1 INTRODUCTION TO ROTATIONAL MOLDING

1.0 Introduction

Rotational molding, known also as *rotomolding* or *rotocasting,* is a process for manufacturing hollow plastic products. For certain types of liquid vinyls, the term *slush molding* is also used. Although there is competition from blow molding, thermoforming, and injection molding for the manufacture of such products, rotational molding has particular advantages in terms of relatively low levels of residual stresses and inexpensive molds. Rotational molding also has few competitors for the production of large (> 2 m^3) hollow objects in one piece. Rotational molding is best known for the manufacture of tanks but it can also be used to make complex medical products, toys, leisure craft, and highly aesthetic point-of-sale products.

It is difficult to get precise figures for the size of the rotational molding 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) with a value of US$1250 million.[1] The corresponding 1995 figure for Europe was a consumption of 101 ktons,[2] and this had risen to 173 ktons by 1998.[3] In 1997, the North American market had a value of about US$1650 million and for most of the 1990s, the U.S. market grew at 10% to 15% per year, spurred on primarily by outdoor products such as chemical tanks, children's play furniture, kayaks, canoes, and mailboxes.[4] In the latter part of the 1990s the North American market growth slowed to single figures. Independent analysts[5, 6] saw this as a temporary dip and explained it in terms of a readjustment of market sectors and increasing competition from other sectors.

Currently, the rotational molding industry is in an exciting stage in its development. The past decade has seen important technical advances, and new types of machines, molds, and materials are becoming available. The industry has attracted attention from many of the major suppliers and this has resulted in significant investment. Important new market sectors are opening up as rotational molders are able to deliver high quality parts at competitive prices. More universities than ever are taking an interest in the process, and technical forums all over the world provide an opportunity for rotational molding to take its place alongside the other major manufacturing methods for plastics.

1.1 The Process

The principle of rotational molding of plastics is simple. Basically the process consists of introducing a known amount of plastic in powder, granular, or viscous liquid form into a hollow, shell-like mold.[7–9] The mold is rotated and/or rocked about two principal axes at relatively low speeds as it is heated so that the plastic enclosed in the mold adheres to, and forms a monolithic layer against, the mold surface. The mold rotation continues during the cooling phase so that the plastic retains its desired shape as it solidifies. When the plastic is sufficiently rigid, the cooling and mold rotation is stopped to allow the removal of the plastic product from the mold. At this stage, the cyclic process may be repeated. The basic steps of (a) mold charging, (b) mold heating, (c) mold cooling, and (d) part ejection are shown in Figure 1.1.

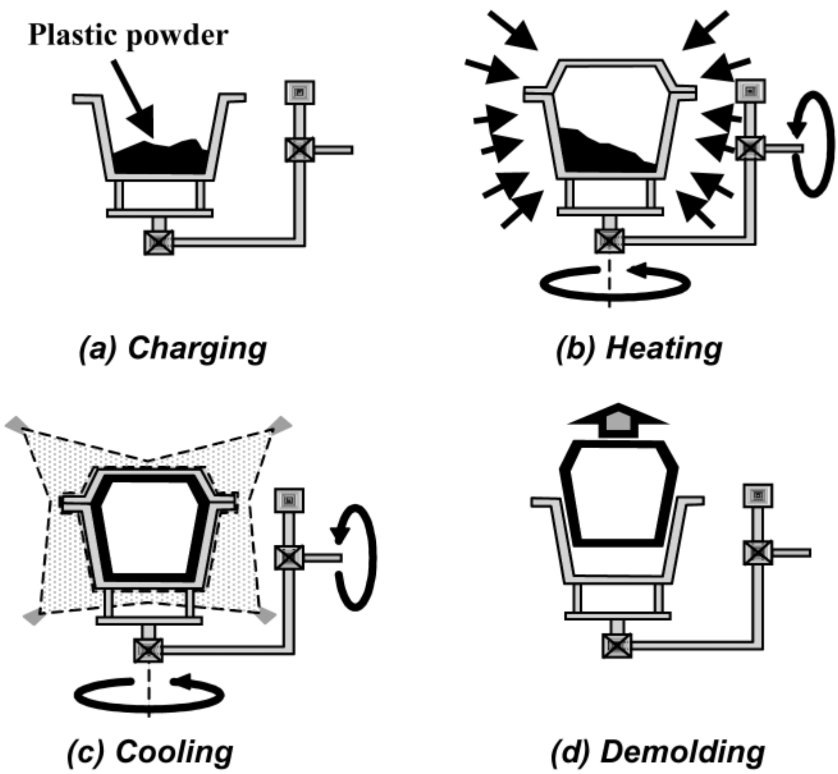

Figure 1.1 Principle of rotational molding, courtesy of The Queen's University, Belfast

