles in Rotationally Moulded Products, in *Rotational Moulding*, Ed., R.J. Crawford, Research Studies Press, 1996, 217.
49. D.-W. Sun and R.J. Crawford, Analysis of the Effects of Internal Heating and Cooling During the Rotational Molding of Plastics, *Polymer Eng. Sci.*, 1993, **33**, 3, 132.
50. X. Wang, *et al.*, Processing Characteristics of Rotational Moulding Grades of Metallocene Polyethylene, *Rotation*, 2000, **9**, 4, 20.
51. L. Xu and R.J. Crawford, Analysis of the Formation and Removal of Gas Bubbles in Rotationally Moulded Thermoplastics, *J. Materials Sci.*, 1993, **28**, 2067.
52. L. Xu, R.J. Crawford and A.G. Spence, Prediction of the Rotational Moulding Cycle, *Rotation*, 1996, **5**, 1, 14.
53. L. Xu, and R.J. Crawford, Analysis of Bubble Size in Rotationally Moulded Products, *Materials Engineers*, 1996, **16**, 27.
54. R. Al-Zubi, *et al.*, Understanding Environmental Stress Crack Resistance, *Rotation*, 2002, **11**, 4, 20.
55. R. Al-Zubi and M. Lampson, Rupture Behaviour of Linear and Crosslinked Polyethylene Storage Tanks, *Rotation*, 2002, **11**, 2, 50.
56. S. Andrzejewski, G. Cheney and P. Dodge, Simple Rules to Follow for Obtaining Proper Cure for Rotomoulded Polyethylene Parts, *Rotation*, 1997, **6**, 3, 18.
57. S. Bawiskar and J.L. White, Comparative Study of Warpage, Global Shrinkage, Residual Stresses and Mechanical Behaviour of Rotationally Moulded Parts, *Polym. Eng. Sci.*, 1994, **34**, 10, 815.

58. S. Bawiskar and J.L. White, Simulation of Heat Transfer and Melting in Rotational Molding, *Int. Polym. Proc.*, 1995, **10**, 1, 62.
59. C.T. Bellehumeur, M. Kontopoulou and J. Vlachopoulos, The Role of Viscoelasticity in Polymer Sintering, *Rheol. Acta.*, 1998, **37**, 270.
60. C.T. Bellehumeur, M.K. Bisaria and J. Vlachopoulos, An Experimental Study and Model Assessment of Polymer Sintering, *Polym. Eng. Sci.*, 1996, **36**, 17, 2198.
61. H.C. Chen and J.L. White, A Guide to Warpage and Shrinkage of Rotationally Molded Parts, in *ARM Fall Meeting*, Toronto, 1989.
62. C.H. Chen, J.L. White and Y. Ohta, A Fundamental Experimental Study of the Mechanisms of Warpage and Shrinkage of PE in Rotational Molding, *Int. Polym. Proc.*, 1991, **6**, 3, 212.
63. C.H. Chen, J.L. White and Y. Ohta, Mold Pressurisation as a Method to Reduce Warpage in Rotational Molding of Polyethylene, *Polym. Eng. Sci.*, 1990, **30**, 23, 1523.
64. M.C.D. Cramez, A Study of the Microstructure and Properties of Rotationally Moulded Plastics, in *Polymer Engineering*, Universidade do Minho, Guimaraes, 2000, 376.
65. K. Evans, Using a Vacuum in Rotational Molding Improves Impact Properties at Low Temperatures and Reduces Cycle Time, in *SPEW RETEC*, Cleveland, Ohio, USA, 1999.
66. G. Gogos, X. Liu and L.G. Olson, Cycle Time Predictions for the Rotational Molding Process with and without Mold/Part Separation, *Polym. Eng. Sci.*, 1998.
67. G. Gogos, Bubble Removal in Rotational Molding, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
68. B. Graham, Rotational Molding of Metallocene Polypropylenes, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
69. K. Iwakura, *et al.*, Experimental Investigation of Rotational Molding and the Characterisation of Rotationally Molded PE Parts, *Int. Polym. Proc.*, 1989, **4**, 3, 163.
70. K. Iwakura, *et al.*, A Basic Study of Warpage and Heat transfer in Rotational Molding, in *SPE ANTEC*, 1989.
71. M. Kontopoulou and J. Vlachopoulos, Bubble Dissolution in Molten Polymers and its Role in Rotational Molding, *Polymer Eng. Sci.*, 1999, **39**, 7, 1189.
72. M. Kontopoulou, E. Takacs and J. Vlachopoulos, An Investigation of the Bubble Formation Mechanism in Rotational Molding, *Rotation*, 2000, **9**, 1, 28.
73. M. Kontopoulou, E. Takacs and J. Vlachopoulos, Particle Coalescence and Densification in Rotational Molding, in *SPE RETEC*, Cleveland, Ohio, USA, 1999.
74. M. Kontopoulou, *et al.*, A Comparative Study of the Rotomolding Characteristics of Various Polymers, in *SPE ANTEC*, Toronto, 1997.
75. M. Kontopoulou, M. Bisaria and J. Vlachopoulos, An Experimental Study of Rotational Molding of Polypropylene/Polyethylene Copolymers, *Int. Polym. Proc.*, 1997, **12**, 2, 165.

