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Warpage control of thin-walled injection molding using local mold temperatures☆

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ABSTRACT

Currently, 3C products are required to be lightweight, portable, and convenient. Injection molding is among the most used techniques for mass production in plastic processing industries; however, producing thinner parts that do not warp is challenging. Although plastic components warp for numerous complicated reasons, warpage primarily is caused by variations in shrinkage during the injection process of plastic part manufacturing. Material properties, part design, mold design, and processing conditions are factors influencing variations in the part shrinkage. For example, inconsistent thickness in component geometry, poor sprue–runner–gate or cooling design in the injection mold, and improper molding condition settings may cause plastic parts to warp excessively. Warpage causes unpredictable component shapes, which may cause poor assembly quality. Although mold cooling achieved by adjusting mold temperatures improves warpage, the conventional single mold temperature setting for each male or female mold plate limits the cooling capability. Therefore, this paper describes local mold temperature settings for a cooling system that can prevent severe warpage in an asymmetric plastic cover for handheld communication devices. The neutral axis theory is introduced to analyze the temperature distribution in the cross section of a part, and then predict the warping trend. Through simulation and experiments conducted in this study, the feasibility of using an effective local mold temperature setting in a cooling system to reduce part warpage was verified.

1. Introduction

Plastic parts that are thin (<1.5 mm) and feature a high ratio of flow length to thickness (>100) form quickly solid layers when molten polymer enters mold cavities, thereby facilitating a short shot caused by the sharp decrease in the flowing channel. Thus, a high injection speed is required to complete filling and packing during the injection molding process [1]. This high-speed injection molding requires using high injection pressure to force molten polymer into mold cavities and overcome flowing resistance, and thus considerable changes inner pressures, particularly those of polymeric materials located near and far from the gates. This phenomenon may induce uneven shrinkage of plastic parts that warp easily after mold release [2–4]. Thin-walled plastic parts are particularly prone to severe warping because of their weak mechanical structures; nevertheless, the effects of improper molding condition settings and uneven cooling result in sectional shrinkage variations. Therefore, warpage control is crucial in manufacturing industries to prevent quality problems during the successive assembly process, and warpage must be minimized within dimensional tolerance.

The main cause of warpage in injection-molded parts is the uneven volumetric shrinkage from high to low temperatures. The volumetric shrinkage level of an injection-molded part can be described using the pressure–volume–temperature (PVT) diagram depicted in Fig. 1. The pattern from Point 1 to 2 represents the filling stage, in which molten polymer enters mold cavities, and cavity pressure is gradually increased corresponding to the degree of enforcing injection pressure. Point 2 is the end of the volumetric mold filling, which is followed by packing; the molten polymer pressure in cavities achieves maximum at Point 3. The pattern from Point 3 to 4 is the transition of packing to static holding that is frequently set at a relatively lower value than the injection pressure; the cavity pressure is slightly reduced by the back flow of molten polymer during the transition. The static holding stage (Point 4 to 5) is performed at constant pressure, compensating for the specific volume reduced by cooling. Notably, compensation achieved by the holding pressure is effective only when molten polymer at the gates is not frozen. The pattern from Point 5 to 7 represents the cooling stage, during which the pressure decreases continually with the degree of volumetric shrinkage during mold cooling; Point 5 to 6 and Point 6 to 7 indicate the constant specific volume and constant pressure conditions, respectively. At Point 7, the molded parts are ejected from mold cavities and then cooled to room temperature (Point 8) under atmosphere pressure. The travel distance between Point 6 and 8 determines the degree of volumetric shrinkage in an injection-molded part.

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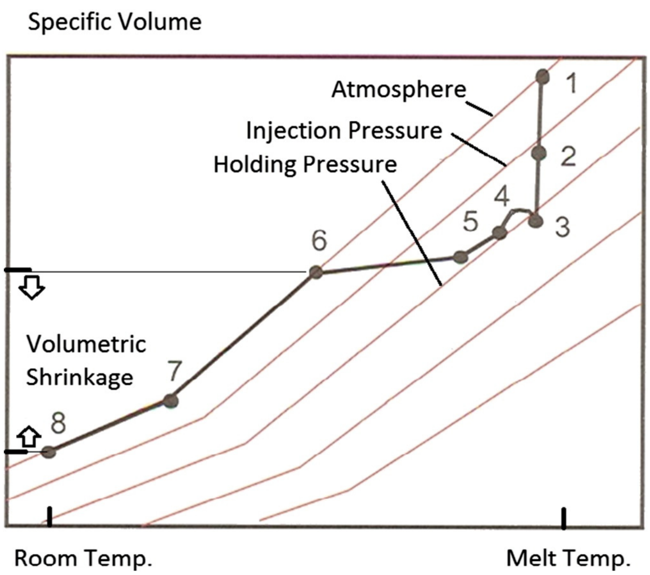

Fig. 1. PVT diagram.