Table 1.1 Typical Applications for Rotationally Molded Products

Tanks	
Septic tanks	Chemical storage tanks
Oil tanks	Fuel tanks
Water treatment tanks	Shipping tanks
Automotive	
Door armrests	Instrument panels
Traffic signs/barriers	Ducting
Fuel tanks	Wheel arches
Containers	
Reusable shipping containers	Planters
IBCs	Airline containers
Drums/barrels	Refrigerated boxes
Toys and Leisure	
Playhouses	Outdoor furniture
Balls	Hobby horses
Ride-on toys	Doll heads and body parts
Materials Handling	
Pallets	Fish bins
Trash cans	Packaging
Carrying cases for paramedics	
Marine Industry	
Dock floats	Leisure craft/boats
Pool liners	Kayaks
Docking fenders	Life belts
Miscellaneous	
Manhole covers	Tool boxes
Housings for cleaning equipment	Dental chairs
Point-of-sale advertising	Agricultural/garden equipment

Nearly all commercial products manufactured in this way are made from thermoplastics, although thermosetting materials can also be used. The majority of thermoplastics processed by rotational molding are semicrystalline, and the polyolefins dominate the market worldwide. The different types of products that can be manufactured by rotational molding are summarized in

Table 1.1. The process is distinguished from spin casting or centrifugal casting by its low rotational speeds, typically 4 – 20 revs/min. The primary competitors to rotational molding are structural blow molding and twin-sheet thermoforming.

As with most manufacturing methods for plastic products, rotational molding evolved from other technologies. A British patent issued to Peters in 1855 (before synthetic polymers were available) cites a rotational molding machine containing two-axis rotation through a pair of bevel gears. It refers to the use of a split mold having a vent pipe for gas escape, water for cooling the mold, and the use of a fluid or semifluid material in the mold to produce a hollow part. In the original patent application this was a cast white metal artillery shell. In Switzerland in the 1600s, the formation of hollow objects such as eggs quickly followed the development of chocolate from cocoa. The ceramic pottery process known today as "slip casting" is depicted in Egyptian and Grecian art, and probably predates history.

1.2 The Early Days

Rotational molding of polymers is said to have begun in the late 1930s with the development of highly plasticized liquid polyvinyl chloride, the thermoplastic competitor to latex rubber.[9–14] In addition to the ubiquitous beach balls and squeezable toys, syringe bulbs, squeezable bottles and bladders and air-filled cushions were developed during World War II. Until polyethylene powders were produced in the late 1950s, most rigid articles were manufactured from cellulosics. The early equipment was usually very crude. Generally it consisted of a hollow metal mold rotating over an open flame. Sometimes a type of slush molding would be used. In this method, the mold would be completely filled with liquid or powdered plastic and after a period of heating to form a molten skin against the mold, the excess plastic would be poured out. The molten skin was then allowed to consolidate before being cooled and removed from the mold.[15]

In the 1950s the two major developments were the introduction of grades of powdered polyethylene that were specially tailored for rotomolding,[16, 17] and the hot air oven. With the new material and equipment it was possible to rapidly advance the types of hollow plastic products that could be manufactured. In North America the toy industry took to the process in a big way and, as shown in Figure 1.2, today this sector still represents over 40% of the consumption in that part of the world.

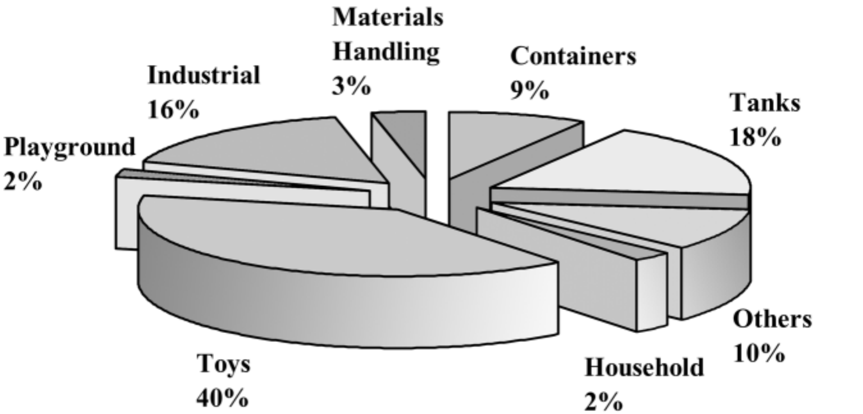

Figure 1.2 North American market sectors by product type (1999), courtesy of The Queen's University, Belfast