76. M. Kontopoulou, A Study of the Parameters Involved in the Rotational Molding of Plastics, in *Chemical Engineering*, McMaster University, Hamilton, Canada, 1995, 139.
77. S.-J. Liu, C.-C. Lai and S.-T. Lin, Optimizing the Impact Strength of Rotationally Molded Parts, *Polymer Eng. Sci.*, 2000, **40**, 2, 473.
78. S.-J. Liu and C. Gung, Reducing the Warpage of Rotationally Moulded Parts. *Rotation*, 2000, **9**, 6, 22.
79. J.L. MacAdams, How to Predict Physical Properties of Rotomolded Parts, in *SPE RETEC*, 1975.
80. M.J. Majurey, A Technique for Evaluating the Processing Behaviour of Rotationally Moulded Polymers, *Rotation*, 1998, **7**, 4, 44.
81. Y. Ohta, C.H. Chen and J.L. White, Warpage in Rotationally Moulded Parts of Polyethylene, *Kunststoffe*, 1989, **79**, 12, 42.
82. R.M. Ogorkiewicz, Ed., *Thermoplastics: Effects of Processing - Rotational Moulding*, Illiffe Books, London, 1969, 227.
83. S. O'Neill, Cooling of Rotationally Moulded Plastics, in *Mechanical Engineering*, The Queen's University of Belfast, 1999.
84. R.C. Progelhof, G. Cellier and J.L. Throne, New Technology of Rotational Molding, in *SPE ANTEC*, 1982.
85. D. Ramazzotti, Rotational Molding - A Quick Update, *Plastics Engineering*, 1975, December, 32.
86. A.G. Spence, Analysis of Bubble Formation and Removal in Rotationally Moulded Products, in *Mechanical and Manufacturing Engineering*, The Queen's University of Belfast, Belfast, 1994, 340.
87. J.L. Throne, Some Factors Influencing Cooling Rates of Rotationally Molded Parts, *Polym. Eng. Sci.*, 1972, **12**, 5, 335.

Chapter 6 – The Future for Rotational Moulding

What does the future hold for rotational moulding? The main areas where there is scope for improvements are *materials*, *moulds* and *manufacturing equipment*. The following sections consider each of these in turn.

6.1 Materials

Over the next 20 years, many more materials will become available for rotational moulding. It is already apparent that most of the large materials suppliers are taking an interest in the process. In recent years there has been a rapid increase in the fundamental understanding of polymer chemistry. This has led to new types of monomers being combined to create exciting new properties, even in traditional materials such as polyethylene. This work will undoubtedly continue to increase dramatically so that polymers can more easily be ‘designed’ to have specific characteristics – conductivity, paintability, toughness, processability, etc. A fundamental problem that rotomoulders face is avoiding thermal degradation of the plastic. It is encouraging therefore that more researchers with an understanding of the chemistry of thermal stability are turning their attention to rotational moulding materials. Also, the drive towards shorter cycle times reduces the exposure of the plastic to the damaging effects of long times at high temperatures. This will speed up the development of new resins for rotomoulding.

