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Residual stress distributions and their influence on post-manufacturing deformation of injection-molded plastic parts

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ABSTRACT

Post-manufacturing thermal exposure of injection-molded parts may result in unexpected permanent deformation. In this study, the mechanism of the post-manufacturing thermal deformation of injection-molded parts is investigated. A simple stress lattice part was used, and injection-molding experiments were carried out to characterize the deformation that occurred in post-manufacturing thermal cycling. The stress lattice part was chosen so that the thermal stress could be investigated with different cooling rates in the same part. The stress lattice parts were thermally cycled using a thermal chamber. A series of computer-aided engineering (CAE) analyses, including injection-molding analysis and finite element analysis (FEA), were performed to describe the deformation following the thermal cycle. The results of these analyses were in good agreement with the experimental results, and revealed that the residual stress formed during the injection molding process was the primary cause of the permanent deformation following the post-manufacturing thermal cycling.

1. Introduction

Polymers are used in a wide range of applications owing to the favorable mechanical and economical properties and excellent manufacturability (Stokes, 1995). The use of acrylonitrile/butadiene/styrene copolymer (ABS), has seen considerable growth in recent years for applications including thin-walled components of consumer products and automotive parts. ABS has a very high flow injection molding grade, as well as good resistance to impact and heat; however, although ABS has good resistance to heat, warpage or permanent deformation may still occur during the life cycle of products when they are exposed to a high-temperature environment. Container transport of consumer products through the equator is one such example. To prevent permanent deformation of products, durability tests are required; however, simulating and minimizing warpage prior to durability tests is desirable as part of the design process.

The advent of computer aided engineering (CAE) technology has led to significant improvements in polymer parts, and made the design process more powerful. Injection molding of polymer materials can be simulated using commercially available software packages to determine optimal processing, including the optical gate placement, runner size and opening times. Simulating and predicting warpage in injection-molded parts has been investigated to optimize the process. Gao et al. (2008) performed process optimization of the simulation to predict the warpage after injection molding. Wagner et al. (1989) attempted to integrate experimental findings through mathematical model of the injection molding process. Mavridis et al. (1986) investigated mathematical modeling of injection mold filling. Gu et al. (2001) studied the numerical simulation with the finite element method to predict warpage and residual stress of injection-molded part generated during the cooling stage of the injection-molding cycle. Himasekhar et al. (1993) studied current trends of simulations in injection molding. Recently, three-dimensional (3D) numerical analysis models have been introduced. Chang and Yang (2001) used incompressible, high-viscosity Newtonian fluids for 3D simulations of injection molding, and extended the analysis to include compressible and non-Newtonian fluids. Khayat et al. (2001) modeled viscous, incompressible fluids using the boundary element method, and Illinca and Hetu (2002, 2006); Illinca and Hetu, 2002 used finite element analysis (FEA). The work of Chang and Yang (2001) resulted in a numerical analysis tool to describe the complete injection molding process, including post-process warpage. Zhou and Turng (2006) developed a 3D mold-filling simulation that was computationally flexible, efficient and stable. Nowak et al. (2006) developed a novel 3D simulation

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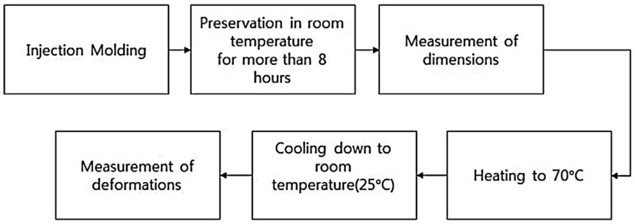

Fig. 1. Diagram of the experimental procedures.

to describe stress and shrinkage of polymer parts. Recently, 3D injection-molding simulation software packages, including SIGMA, Moldflow and CoreTech, have become widely used by industrial companies to describe the injection molding process (Potente et al., 1999; Knights, 2007). Panchal and Kazmer (2010) studied an experimental method to verify the simulated shrinkage during injection molding. All these studies investigated numerical simulation methods to predict warpage in parts during the injection molding process.

Residual stress is introduced in plastics when the polymer melt cools, and may lead to damage to products during the lifetime of the part. Distortion, cracking and crazing may occur when the parts undergo stress relaxation due to thermal cycling. Experimental measurements have been used to investigate the existence of residual stresses in plastics following manufacturing (Feingold, 2005; Hauk et al., 1987). Santhanam et al. (1991/1992) predicted the warpage and shrinkage of an injection-molded plastic part, and evaluated its load–deflection behavior. They compared the results of the simulation analyses with those of simple load–deflection experiments; however, there has been insufficient study of the effects of residual stress on permanent deformation following post-manufacturing thermal cycling.