In Europe the nature of the market has always been different, with toys representing less than 5% of the consumption and other sectors such as containers and tanks tending to dominate (see Figure 1.3).

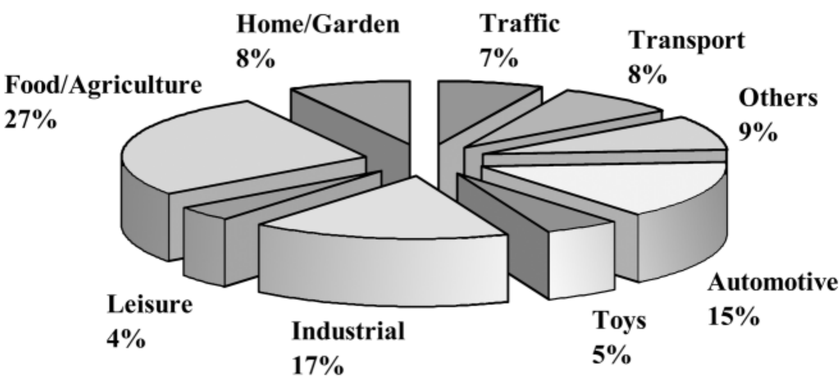

Figure 1.3 European market sectors by product type (1999), courtesy of The Queen's University, Belfast

Ever since its inception, a characteristic feature of the rotational molding industry has been its abundance of innovative designers and molders taking what is basically a very simple, and some would say crude, process and creating complex, hollow 3-D shapes in one piece. Geometry and shape have to be used particularly effectively because, the dominant polymer, polyethylene, has a very low inherent modulus and thus stiffness. In order to impart stiffness and rigidity to the end product it is necessary to use many types of special geometrical features, many of which are unique to rotational molding. It is also necessary to encourage the plastic powder to flow into narrow channels in the mold, and this only became possible with the special grades of high quality powders developed for the process and with the additional control over heating that became available in the oven machines.

The contribution that rotational molding has made to the design of plastic products has not yet been fully appreciated by other industries. Not only has the North American toy industry produced very clever structural shapes to impart stiffness to polyethylene, geometry has also been used effectively to conceal shortcomings in the manufacturing method. The lessons learned here are only now being transferred to other technologies. In addition, special types of features, such as "kiss-off" points, have been developed by rotational molders to enhance the load carrying capacity of relatively thin walled, shell-like moldings. If rotational molding can overcome some of its disadvantages, such as long cycle times and limited resin availability, then there can be no doubt that the next 50 years will see a growth rate that will continue to track what has been achieved in the first 50 years.

1.3 Materials

Currently polyethylene, in its many forms, represents about 85% to 90% of all polymers that are rotationally molded. Crosslinked grades of polyethylene are also commonly used in rotational molding.[18,19] PVC plastisols[20–22] make up about 12% of the world consumption, and polycarbonate, nylon,[23] polypropylene,[24–27] unsaturated polyesters, ABS,[28] polyacetal,[29] acrylics,[30] cellulosics, epoxies,[31] fluorocarbons, phenolics, polybutylenes, polystyrenes, polyurethanes,[32–36] and silicones[37] make up the rest.[38] This is shown in Figure 1.4.

High-performance products such as fiber-reinforced nylon and PEEK aircraft ducts show the potential of the technology, but truly represent a very small fraction of the industry output.[39] There have also been attempts to include fibers in rotationally molded parts but there are few reports of this being done commercially.[40]

The modern rotational molding process is characterized as being a nearly atmospheric pressure process that begins with fine powder and produces nearly stress-free parts. It is also an essential requirement that the polymer withstand elevated temperatures for relatively long periods of time. Owing to the absence

