Improving the Performance of Rotomolding Resins

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Abstract

Rotational molding is one of the fastest growing processes in the plastics industry today. However, this growth has been somewhat restricted by the number of and types of resins available to the molder. Polyethylene has traditionally been the workhorse for the industry because of its ease of processing. Unfortunately polyethylene lacks stiffness, along with other mechanical properties, compared to the resins used in competitive processes. This paper outlines methods to improve the performance of rotomolding resins using processing techniques, modifying the design of the part and by the inclusion of strengthening additives in the polymer matrix.

Introduction

Before considering ways to improve the stiffness of rotationally molded products, it is important to understand the properties of the most commonly used resins. Table 1 lists a number of commonly used polyethylene resins. The properties listed highlight the relationship between density and flexural modulus i.e. higher density = higher flexural modulus. The vast majority of these resins are Linear Low/Medium Density Polyethylenes. These materials are typically used in densities ranging from 920 to 944 kg/m^3 and melt indices ranging from 2.0 to 7.0 g/10minutes. This combination of density and melt flow index yields flexural modulus properties ranging from 480 to 830 MPa – as measured by the ASTM standard D 790. The flexural modulus value is an indication of the material's resistance to bending under load i.e. its stiffness.

Deflection Theory

Single Layer Structures

Understanding the laws that govern the deflection or bending of a single wall under load is extremely important if improvements to the stiffness properties of a molded part are desired. Consider the example illustrated in Figure 1. For a horizontal beam subjected to transverse flexural loading, the maximum deflection, δ, will be given by[1]:

$$\delta = \alpha (FL^3/EI) \qquad (1)$$

where: α = a constant that depends on the type of loading
I = the second moment of area ($I = WD^3/12$), for a rectangular cross-section beam)
E = modulus
F = applied force

The stiffness of the material is given by the applied force divided by the corresponding deformation:

$$\text{Stiffness,} \quad F/\delta = \alpha (EI/L^3) \qquad (2)$$

From this theory it is apparent that if the size of the product and loads applied to the product remain constant, then the options for the designer to achieve the required stiffness include:

- Increasing the thickness of the wall (D)
- Selecting a different material with a higher modulus (E)
- Modifying the surface of the product to include load-bearing features e.g. ribs (I).

Designing for Stiffness

Ribs

Ribs are without doubt the most commonly used design features to enhance the stiffness of rotationally molded products. Figure 2 illustrates a typical rib cross section, highlighting key parameters that can be adjusted to provide the best resistance to the applied load. The draft angle on the rib is an important feature and is necessary to aid part removal from the mold.

Research work carried out by The Queen's University of Belfast has extensively investigated the structural contribution that ribs offer to rotationally molded parts[2]. This work investigated transverse loading, both parallel and perpendicular to the direction of the ribs and axial loading perpendicular to the direction of the ribs. The results from this work demonstrated that:

- Wide/shallow ribs yielded the best resistance to both perpendicular axial loading and parallel transverse loading.
- Narrow/deep ribs yielded the best resistance to perpendicular transverse loading.

It should be noted that the second moment of area, I, is the key parameter that defines the transverse load bearing capabilities of any rib design. The conclusions from this work showed there was no single optimal design, but that each case should be treated individually.

Crawford[3] applied existing engineering principles to better understand the inter-relationships between stiffness and the geometry of the rib. He confirmed that the ratio of the depth of the rib to the thickness of the rib has the greatest influence on the structural load bearing capabilities of the part. In addition, the balance of transverse to axial loading was investigated in an attempt to optimize the rib depth and width. A general recommendation was given for design guidelines recommending a rib depth/height of 4 times the wall thickness and a rib width of 5 times the wall thickness.

It is also worth noting that the use of computer packages, such as Finite Element Analysis (FEA), has added a new level of predictability to the performance of molded-in ribs[4]. FEA not only ensures that the rib design is capable of resisting the applied loads, but also predicts when excessive rib depth may result in failure due to buckling.

Kiss-off Joints

Kiss-off joints are a unique capability of the rotational molding process. This reinforcement point is formed when two walls become attached to each other. The design considerations for this feature have been documented[5] and are illustrated in Figure 3. Although no data exists the enhancement to the load bearing capabilities of the part perpendicular to the joint are obvious. For some applications the actual kissing-off is not desirable as it can result in witness marks in the exposed surface of the part.

