

STUDY OF SHRINKAGE OF THERMOPLASTICS IN INJECTION MOLDING

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Abstract: The article is devoted to problem of plastic materials deformation in process of production by injection molding. The stages of plastic processing are considered, including heating, melting, mold filling and subsequent solidification. The main types of shrinkage and key ways of measuring it are described. A series of experiments using polypropylene, high-density polyethylene and two modifications of polyvinyl chloride are carried out. The influence of processing temperature regimes and rheological characteristics of materials on final dimensional parameters of products has been investigated. Correlation dependences between coefficient of thermal expansion, range of working temperatures of mold and yield index for each type of polymer have been established. The optimum technological modes providing minimum geometrical deviations of finished parts have been revealed. The results of study can be used to improve technological processes and increase accuracy of manufacturing polymer products of complex configuration.

Keywords: injection molding, thermoplastics, shrinkage factors, thermal expansion coefficient, melt flow index

1. INTRODUCTION

Today, plastic products are widely used due to their strength, lightness, resistance to external influences and the possibility of giving them almost any shape, which makes them indispensable in automotive, electronics, construction, medicine and other industries. [1-4]

Injection molding is one of most common methods of processing thermoplastics, used for mass production of products with high precision and complex geometries. [5-8]

One of key factors affecting quality of final product is material shrinkage. It manifests itself as reduction in dimensions of product after cooling and leads to changes in geometry, internal stresses and even defects.

The study of thermoplastic shrinkage is of great importance for optimization of production processes. A thorough understanding of this phenomenon allows not only to improve molding parameters, but also to predict material behavior, ensuring that products meet specifications.

The goal of work is to study shrinkage of thermoplastics during injection molding, to determine factors affecting its magnitude.

To achieve goal it is necessary to solve following tasks:

- analysis of shrinkage main causes;
- methods of shrinkage measurement;
- study of factors affecting shrinkage.

2. THEORETICAL CONSIDERATIONS

Shrinkage of thermoplastics during injection molding is due to complex physical and chemical processes occurring in material at various processing stages. [8, 9]

The main aspects are related to behavior of polymers during:

- heating;
- melting;
- filling mold and then cooling down.

The key steps in injection molding process are shown in Figure 1:

1. Uploading of material – polymer granulate is loaded into hopper of injection molding machine.
2. Plasticization – granulate is heated in cylinder where it melts and turns into viscous melt.
3. Injection – melt is injected under high pressure into closed mold, filling its cavity.
4. Pressure holding and sealing – after filling mold, material is compacted with additional pressure to prevent shrinkage and void formation.
5. Cooling – melt is cooled inside mold until it solidifies completely, and shrinkage occurs.
6. Removing product – after hardening, mold is opened and finished product is removed.
7. Finishing processing (if necessary) – deflashing, grinding or other refinement of product.

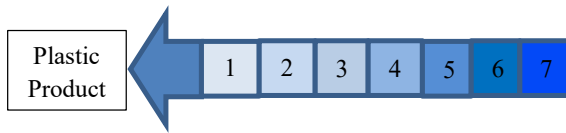


Figure 1. Key steps in injection molding process

Important factors affecting shrinkage are material properties:

- coefficient of linear thermal expansion;
- crystallinity;
- melt viscosity;
- level of residual stresses.

Technological parameters affecting shrinkage:

- injection pressure;
- melt temperature;
- mold temperature;
- cooling rate.

These parameters play key role in shaping dimensions and geometry of product. Consideration of these factors allows for deeper understanding of shrinkage nature and provides theoretical basis for development of methods for its prediction and minimization.

The following types of shrinkage are possible in plastic injection molding:

- linear shrinkage is change in dimensions of part in length, width, and thickness after removal from mold;
- volumetric shrinkage is reduction in volume of part after molding;
- internal shrinkage is formation of voids and pores within casting (Figure 2, a);
- surface shrinkage is formation of sinks, depressions and other defects on surface of part (Figure 2, b).

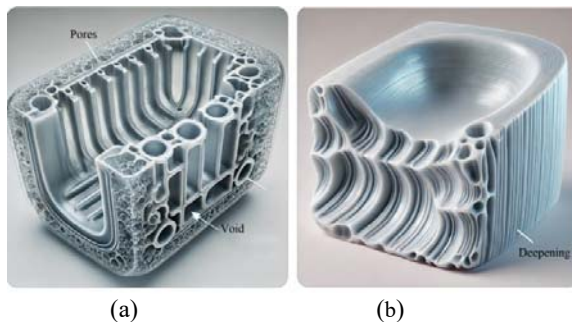


Figure 2. Examples of parts with shrinkage: (a) internal shrinkage; (b) surface shrinkage

The main ways to measure shrinkage in plastic injection molding include:

1. linear shrinkage measurement. A test piece is made and its dimensions are measured before and after molding. The difference between dimensions gives value of linear shrinkage.
2. Volumetric shrinkage measurement. The volume of test piece is measured before and after molding. The difference in volume allows volumetric shrinkage to be calculated.