At present, whilst we do not know everything about what makes a good rotomoulding resin, we can define some of the basic requirements – thermal stability, low zero shear viscosity, low viscosity soon after melting, and low elastic modulus in the melt. At a more fundamental level there is a need to develop control over the thermal properties of plastics. At present rotational moulding is restricted more than most plastic processes by the relatively slow rate of heat transfer from and to the plastic. Also, poor thermal conductivity in the plastic causes large thermal gradients across the plastic part wall and this can lead to problems such as scorching of the outer surface of the part during heating and warpage during cooling. Chemists and physicists are starting to learn how to control electrical conductivity in plastics. Similar efforts are needed to enable us to increase and reduce the thermal conductivity of plastics. The use of additives, perhaps at the ‘nano’ level may be a factor here although chemical modification of the structure of plastics is also likely to play a role. Since thermal insulation of moulded plastic parts is a characteristic that it may be desirable to retain, it is control of the thermal properties that will be the key. Low resistance to heat transfer when shaping is taking place but good insulation properties in the solid state is what is needed and probably can be achieved. There are many challenges that rotational moulding can set for material scientists and the rewards can be reaped by the plastics processing community in general.

One attraction of better heat transfer in plastics is that it would permit granules rather than powder to be used. This could reduce material costs. However, powders have flow characteristics that are attractive in rotational moulding – this ensures good coverage of the mould surface and accurate reproduction of detail. It is possible over the next 20 years that many more plastics will become available in liquid form. This will improve even more the ability of the plastic to flow into narrow recesses in the mould, but it must be remembered that liquids flow differently to powders and so other associated changes in process control would be needed for liquids.

It is likely that the attractive mechanical and thermal characteristics of foam sandwich sections will be used to even greater advantage in the future. This will involve not just a better understanding of the utilisation of foaming agents but a re-design of moulds and machinery to make their use more convenient and efficient.

The use of multiple layers of different materials will also become more prevalent in rotational moulding. The use of polyethylene in combination with engineering polymers and low gas permeation materials like ethylene-vinyl alcohol (EVOH) is already at the research stage. As fuel emission laws become ever more stringent, applications, already common in blow moulding and extrusion, utilising multilayer technology will become commonplace.

6.2 Moulds

A basic requirement in rotational moulding is that the plastic takes up the shape of the inside surface of the mould. If the plastic starts in the solid phase then it must be transformed into a liquid. This is normally achieved through the application of heat. There are a number of ways of transferring heat to the initially solid plastic. Conduction heat transfer from a metal mould is the main method used today. Also, no matter how the plastic is heated, conduction to a mould is the primary means of taking heat out of the molten plastic that has taken the shape of the mould. It seems likely that conduction heat transfer will be retained as a key stage in rotational moulding, if only during cooling. This means that any new mould material must offer very good thermal characteristics. Is it likely that metal will be replaced as the mould material over the next 20 years? The combination of easy fabrication, robustness and good thermal conductivity offered by metals will make this difficult. However, 'soft' metal moulds created via rapid prototyping and 'spray' metal systems may find niche areas in certain low volume products. Who knows what developments will take place in this arena – we must be alert enough to embrace whatever new technology comes along.

It is well known that materials that undergo a phase change can transfer large amounts of heat. Heat pipes use this principle and have been around for many years but they have had limited usage in the rotational moulding world. Perhaps this concept needs to be re-visited. Not only does the mould need to be heated, inside and out, but there are other ancillary items such as the arm of the machine that could benefit from better heat transfer.

As we consider ways of increasing output from rotational moulding machines, it must be appreciated that as we are in a transient heat transfer situation, thermal properties other than conductivity exert a major influence. For example, the mass of the mould is a very important factor. Generally the mould does not cause the long cycle times in rotational moulding. Metal moulds can transfer heat quickly because they have thermal characteristics that are much better than that of the plastic. However, the heat transfer from the heating environment to the mould must improve. Most commercial rotational moulding machines are based on a hot air oven, despite the fact that heating the mould in a hot air environment is not an efficient way of getting it up to its required temperature. It is the mould temperature that forces up the temperature of the plastic and yet all measurements show that the rate of temperature rise of the mould decreases quite significantly during the period in the oven. Also, it takes a long time for the mould to reach its desired temperature. This is because it is the temperature difference between the mould and the heating

environment that controls its rate of temperature rise. As the mould gets closer to the set temperature, the thermal driving force decreases. A possible consequence of this is that we should increase the temperature of the heating environment continuously during the cycle in order to maintain the desired heating rate of the plastic. Of course this can lead to temperature overshoot, so it is evident that more sophisticated controls will be needed to anticipate this type of effect.

Heating the mould with an open flame is more efficient but has limitations in terms of the difficulty of providing precise control over uniform mould temperature rise. Also the use of open flames is likely to become less socially acceptable for health and safety reasons. Infrared heating, microwave heating or induction heating are all possible contenders for the process of the future, but significant developments will be needed in these technologies to make them amenable to the wide range of complex plastic parts that must be moulded.