Uneven volumetric shrinkage can be induced by thermal effects, pressure, part geometry, and flowing orientation effects. The details are presented as follows.

1.1. Thermal effect

Temperature primarily causes the specific volume change in processed polymers. As depicted in the PVT diagram (Fig. 1), the specific volume of injection-molded parts cooled from high temperatures and surrounded by constant pressure change, causing a high shrinkage rate. In thin-walled molding, molten polymer that enters cavities is quickly cooled with energy dissipated from cavity surfaces. Consequently, polymer temperatures close to the mold surface are lower than those in the polymer's center, generating a relatively lower shrinkage rate. Moreover, the thick portions shrink more than do the thin portions. Thus, injection-molded parts with uneven thicknesses undergo nonuniform shrinkage and subsequent warpage.

In addition, differential cooling results in variations in sectional shrinkage. The temperature difference between the upper and lower surfaces causes differential shrinkage between the cavity and core, producing a bending moment after the part is ejected from mold. This bending moment creates warpage or residual stress, depending on the mechanical stiffness of the part [5,6]. The cooling channel layout and the core and cavity material properties also affect the cooling rate uniformity. Basically, deviation in the cooling rate causes uneven shrinkage, particularly in thick parts that shrink substantially. In addition, a hot mold surface shrinks more than does a cold surface. The thermal effect contributes to generating internal stress in injection-molded parts during the cooling stage; the outer layer along the thickness direction solidifies first and limits the shrinkage direction of the inner part that cools later. Cooling channels are favorable to be placed close to the part whenever possible. However, varying the distance between the cooling channels and the part can facilitate controlling the differential cooling effects.

1.2. Pressure effect

Pressure is another crucial factor affecting the specific volume of polymer. As shown in the PVT diagram, injection-molded parts cooled under high pressure shrink less. The pressure level is associated with the location of molten polymer in the cavities. For example, the polymer near the gate is surrounded with high pressure, and therefore shrinks less. By contrast, the polymer far from the gate and treated with low pressure shrinks more. In thin-walled molding, molten polymer is rapidly cooled, generating a substantial pressure gradient along the thickness direction that produces nonuniform residual stress, and then creates uneven shrinkage after cooling, thereby generating part warpage. The molten polymer can efficiently release internal stress at a high temperature and shrinks less when sufficiently cooled.

Packing profiles can be used to establish an approximately uniform distribution of volumetric shrinkage throughout a molded product. In general, lower pressures cause volumetric shrinkage to increase, whereas higher pressures reduce volumetric shrinkage. A constant packing pressure results in volumetric shrinkage and is maximal at the end of

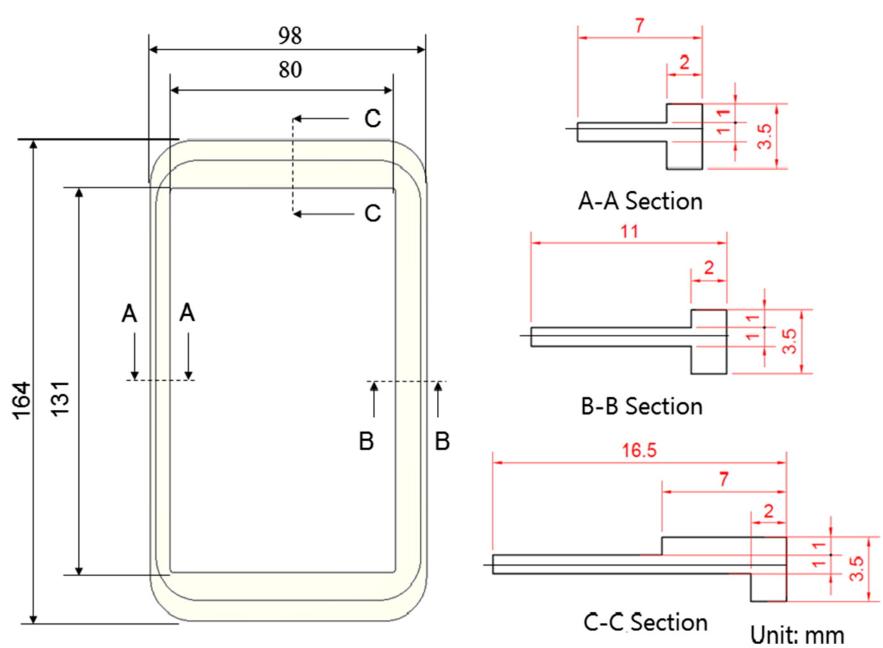

Fig. 2. Geometry of the portable cover.