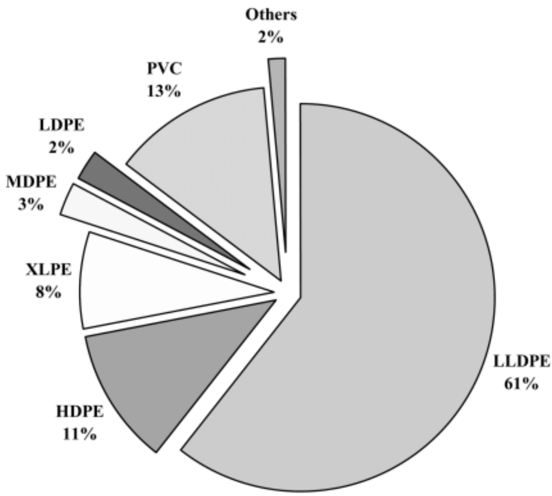

Figure 1.4 Typical usage of plastics in North American rotational molding industry,[1] information used with permission of copyright holder

of pressure, rotational molds usually have relatively thin walls and can be relatively inexpensive to fabricate. For relatively simple parts, mold delivery times can be days or weeks. Modern, multiarmed machines allow multiple molds of different size and shape to be run at the same time. With proper mold design, complex parts that are difficult or impossible to mold any other way, such as double-walled five-sided boxes, can be rotationally molded. With proper mold design and correct process control, the wall thickness of rotationally molded parts is quite uniform, unlike structural blow molding or twin-sheet thermoforming. And unlike these competitive processes, rotational molding has no pinch-off seams or weld lines that must be post-mold trimmed or otherwise finished. The process allows for in-mold decoration and in situ inserts of all types. Typical products manufactured by rotational molding are shown in Figure 1.5.

Although the rotational molding process has numerous attractive features it is also limited in many ways. The most significant limitation is the dearth of suitable materials. This is primarily due to the severe time-temperature demand placed on the polymer, but it is also due to the relatively small existing market for nonpolyolefins. Where special resins have been made available, the material 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. In addition, the inherent thermal and economic characteristics of the process favor production of few, relatively large, relatively bulky parts such as chemical tanks.

Figure 1.5 Examples of rotationally molded products (paramedic box by Australian company, Sign by Rototek Ltd., U.K., Smart Bar by Team Poly Ltd., Adelaide, Australia)

Part designers must adjust to the generous radii and relatively coarse surface textures imposed by the process. Furthermore, the process tends to be labor intensive and until recently, the technical understanding of the process lagged behind those of other processes such as blow molding and thermoforming. Part of the reason for this is that, unlike nearly every other manufacturing method for plastic parts, the rotational molding process relies on coalescence and densification of discrete powder particles against a rotating mold cavity wall, an effect that is extremely difficult to model accurately. Another part of the reason is that the process has not attracted academic interest in the same way as other processes such as compounding, extrusion, and injection molding.

Probably the greatest limitation has been the general opinion that rotational molding is a cheap process, and therefore, by implication, one that produces parts of lesser quality than those made by other processes. Unfortunately, in the past, rotational molders did not discourage this opinion. This situation is now changing and the Association of Rotational Molders (ARM) formed in 1976 has been instrumental in acting as the focal point for many important advances in the industry. A number of other similar organizations have also been set up in Europe and Australasia. Traditionally this sector has been dominated by small companies, which by their nature must focus on their own short-term needs. ARM has acted as a voice for the industry, providing opportunities to pool resources to fund R & D, and to promote the industry. These efforts have undoubtedly helped rotational molding to become the fastest growing sector of the plastics processing industry. In 2000, the Society of Plastics Engineers (SPE) chartered the Rotational Molding Division in order to promote greater technical discussions about the process. This will result in a larger number of academic institutions taking an interest in the process, which has to be good for the future advancement of rotational molding.

1.4 Advantages and Disadvantages

The main attractions of rotational molding are:

- A hollow part can be made in one piece with no weld lines or joints
- The end product is essentially stress-free
- The molds are relatively inexpensive
- The lead time for the manufacture of a mold 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 molded together on the one machine
- Inserts are relatively easy to mold in
- High quality graphics can be molded in

The main disadvantages of rotational molding are:

- The manufacturing times are long
- The choice of molding 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 mold

Table 1.2 compares the characteristics of the processes that can be used to make hollow plastic products.

Table 1.2 Comparison of Blow Molding, Thermoforming, and Rotational Molding (Adapted from Ref. 41.)