3. Density measurement. The density of product before and after molding is compared. The difference in density is proportional to volumetric shrinkage.

4. Microstructure analysis. Microscopic examination of cross-section of product can reveal changes in structure associated with shrinkage.

5. Computer-aided modeling. The use of CAE systems (e.g. Moldflow) makes it possible to predict shrinkage at design stage of product and injection mold.

3. EXPERIMENTAL PART

This study will be aimed at analyzing material properties on which shrinkage of plastics depends.

The influence of temperature parameters on shrinkage of plastics during injection molding is important because cooling and solidification processes of material are directly related to temperature changes.

The following temperature parameters influence shrinkage of plastics:

- melt temperature;
- mold temperature;
- ambient temperature and curing temperature of material.

In this study, we will focus on effect of mold temperature on material properties.

The mold temperature plays key role in cooling process and hence in plastic shrinkage. In injection molding, mold is usually cooled through system of cooling channels, which affects cooling rate and uniformity.

At lower mold temperatures, cooling will occur faster, resulting in more shrinkage as material hardens and shrinks faster.

Rapid cooling can also cause internal stresses and deformation, especially if cooling is uneven, which can lead to cracks and defects in product.

Different types of plastic materials are currently used in manufacturing processes. Thermoplastics are selected for study.

Because there are reactoplastics – plastic materials with rigid and strong characteristics that can be molded once (they do not melt after curing). You cannot reshape or remold thermoset plastic once it has taken its original shape.

Therefore, thermoplastics are more relevant as they have flexible and elastic properties, unlike reactoplastics which are rigid and strong. It is possible to reshape or remold thermoplastic to after it has taken its original shape.

Reactoplastics have very high melting point because they are resistant to high temperatures after initial molding. Thermoplastics have low melting points that are susceptible to melting when exposed to high temperatures.

The thermoplastics selected are:

1. Polypropylene (PP) is thermoplastic that is widely used in various molding processes including injection molding. Important parameter for this material is temperature at which it becomes flowable enough to fill mold, but still maintains good strength and structure.

Selected Polypropylene (Copolymer) is widely used for injection molding. Lower melting and processing temperature compared to homopolymer polypropylene. Better melt flowability allowing efficient mold filling.

2. High-density polyethylene (HDPE) – is thermoplastic that is used in variety of processes, including injection molding. To successfully mold polyethylene, its temperature characteristics must be taken into account, as this determines both flowability of melt and its subsequent cooling.

3. Polyvinyl Chloride (PVC) – is widely used thermoplastic with good strength and chemical resistance. PVC, Plasticized (PVC-P) is chosen because this material contains plasticizers that make material more elastic and efficiently workable in injection molding process. It has good melt flow, which makes it easier to fill injection molds. Finished products made of plasticized PVC are more flexible and impact resistant. PVC-U (Polyvinyl Chloride, Unplasticized) was chosen because it is opposite of PVC-P, i.e. it does not contain plasticizers, is stiffer and harder. PVC-P has lower melt fluidity but greater dimensional stability. PVC-U finished products have high strength, stiffness and heat resistance.

4. RESULTS AND DISCUSSION

Experimental studies were carried out on thermoplastics. Table 1 shows coefficient of linear thermal expansion (CLTE) for three types of thermoplastics and melt and molding temperatures. [10-13]

Table 1. Experimental data

Material	PP	HDPE	PVC P	PVC U
Melt temperature range, °C	200-280	210-270	170-190	160-210
Mold temperature range, °C	30-80	20-60	20-40	20-60
CLTE, 10 ⁻⁶ /°C	70-170	60-110	50-200	50-180

The coefficients of linear thermal expansion can be determined by formula [12-14]:

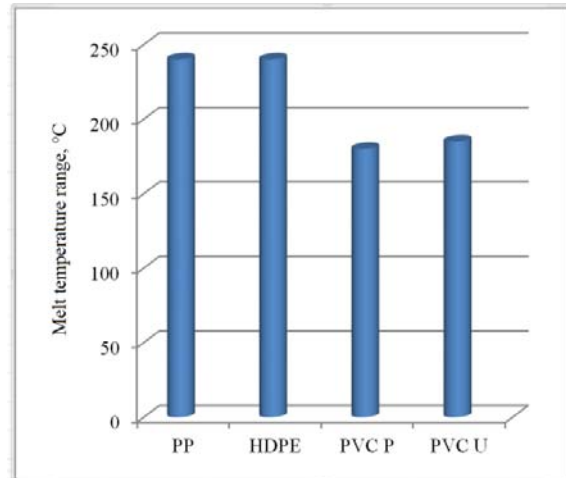
$$\alpha = \frac{\Delta L}{L_0 \cdot \Delta T}$$

α is coefficient of linear thermal expansion per degree Celsius;

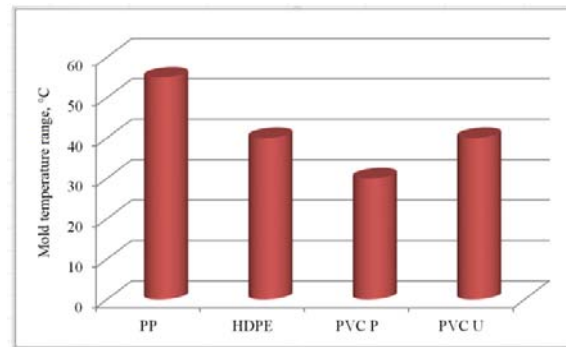
ΔL is change in length of test specimen due to heating or to cooling;

L_0 is original length of specimen at room temperature; ΔT is temperature change, °C, during test.

First, let's imagine how melting and mold temperatures differ for each material (PP, HDPE, PVC P, PVC U) (Figure 3, a, b).



(a)



(b)

Figure 3. Dependence of average temperatures for different types of plastics:

- (a) Melt temperature range
- (b) Mold temperature range

Figure 3, a is presented for shrinkage analysis, since it directly depends on molding conditions. Melt temperature affects uniformity of material filling mold. Materials with higher melting points (e.g. PP and HDPE) require higher process temperatures and this can increase shrinkage due to larger cooling range.

Figure 3, b is presented for shrinkage analysis because mold temperature directly affects cooling rate of material and degree of internal stresses that can cause shrinkage. Low mold temperatures can lead to rapid cooling, which increases likelihood of internal stresses and increased shrinkage.

High mold temperatures promote uniform cooling and less shrinkage. For PP, range of 30-80 °C is used, which helps to compensate for its high CLTE.

Figure 4 shows dependence of average CLTE for different plastics.

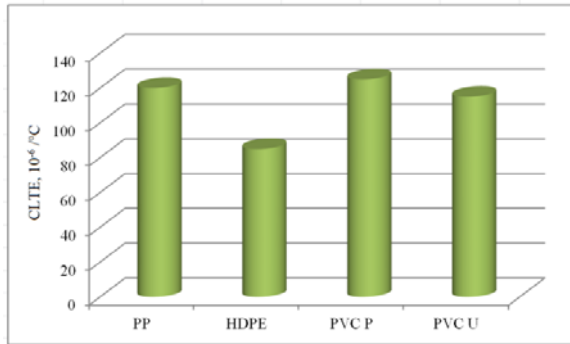


Figure 4. Dependence of average CLTE for different types of plastics

The higher coefficient of linear thermal expansion, more material will change its dimensions with temperature changes.

Thus, PP and PVC P have higher CLTE values (120-125 on average), indicating greater shrinkage.

HDPE shows lower CLTE (~85), indicating less shrinkage compared to other materials.

The results of analysis are shown in Figure 5.

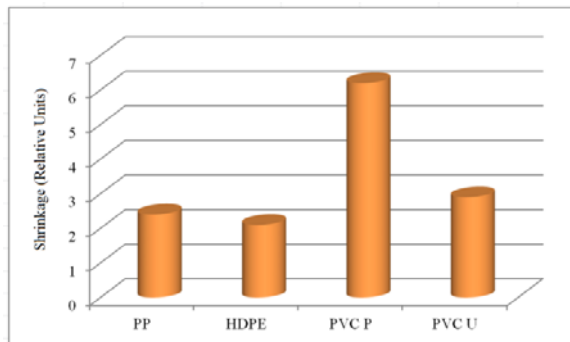


Figure 5. Relative shrinkage for different materials

PVC P has highest shrinkage tendency due to its high CLTE and narrow mold temperature range.

HDPE shows least shrinkage due to its low CLTE and moderate mold temperature range.

PP shows average shrinkage despite wide mold temperature range due to high CLTE.