Core Holes

Core holes offer another potential avenue to increase the load bearing capabilities of a rotationally molded part. A hole protruding through the part can be used to join one layer with another, providing enhanced stiffness characteristics perpendicular to the hole (see Figure 4). However, like kiss-off joints, core holes can adversely affect the aesthetic quality of the part.

Molded-in Metallic Stiffeners

In extreme circumstances metallic stiffeners are molded into the plastic for enhanced performance. Depending on the design, it can be difficult to attract enough heat to the metallic stiffener to achieve a sufficient coating of plastic. Also, the two materials have incompatible shrinkage rates. However, the benefits are significant, as most metals are 100 times stiffer (or greater) than polyethylene.

Use of Foam to Improve Stiffness

Polyethylene Foam

The utilization of polyethylene foam is a relatively cost effective way to increase the stiffness of a rotationally molded part. Polyethylene foam can either be used to form a second layer – the first being a solid skin, or to fill a cavity between two solid layers. The advantage of using foam is primarily a cost reduction due to less material being needed, combined with an enhanced stiffness to weight ratio. It should be noted that the foam layer has in itself significantly reduced mechanical strength compared to a solid layer. However, the foam cell structure has the potential to increase the wall thickness of the part by 8-10 times for the same amount of polyethylene material. It is this fact, combined with the outer skin layer that yields a stiffness to shot weight advantage for the foamed product.

Skin/Foam Structure

In order to determine the stiffness advantage offered by a skin/foam layer, it is necessary to know the second moment of area, I, for the section. This can be achieved by considering the two different materials as a single equivalent section[6], as illustrated in Figure 5. This equivalent section will form a 'T' section and the thickness of the web is simply given by:

$$b_{s1} = (E_f / E_s) b_f \qquad (3)$$

where: E_s = modulus of solid material
E_f = modulus of foam material
b_f = width of foam section
b_{s1} = equivalent width of solid web

The only problem with equation (3) is that although it is not difficult to get the modulus, E_s, of the solid material, it is not as easy to determine the value of the foam material, E_f. However, the density of a foamed material can be relatively easily determined. Knowing the density of both materials, an existing relationship[7] can be used to calculate the modulus of the foam :

$$(E_f / E_s) = (\rho_f / \rho_s)^2 \qquad (4)$$

where: ρ_s = density of solid material
ρ_f = density of foam material

Sandwich Structures

A significant enhancement to a two-layer skin-foam product is to add another layer of solid material, hence creating a sandwich construction. Similar theory applies to determine the second moment of area of the equivalent section, which looks like an 'I' beam. For the example shown in Figure 6, the second moment of area is given by :

$$I = b_s (2D_2 + d_2)^3/12 - b_s (d_2)^3/12 + b_{s2} (d_2)^3/12 \qquad (5)$$

This type of structure maximizes the stiffness to weight ratio, however it also creates a new level of complexity to the mold process. Other advantages from using polyethylene foam include the improved insulation properties and noise damping properties. These advantages are somewhat offset by the additional cost of a drop-box (for some applications) and extended cycle time.

Polyurethane Foam

Polyurethane tends to be used to foam-fill parts after they have been molded. This type of foam does not readily bond to the polyethylene skin layer and therefore acts as a support when the external surface of the part is loaded. The foam does not have much compressive strength and so the benefits related to stiffness enhancement are limited.

Use of Fillers to Improve Stiffness

Fiber-Reinforcement

A research project carried out by The Queen's University of Belfast investigated the use of fiber reinforcement to improve the stiffness of polyethylene[8]. A gain in flexural modulus of 127% was achieved when a critical molding recipe involving the following parameters was used:

- Fiber quantity
- Fiber length
- Fiber micro-pelletization
- Fiber coupling agent
- Multiple layers
- Mold pressurization

The research work demonstrated that the use of fiber reinforcement was feasible and that significant gains in stiffness could be achieved.

Talc and Mica

Another research program, currently ongoing at The Queen's University of Belfast[9], is investigating the use of Mica and Talc primarily to improve stiffness. These fillers are commonly used in other plastic processes for the same purpose. The current research program has demonstrated that both additives have the potential to improve the stiffness of rotationally molded polyethylene by 40-50%. Like the inclusion of fibers, a critical recipe is required to achieve the best results, which includes the use of a coupling agent and an optimal addition level.

Higher Stiffness Polyethylene Resins

Recent developments by polyethylene material suppliers have yielded a range of very high density resins that have improved stiffness properties beyond what has been commonly used by the industry. Table 2 lists some of these resins, along with their respective property data sheet values.