In this study, stress lattices were formed from ABS using injection molding. Post-manufacturing thermal cycling was carried out to generate warpage. Numerical analyses were carried out to investigate the residual stress resulting from the injection molding process, as well as deformation due to the post-manufacturing thermal cycling. Plastic material model was investigated to describe the deformation of the part and the results of the simulations were compared with these experimental results. Using the technique described here, we may optimize the design of plastic and the injection-molding process to minimize the warpage due to thermal cycling during the lifetime of the part.

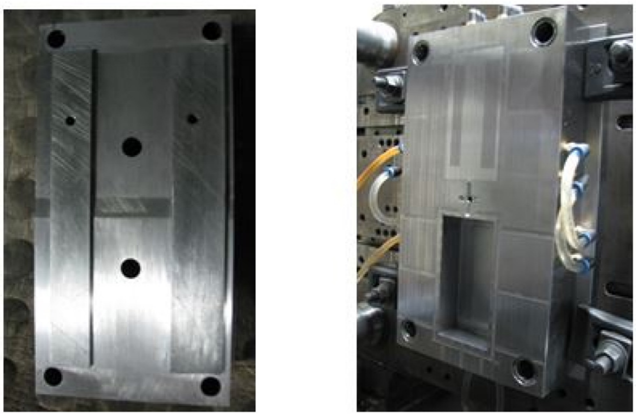

Fig. 3. The mold and the injection molding machine used to form the polymer stress lattice parts.

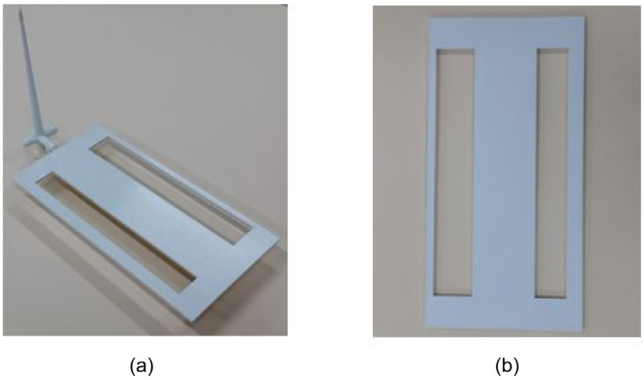
(a) (b)

Fig. 4. The molded stress lattice used for the experiment. (a) Before removing the gate, sprue and runner, and (b) after removing the gate, sprue and runner.

2. Post-manufacturing thermal cycling experiement

Dimensional consistency is critical for injection-molded parts, not only immediately following manufacture, but also during the lifetime of the part. Several factors can affect the dimensional consistency of injection-molded parts following post-manufacturing thermal cycling. To investigate the associated deformation of the parts experimentally, we fabricated a number of injection-molded parts, and subjected them to thermal cycling, as shown in Fig. 1. A

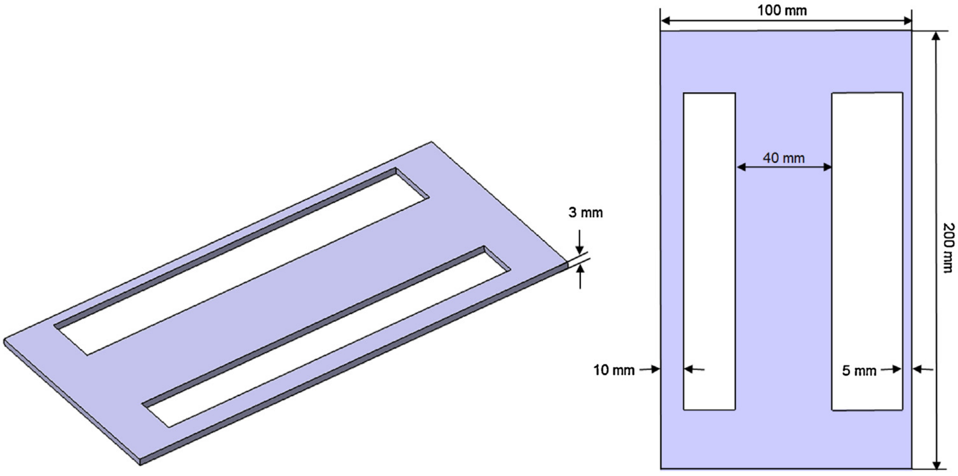

Fig. 2. The configuration of the stress lattice injection-molded ABS parts.