PVC U has less shrinkage than PVC P due to larger mold temperature range.

As result, PVC P is more prone to shrinkage due to its high CLTE and narrow mold temperature range. HDPE is least prone to shrinkage due to its low CLTE and moderate mold temperature range.

Next, we examine material parameter such as melt viscosity, as this characteristic determines how easily material will flow and fill molds during processing. This affects shrinkage, as viscosity determines how material will deform and shrink in volume during crystallization and cooling.

Table 2 summarizes the recommended conditions for determining melt flow rate and volumetric melt velocity for common materials. [15-18]

Table 2. Experimental data of melt flow velocity and melt volume velocity

Material	PP	HDPE	PVC P	PVC U
ISO Standard Conditions (°C/kg)	230/2, 16	190/2,16 ; 190/5,0	180/2,16 ; 180/5,0	190/5,0 ; 190/10,0

Ranges of averaged values of yield indices were determined in course of conducted research:

- PP: 2-35 g/10 min
- HDPE: 0,2-20 g/10 min
- PVC-P: 2-25 g/10 min
- PVC-U: 1-15 g/10 min.

From calculation, Melt Flow Index (MFI) and viscosity are inversely related (Figure 6).

High MFI \implies Low viscosity

Low MFI \implies High viscosity

Figure 6. Dependence of MFI and viscosity

Viscosity is resistance of material to flow under applied force.

Polypropylene (PP) has low melt viscosity as it has high melt flow index, which makes it convenient to use in injection molding.

The results of MFI analysis of materials are shown in Figure 7.

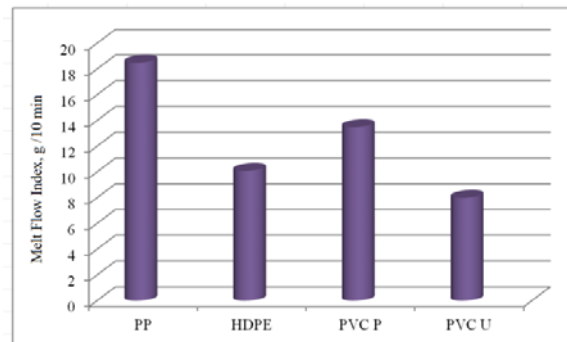


Figure 7. Average MFI for different materials

As result, PP has highest MFI; more mobile molecular chains and greater crystallization ability, that is, it is determined to be most prone to shrinkage high shrinkage (1,0-2,5 %).

HDPE has medium MFI; more ordered structure and high density, i.e. it is assumed to have medium shrinkage (1,5-3 %)

PVC-P has medium-high MFI; plasticizer increases mobility; amorphous structure, i.e. medium shrinkage (1,0-2,0 %) is assumed.

PVC-U has low PTR, which means high viscosity; rigid molecular chains; amorphous structure, i.e., low shrinkage (0,5-1,0 %) is expected.

Thus, higher CLTE, more material changes its dimensions with temperature. A material with high

CLTE will shrink more on cooling, which is especially important for large-sized products.

Uneven mold temperature range affects shrinkage. A narrow temperature range can lead to uneven cooling of different parts of product; internal stresses; and uneven shrinkage.

A high yield index (MFI) means:

- lower melt viscosity;
- greater mobility of molecular chains;
- increased tendency to deform during molding;
- potentially greater shrinkage on cooling.

These factors are interrelated and must be considered when designing casting process to minimize defects in finished product.

5. CONCLUSIONS

This study investigated shrinkage of thermoplastics during injection molding, which is critical for ensuring the quality of plastic products widely used in various industries.

The paper analyzes the main causes of shrinkage, describes main methods of shrinkage measurement; studies of factors affecting shrinkage were carried out.

The experimental part was carried out on four types of thermoplastics (PP, HDPE, PVC-P and PVC-U) with analysis of key parameters: coefficient of linear thermal expansion (CLTE), melt and mold temperature ranges, and melt flow index (MFI). As result, important relationships were established: PVC-P exhibits highest shrinkage due to its high CLTE and narrow mold temperature range, although its fluidity is medium;

HDPE shows the lowest shrinkage due to its low CLTE, moderate fluidity, and stable temperature range; PP shows high shrinkage due to its high fluidity, but less than PVC-P due to its lower CLTE; PVC-U has lowest shrinkage due to its low fluidity and moderate CLTE.

The obtained results have practical significance, allowing to predict behavior of various thermoplastics during molding, to optimize the process parameters, to minimize defects of finished products and to carry out rational choice of materials for specific applications, which together contributes to improving quality of manufactured plastic products.

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