New Resins

As you would expect, the densities of all of these resins listed in Table 2 are higher than those commonly used in the industry today. However, there is not an exact correlation with density and flexural modulus i.e. the highest densities do not have the highest flexural modulus values. The reasons for this could be due to subtle differences in the test methods used by the suppliers, different additive packages, different polymerization methods, different co-monomers etc.

There are always trade-offs associated with changing some of the primary properties of the resins, such as its density. Increasing density to achieve greater stiffness results in some properties being improved, such as: tensile strength, hardness, heat distortion and chemical resistance. Other properties are effected in an adverse way, such as: Environmental Stress Cracking Resistance (ESCR), increased shrinkage and reduced impact strength.

Processing

Processing can also be tailored to influence the stiffness of a rotationally molded resin. Work carried out by Nova Chemicals[10] demonstrated that the density of a 0.938 kg/m^3 resin could be increased to over 0.941 kg/m^3 with a slow (all air) cooling cycle or decreased to 936 kg/m^3 with a faster (all water) cooling cycle. These changes in density correlated to differences in flexural modulus, with the high density having a flexural modulus value of approximately 700 MPa and the lowest density having a flexural modulus of 550 MPa. However, the gain in properties has to be offset by extension to the processing cycle time.

Less Commonly Used High Stiffness Resins

Polyethylene represents approximately 85-90% of the material used by the rotational molding industry. However, several other resins are used in smaller quantities that offer enhanced stiffness properties[11]. These resins are listed in Table 3.

Nylon 6 (PA6) represents the highest stiffness of any moldable resin that is available to the industry. However it should be noted that the stiffness of this material is directly related to its moisture content. This material is hydroscopic and will absorb moisture from the surrounding atmosphere until it reaches equilibrium. This will cause the material to plasticize, reducing its flexural modulus significantly. Polypropylene (PP) is another material used because of its enhanced stiffness properties. Unfortunately its low impact properties limits its use. Polycarbonate (PC) is also used to a limited extent but can be difficult to mold.

These materials (PA6, PP and PC) are available to the rotational molder at a much greater cost than polyethylene (by as much as 4 to 8 times). This factor, coupled with the processing challenges and extended cycle times when molding PA6 and PC, as well as the low impact strength of PP, tends to make them less desirable options.

Conclusions

1. The inclusion of properly designed rib profiles in the wall of a rotationally molded part can significantly increase its resistance to bending under load.
2. Molded-in features such as kiss-off joints, core holes and metallic inserts can be used to enhance load-bearing capabilities.
3. The inclusion of foam, particularly molded-in polyethylene foam, is a cost-effective way to increase the stiffness to shot weight ratio.
4. Research work carried out by The Queen's University of Belfast has shown that additives such as fibers, talc and mica can all be used to enhance the stiffness properties of rotationally molded products.
5. New polyethylene materials are emerging onto the market with higher densities that exhibit higher flexural modulus properties.
6. Other resins such as nylon 6, polypropylene and polycarbonate have superior stiffness properties compared to polyethylene, but are more expensive.

Acknowledgements

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Property	Resin A	Resin B	Resin C	Resin D	Resin E
Density (kg/m^3)	924	932	935	937	939
Melt Index (g/10min)	4.5	5.2	5.9	5.0	3.4
ESCR (hours@ 100% Igepal)	>1,000	>1,000	>1,000	>1,000	>1,000
Flexural Modulus (MPa)	414	504	642	752	834
Tensile Strength at Yield (MPa)	11.7	15.9	18.3	19	20
Heat Distortion Temperature (C)	45	49	56	63	64
Low Temperature Impact (J)	No data	70	79	92	95

Table 1 Commonly Used Rotational Molding Polyethylene Resins

Property	Resin F	Resin G	Resin H	Resin I	Resin J
Density (kg/m^3)	952	948	945	955	948
Melt Index (g/10min)	6.2	8.0	1.2	4.0	5.0
ESCR (hours@ 100% Igepal)	10	11	>1,000	No data	16

Flexural Modulus (MPa)	1,241	1,014	1,000	966	828
Tensile Strength at Yield (MPa)	26.2	22.4	24.14	21.17	22.07
Heat Distortion Temperature (C)	74	72	66	77	57
Low Temperature Impact (J)	40	54	95	88	66

Table 2 Higher Stiffness Polyethylene Resins Available to the Rotational Molding Industry