Heating the mould with a circulating fluid is used commercially today and may be developed further due to its effectiveness. A refinement of this may well be a metal mould containing a liquid heated by electrical resistance elements. Such a mould would lend itself to close control over heating rates and the liquid will transfer the heat quickly and uniformly to the mould. Heat pipes may have a role to play here. In some other processing technologies for plastics, insulated electrical heating elements are embedded in metal moulds to give fast accurate heating. This may find a place in rotational moulding. The question of passing electrical current to the rotating mould will need to be addressed but should not be a major problem. This has been shown to be feasible in several of the new types of commercial machines. Rapid cooling of directly heated moulds is also an area that needs to be addressed.

Alternatively, the rotational moulding machine could have an oven or heating jacket, which conforms more closely to the shape of the mould and rotates with the mould. In this case the mechanism for rotating the mould is outside the heated environment, which brings advantages in terms of process control and less demanding conditions for the rotating joints. It is important to note that some types of mould developments may change the basic nature of the process. For example, if electricity (in the form of resistance heaters or infrared or induction heaters) or a circulating fluid heats the mould then there is no need for an external heating environment (oven). The mould becomes more expensive but it is also the 'moulding machine'.

The general performance of conventional types of moulds must be upgraded from what we have today. In particular, the parting lines must be made airtight and the mould must be robust enough to withstand internal pressure. There is indisputable evidence that control of the pressure inside the mould during heating and cooling offers major advantages to rotational moulders – improved mechanical properties and reduced cycle times. Such control will become standard in the future. It is also likely that the vent access port will become multi-functional – for monitoring/controlling internal temperatures and pressures as well as introducing internal heating and cooling. Therefore, moulds of the future will have precise control over the nature of the atmosphere inside the mould. It is already recognised that internal temperature measurement is invaluable, and simultaneous monitoring of the pressure inside the mould will further enhance the control that the moulder has over the process.

In moulds of the future, more use will be made of ejection aids and venting will be controlled throughout the process. Porous metals are also likely to find a role in rotational moulding to facilitate removal of air between the part and the mould and to keep the plastic part against the mould wall until it is deemed necessary to allow separation to occur.

Computers will have a crucial role in the future of mould design and manufacture. Long before moulds are manufactured, the proposed shape will be analysed using simulation programs that optimise mould shape and rotational speeds to achieve desired wall thickness distributions in the moulded part. As part of this, the strength and stiffness of the mould will be optimised for stresses imposed during operation. Thermal analysis will also be carried out to identify hot spots or cold spots, and mould geometry or thickness adjusted accordingly. It will no longer be necessary to apply global figures for shrinkage. The shrinkage of the plastic part will be predicted in every area, and local dimensions of the mould will be adjusted to give the desired part shape. As part of this analysis, the performance of the end-product will also be assessed and adjusted using Finite Element Analysis (FEA). Thus the part design and the mould design will be a single, seamless process that optimises the performance of the part and mould, in terms of heat transfer, mechanical properties and manufacture. Computer files will then be transferred to CNC machines to enable the mould to be manufactured.

CNC tooling is likely to take on even greater importance in the future of rotational moulding. The close dimensional tolerances and repeatability that CNC machining offers can be used to great advantage in rotational moulding – resulting in reductions in cycle time and permitting localised control of heat transfer through the mould.

Mould handling and servicing are also key areas for development. Already it has been demonstrated in commercial systems that automatic mould handling and material feed is feasible. These types of system will without doubt be part of the machines of the future. If manufacturing times are to be reduced then fast, consistent part removal and mould charging will be essential.

6.3 Moulding Equipment

The fundamental nature of rotomoulding dictates that the mould rotates. It may be feasible to use a multi-axis robot arm to spray plastic on to the inside of a static mould, or on to the outside of a flexible or sacrificial mould, but it seems likely that the mainstay of the rotational moulding industry will continue to be a rotating mould of the type we know today. It is debatable whether or not full biaxial rotation will be needed because with improvements in the control of mould rotation and positioning, it may be possible to make most types of complex hollow plastic parts using a full 360° rotation about one axis only. This type of motion offers considerable advantages in terms of:

- (a) easier construction
- (b) easier access to the mould for instrumentation
- (c) better opportunity to feed material continuously as required to the rotating mould.