Factor	Blow Molding	Thermo Forming	Rotational Molding
Typical product volume range (cm^3)	10^1–10^6	5×10^0–5×10^6	10^1–10^8
Plastics available	limited	broad	limited
Feedstock	pellets	sheet	powder/liquid
Raw material preparation cost	none	up to +100%	up to 100%
Reinforcing fibers	yes	yes	yes, very difficult
Mold materials	steel/ aluminum	aluminum	steel/ aluminum
Mold pressure	<1 MPa	<0.3 MPa	<0.1 MPa
Mold cost	high	moderate	moderate
Wall thickness tolerance	10%–20%	10%–20%	10%–20%
Wall thickness uniformity	tends to be nonuniform	tends to be nonuniform	uniformity possible
Inserts	feasible	no	yes
Orientation in part	high	very high	none
Residual stress	moderate	high	low
Part detailing	very good	good, with pressure	adequate
In-mold graphics	yes	possible	yes
Cycle time	fast	fast	slow
Labor intensive	no	moderate	yes

1.5 General Relationships between Processing Conditions and Properties

The rotational molding process is unique among molding methods for plastics in that the plastic at room temperature is placed in a mold at approximately room temperature and the whole assembly is heated up to the melting temperature for the plastic. Both the mold and the plastic are then cooled back to room temperature. 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 and this will be discussed in detail in later chapters. At this stage it is useful to be aware that if the oven time is too short, or the oven temperature is too low, then the fusing and consolidation of the plastic will not be complete. This results in low strength, low stiffness, and a lack of toughness in the end product. Conversely, if the plastic is overheated then degradation processes will occur in the plastic and this results in brittleness.[42–44] In a commercial production environment the optimum "cooking" time for the plastic in the oven often has to be established by trial and error.[45] In recent years it has been shown that if the temperature of the air inside the mold is recorded throughout the molding cycle, then it is possible to observe in real time many key stages in the process.[46, 47] This technology will be discussed in detail in Chapter 5. At this stage an overview will be given of the relationships between processing conditions and the quality of the molded part.

It is important to understand that rotational molding does not rely on centrifugal forces to throw the plastic against the mold wall. The speeds of rotation are slow, and the powder undergoes a regular tumbling and mixing action. Effectively the powder lies in the bottom of the mold and different points on the surface of the mold come down into the powder pool. The regularity with which this happens depends on the speed ratio, that is the ratio of the major (arm) speed to the minor (plate) speed. The most common speed ratio is 4:1 because this gives a uniform coating of the inside surface of most mold shapes. The importance of the speed ratio in relation to the wall thickness distribution will be discussed in Chapter 5.

When the mold rotates in the oven, its metal wall becomes hot, and the surface of the powder particles becomes tacky. The particles stick to the mold wall and to each other, thus building up a loose powdery mass against the mold wall. A major portion of the cycle is then taken up in sintering the loose powdery mass until it is a homogeneous melt.[48–50] 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 pinholes, 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.[51–55]

Molders sometimes use the bubble density in a slice through the thickness of the molding as an indication of quality. If there are too many bubbles extending through the full thickness of the part then it is undercooked. If there are no bubbles in the cross section then it is likely that the part has been overcooked. A slice that shows a small number of bubbles close to the inner free surface is usually regarded as the desired situation.

Other indications of the quality of rotationally molded polyethylene products relate to the appearance of the inner surface of the part and the smell of the interior of the molding. The inner surface should be smooth with no odor 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.[56–60]

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 molding, cooling is from the outside of the mold only. This reduces the rate of cooling and the unsymmetrical nature of the cooling results in warpage and distortion of the molded part.[61-63] The structure of the plastic is formed during the cooling phase and rapid cooling (using water) will result, effectively, in a different material compared with slow cooling (using air) of the same resin. The mechanical properties of the plastic will 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 molding but it will be less stiff. The shape and dimensions of the part also will be affected by the cooling rate.

This brief introduction to the interrelationships between processing and properties emphasizes the importance of understanding the *technology of rotational molding*. Although it appears to be a simple process, there are many complex issues to be addressed. The molder needs to understand what is happening at each stage in the process and more importantly, it is crucial to realize that control can be exercised over, not just the manufacturing times, but the quality of the end product. The technology of rotational molding is now at an advanced stage and it is possible to quantify what is happening at all stages of the process. The following chapters describe in detail the various aspects of the process and wherever possible an attempt has been made to provide quantitative estimates of the relative effects of the process variables.

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