Property	Nylon 6	Polypropylene	Polycarbonate
Density (kg/m^3)	1130	900	1200
Melt Index (g/10min)	4.5 - 10	12 - 20	5
ESCR (hours @ 100% Igepal)	No effect on Nylon 6	>1,000	No data available
Flexural Modulus (MPa)	1,380 – 2,620*	1,035 – 1,240	2,275
Tensile Strength at Yield (MPa)	51.7 – 72.4*	19.3 – 27.6	62
Heat Distortion Temperature (C)	148 - 177	79 – 85	135

Table 3 Less Commonly used High Stiffness Resins (* Note: Hydroscopic resin – properties decrease with moisture absorption)

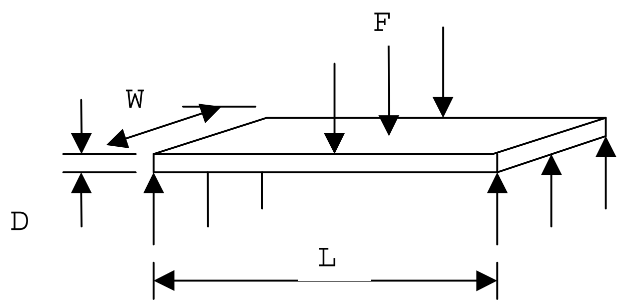

Figure 1 Flexural Element

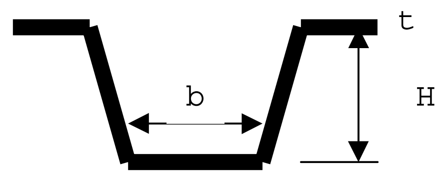

Figure 2 Typical Rib Design Profile

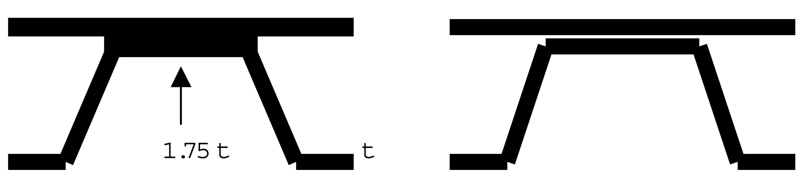

Figure 3 Kiss-off Joints (Complete and Incomplete)

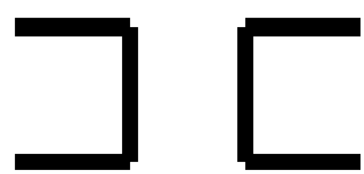

Figure 4 Through Hole

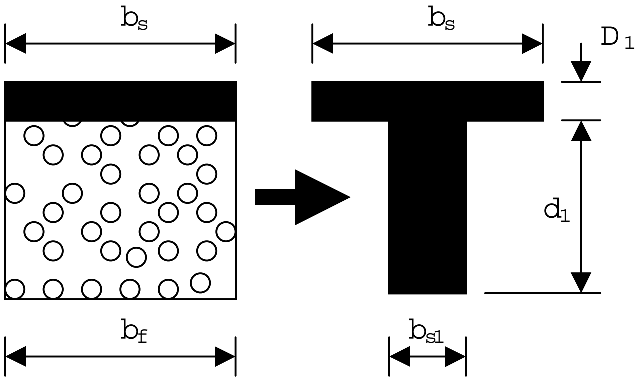

Figure 5 Equivalent Sections for 2 Layer Structures

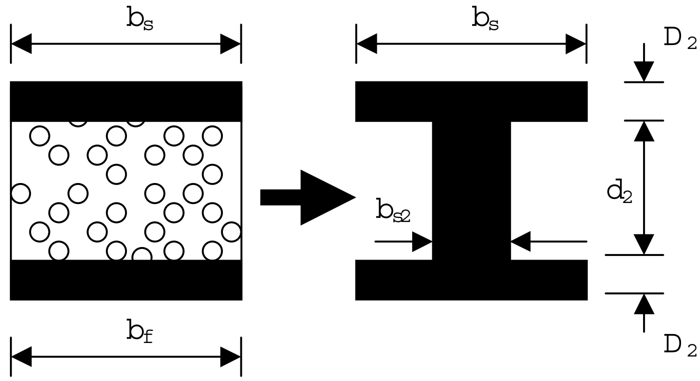

Figure 6 Equivalent Sections for Sandwich Structures

Key Words and Phrases

Rotational Molding, Stiffness, Flexural Modulus, Mechanical Properties.