In the future, all rotational moulding machines will be controlled directly from the temperature of the mould, the temperature of the air inside the mould and the pressure inside the mould. In addition, the speeds of rotation in future machines will not be fixed.

The machine controls will respond to sensors or other inputs that detect the thickness of the plastic at all points over the surface of the mould. The speeds of rotation and speed ratio will then be adjusted to provide the desired wall thickness distribution. The information needed to control the speeds could be measured directly in real time or predicted from algorithms based on real time simulations of the process.

Machine designs of the future must address seriously the issue of faster production rates. It is too easy to say that we need shorter cycle times. In reality what is needed are shorter manufacturing times. The subtle difference relates to the fact that there are finite limits as to how fast we can heat and cool metals and plastics. Unless there are major developments in improving heating technology or increasing the thermal characteristics of metals and plastics then at present we are probably within about 25% of the best cycle times that can be achieved. Thus we must improve our manufacturing technology if we are to reduce manufacturing times. At General Motors, a new car comes off the production line every minute. Boeing delivers a new 737 aeroplane every day. In the manufacturing facilities for consumer goods they make 100 new refrigerators every hour – and each could be any one from a range of 50 models. In all cases it takes a lot more time to make and put together all the bits and pieces that make a car or an aeroplane or a refrigerator. The point is that they employ very efficient manufacturing methods to convert long cycle times into fast production rates. Many events occur simultaneously (as in injection moulding) rather than sequentially (as in rotational moulding).

Rotational moulding machines in the future will have to follow this example. Plastics and mould materials with better thermal properties may become available, and we may improve the efficiency of heating and cooling but fast production rates are only likely to come from continuous machine operation with lots of things happening in parallel. If we focus on it, a much more efficient machine could be engineered – efficient not only in terms of energy but also in terms of time. Allowing the oven temperature to cycle between very different temperatures does not make sense. And using a cooling environment that is subject to the vagaries of ambient conditions is unwise.

One could imagine a moulding machine where the heating chamber is held at a constant temperature and continuously heats moulds that pass through it on a conveyor system. Similarly the cooler could be a constant temperature environment that continuously extracts heat from moulds. A series of rotating moulds could pass through these heating and cooling areas, or the rotating moulds could be fixed in space and the heating and cooling areas could move. Of course, different moulds or combinations of moulds will require different heating and cooling rates. This might be accommodated by the relative speed of the mould carriage, or it might be possible to alter the heat/cooling locally around a particular mould set. An underlying principle of such a machine design is that the order of the moulds can change as they move, to establish whatever order is most efficient. Individual mould sets could have a bar code (or similar device) that sends information to the heating and cooling chambers, giving specific instructions about temperature and time requirements, speeds of rotation, internal pressure control, etc. Ovens and cooling areas could respond directly to the rotational position of the mould at every moment in time, as well as mould and internal air temperature data from each mould set.

Over the past decade we have seen dramatic improvements in moulding machines, moulds and materials for rotational moulding. Even if we simply repeat this rate of progress then the nature of the rotational moulding industry in 20 years time will be quite different from

what it is today. Past experience with such advancements has shown that we can realistically expect a much faster rate of progress in the future and so we can expect very exciting times – if we focus our talents on the key challenges.

6.4 The Challenges

There are many challenges that the rotational moulding industry must face if it is to expand its market share. To compete seriously with the other major processing technologies the industry must:

- Reduce manufacturing times to less than a quarter of what they are today.
- Have available a comprehensive palette of materials to offer the customer.
- Have full control over all process variables to provide consistent part quality.
- Move towards full automation of all aspects of the process.
- Reflect on new machine and mould design concepts to improve the efficiency of the process.

6.5 The Role that the Moulder Must Play

The moulder cannot sit back and expect someone else to initiate and implement all the changes that are needed in our industry.

- Moulders must aggressively move into new market sectors - the demands placed by new types of products will result in process innovations.
- Moulders must take a fresh look at the economics of the process – high performance moulds and machines will cost more in absolute terms but the value that they offer in terms of reduced manufacturing times and new market sectors will more than offset this cost.
- Moulders must take a modern approach and embrace new technology – dismissing new ideas as impractical or uneconomic will discourage those with the desire and abilities to make the changes that are needed.
- Moulders must not sit back and accept the status quo – imagination is needed to set challenges for suppliers.
- Moulders must take a pride in their industry – manufacturing facilities must be upgraded so that we are proud to show potential customers, designers and young people how the process works and what it is capable of.
- Moulders must be prepared to share technology – this does not mean giving away secrets. It means ensuring that all rotomoulded parts are made to the best possible standards so that the reputation of our industry is high. Business advantages can be gained through marketing and efficient manufacturing practices, which in themselves will advance the industry.
- Moulders must recognise that individually, or in small groups, their voice will go unheard by the major suppliers. However a strong, single voice of moulders from all over the world will be heeded.

6.6 The Role that the Suppliers Must Play

The machinery manufacturers, mould makers and material suppliers have a key role to play in the future of rotational moulding. They have a vested interest in its success since in many cases it is their core business. To date, the suppliers have pushed forward the technology of the industry and this has been good. However, it has tended to be at a pace that they are comfortable with, or that their competitor forces, or that a particular customer demands. Changes have been evolutionary and incremental rather than revolutionary. There is a need for a more creative and innovative approach to achieve what is needed.

- Material suppliers must provide more rotational moulding materials. It is inexcusable that rotational moulders are limited to such a small range of materials.
- Material suppliers must address some of the fundamental issues such as control over thermal properties in the melt and solid states. This may result in a revolutionary change in polymer chemistry but is fundamental to all types of plastics processing.
- Machinery and mould manufacturers must address the question of reducing manufacturing times. This will involve a complete re-assessment of the basic nature of the process.
- Machinery and mould manufacturers must provide the mechanism to measure and control temperatures and pressures inside the mould throughout the moulding cycle.
- Machinery and mould manufacturers must work together to provide standardization in regard to the machinery/mould interface. In the future this interface may become indistinct.
- Machinery and mould manufacturers must look for innovative ways to provide material to the mould. This may involve multiple charges of the same or different materials as the mould rotates.
- Machinery and mould manufacturers must make the mould, material and part handling efficient, and where possible, fully automatic.
- Mould manufacturers must be creative in exploring the benefits of new mould materials.

Abbreviations and Acronyms

ABS	acrylonitrile-butadiene-styrene terpolymer
AZ	azodicarbonamide
CBA	chemical blowing agents
CNC	computer numerical controlled
EBA	ethylene-butyl acrylate
ECTFE	ethylene-chlorotrifluoroethylene
ESC	environmental stress cracking
ESCR	environmental stress cracking resistance
EVA	ethylene-vinyl acetate
FDA	US Food and Drug Administration
FEA	finite element analysis
FEP	fluoroethylene
HALS	hindered amine light stabilisers
HDPE	high density polyethylene
HM	heavy metal
IAT	internal air temperature
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
MDPE	medium density polyethylene
MFI	melt flow index
PC	polycarbonate
PEEK	polyether etherketone
PEKK	polyether-ketoneketone
PES	polyethersulfone
PET	polyethylene terephthalate
PPS	polyphenylene sulfide
PSD	particle size distribution
PTFE	polytetrafluoroethylene
PU	polyurethane
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
RIM	reaction injection moulding
SAN	styrene-acrylonitrile
UV	ultraviolet
UVA	ultraviolet absorbers

Index

A

ABS 91, 98
additives 99
air mover 70
aluminium 29, 30, 31
amorphous 89, 133
anisotropy 134
anti-oxidants 100
atmospheric casting 31

B

baffling 70
beryllium-copper 38
blow moulding 5, 129
blowing agents 101, 153
bosses 22, 33
breather 78
bridging 117
brittleness 18
bubbles 18, 73
bulk density 114, 116

C

carbon black 100
carbon steel 30
carousel 55
cast aluminium 29
centrifugal casting 11
charge 8, 52
clamps 34
clamshell 58
coalescence 18, 73
compounding 104, 118
convective heat transfer 80
cooking 73
cooking time 18
cooling 12, 44, 71, 133
core 37
creep resistance 90
crosslinking 101
crystalline 89, 133
crystallinity 89, 122
crystallisation 134
cycle time 5, 80

D

degradation 20, 80
demoulding 13, 75
density 93, 133, 139
differential shrinkage 133
direct conduction 63
draft angles 40
drop arm 66
drop box 102, 152
dry blend 118
dry flow 112, 116
dry mixing 104

E

electroformed nickel 29, 31
endothermic 153
environmental stress cracking 90, 143
ethylene-butyl acrylate 91, 96
ethylene-chlorotrifluoroethylene 97
ethyl-vinyl acetate 91, 95
exothermic 153

F

fillers 99
fixed arm machine 56
flame retardants 101
flanges 34
fluoropolymer 91, 97
foam sandwich structure 102
foaming 151, 152
foaming agents 101

G

grinding 105, 107
grit blasting 40

H

hardness 90
high density polyethylene 93, 94
high speed mixers 118
hindered amine light stabilisers 100
hydroforming 31

I

Impact strength 20, 74, 90
independent arm machine 56
induction heating 63
information panels 36
infrared machines 63
in-mould decoration 146
inserts 14, 35
internal air temperature measurement 72

J

jigging 140

K

kiss-off 17, 33, 51, 155

L

Leonardo machine 64
low density polyethylene 93, 94
logos 36
lubricants 100

M

major axis 11
major axis speed 69
market 6
melt flow index 92
mesh size 111
metallocene polyethylene 95
micropellets 117
minor axis 11
minor axis speed 69

modulus (stiffness) 133
mould 8
mould frame 34
mould-in-insert 14, 35
mould pressurisation 82
mould release 33, 41
mould swing 66

N

nickel 29, 30, 31
nucleating agents 134
nylon 23, 89, 90, 91, 96, 102, 133

O

one shot foaming system 102
one-step (or one-shot) foaming 152
open flame 61
overshoot 74

P

painting 144
particle size distribution 92, 111
parting line 33, 80
pigments 104, 118, 121, 134
pin-holes 18
plasticisers 100
plastisol PVC 1, 31, 90
polycarbonate 89, 90, 91, 144
polyester 98
polyethylene 1, 89, 90, 91, 92, 93
polypropylene 89, 90, 91, 96, 99, 133
polystyrene 91, 144
polyurethane 16, 91, 98
polyurethane foam 101
polyvinylidene fluoride 97
porosity 31, 40
pressure 80
pressure casting 31
pressure rolling 31
pressure-sensitive adhesive 146
PTFE 43
pulverising 105
PVC 1, 17, 31, 71, 90, 91, 97, 99, 144

R

release 33, 41
release agent 41, 138
release point 134
residual stress 137, 140
ribs 17, 22, 33
rigidity 90
RMC³ 49
rock and roll 55, 61, 81
rocking oven machine 62, 81
rotary machine 55
rotational speed 117, 131
rotocasting 1
Rotolog 12, 75, 76, 152
RotoSim 11, 53

S

SAN 98
sandwich structure 152, 156
semi-crystalline 89
sheet steel 29
shielding 132
shrinkage 33, 38, 74, 80, 90, 93, 130, 133
shuttle machine 57
sieves 110
silicone 91, 98
slip casting 1
slip rings 64
speed ratio 11, 68, 117, 131, 132
spiders 70
stabilisers 100
stainless steel 30
stiffness 20
straight arm 66
stress cracking 136

T

tails 116
tanks 6
Teflon 43
temperature 81
thermocouple 76
thermoforming 5, 129
thermoplastic 89
thermosetting 89
threads 38
tolerance 129
toughness 90
toy industry 7
turbo blenders 118
turbo/high speed mixing 104
turret 55

U

ultraviolet stabilisers 100
undercooked 18
undercuts 33

V

vacuum casting 31
vent 80
vent pipe 1
vent port 39
vent tube 78
venturi 70
viscosity 90

W

wall thickness distribution 129
warpage 44, 71, 74, 130, 135, 136
water mist 46
water spray 46



ISBN: 1-85957-387-8



Rapra Technology Limited

Rapra Technology is the leading independent international organisation with over 80 years of experience providing technology, information and consultancy on all aspects of rubbers and plastics.

The company has extensive processing, analytical and testing laboratory facilities and expertise, and produces a range of engineering and data management software products, and computerised knowledge-based systems.

Rapra also publishes books, technical journals, reports, technological and business surveys, conference proceedings and trade directories. These publishing activities are supported by an Information Centre which maintains and develops the world's most comprehensive database of commercial and technical information on rubbers and plastics.

rapra
TECHNOLOGY

Shawbury, Shrewsbury, Shropshire SY4 4NR, UK
Telephone: +44 (0)1939 250383 Fax: +44 (0)1939 251118
<http://www.rapra.net>

www.iran-mavad.com

مرجع دانشجویان و مهندسين مواد