Korea-Australia Rheology Journal
Vol. 19, No. 4, December 2007 pp. 183-190

Residual stresses and viscoelastic deformation of an injection molded automotive part

Sung Ho Kim, Chae Hwan Kim, Hwajin Oh, Chi Hoon Choi[1], Byoung Yoon Kim[1], and Jae Ryoun Youn*
Department of Materials Science and Engineering, Seoul National University, 151-742, Korea
[1]Advanced Technology Center, Hyundai-Kia Motors, Hwaseong-Si, 445-706, Korea
(Received July 31, 2007)

Abstract

Injection molding is one of the most common operations in polymer processing. Good quality products are usually obtained and major post-processing treatment is not required. However, residual stresses which exist in plastic parts affect the final shape and mechanical properties after ejection. Residual stresses are caused by polymer melt flow, pressure distribution, non-uniform temperature field, and density distribution. Residual stresses are predicted in this study by numerical methods using commercially available softwares, Hypermesh^{TM}, Moldflow^{TM} and ABAQUS^{TM}. Cavity filling, packing, and cooling stages are simulated to predict residual stress field right after ejection by assuming an isotropic elastic solid. Thermo-viscoelastic stress analysis is carried out to predict deformation and residual stress distribution after annealing of the part. Residual stresses are measured by the hole drilling method because the automotive part selected in this study has a complex shape. Residual stress distribution predicted by the thermal stress analysis is compared with the measurement results obtained by the hole drilling method. The molded specimen has residual stress distribution in tension, compression, and tension from the surface to the center of the part. Viscoelastic deformation of the part is predicted during annealing and the deformed geometry is compared with that measured by a three dimensional scanner. The viscoelastic stress analysis with a thermal cycle will enable us to predict long term behavior of the injection molded polymeric parts.

Keywords : injection molding, residual stress, elastic deformation, viscoelastic deformation, layer removal, hole drilling, rosette

1. Introduction

Computer-aided engineering (CAE) has been developed and applied to the design of the part and processing conditions. In the case of injection molding of polymeric parts, numerical analysis softwares are used to determine the shape of the part, mold cavity geometry, and molding conditions before the mold production. Commercially available numerical simulation programs have been improved extensively in the last decade and utilized frequently as routine tools for determination of the mold design and process conditions. Injection molding simulation packages are effective for resolving such issues as gate placement, runner sizing, and clamp force requirements (Manzione, 1987). In spite of the recent advances in injection molding simulations, one of the most challenging tasks in the injection molding is the prediction of shrinkage of the molded part and proper dimensional tolerances in mold design (Santhanam *et al.*, 1991/1992). A number of studies have been published on the shrinkage and warpage of injection molded parts. Jansen *et al.* (1998) measured the shrinkage of seven types of plastics to investigate the effects of processing conditions (Chiang *et al.*, 1993). It was reported that the important processing parameters were packing pressure and melt temperature. Higher packing pressure and lower melt temperature reduce the shrinkage. Bushko and Stokes (1995, 1996) studied the effect of processing conditions on the shrinkage, warpage, and residual stresses of the polymeric parts. Their results showed that higher packing pressure resulted in lower shrinkage in both the in-plane and thickness-wise directions. Higher mold temperature increased shrinkage in the thickness-wise direction, but it had no effect on the shrinkage of the in-plane direction.

When the molded part is ejected from the mold, the geometric constraint is released suddenly and final dimension of the product changes considerably due to new force equilibrium of the internal residual stresses. Injection molding usually induces residual stresses (Courtney, 1999; Jung *et al.*, 1999; Kim *et al.*, 2002; Sweeney *et al.*, 1999; Treuting and Read, 1951; Youn *et al.*, 2005; Zoetelief *et al.*, 1996) which exist in the molded part without application of any external load. Development of residual stresses causes the

*Corresponding author: jaeryoun@snu.ac.kr

instantaneous deformation upon ejection as well as long-term thermo-viscoelastic deformation of the part. Durability and quality of industrial products which consist of various polymeric components will depend upon the short-term and long-term deformation of the polymeric components, *e.g.*, home appliances, automobiles, and electronic equipments. It is important to identify the residual stress distribution of the part to predict its performance under various environments. Residual stresses can be either detrimental or beneficial depending on the situation. Compressive residual stress on the surface can prevent the initiation of cracks and increase the fatigue strength. Conversely, when stresses induced by the external loads are added to the residual stress, plastic yielding will begin at lower external load.

The goal of this study is to predict the residual stresses in an injected-molded automotive part with complex geometry. Numerical prediction and measurement of the residual stress distribution as a function of processing conditions can provide knowledge to improve injection molding process and performance of the part. Thermal stress analysis of the part is carried out by assuming not only isotropic elastic but also viscoelastic solid. Thermo-viscoelastic analysis is conducted to calculate long-term deformation of the plastic part when it is exposed to certain environmental conditions. Residual stress distribution predicted by the thermal stress analysis is compared with the experimental results obtained by the hold drilling method. Geometry of the automotive part is measured by a three dimensional scanner when it is stored at room temperature after ejection and it is annealed at elevated temperature.

2. Experiments

The layer-removal method is one of the most frequently used methods for measurement of residual stresses of the plastic parts. However, the layer removal method can not be applied to injection molded products with variable shapes. The hole drilling method which has been used for metallic parts is applied to the molded plastic part in this study. The incremental hole drilling method is chosen to measure the residual stress distribution with respect to the depth at each point where the strain gage, rosette, is attached. The hole drilling method is applicable to a small area of the part, or a specimen with complex geometry. But few reports have been published on application of the measurement method to polymeric parts. In this study the integral method is used to measure the residual stress as a function of the thickness because it is adequate for measurement of the residual stress field varying with depth. The integral method is proper for evaluation of the residual stress variation in thickness direction during the incremental hole drilling measurement

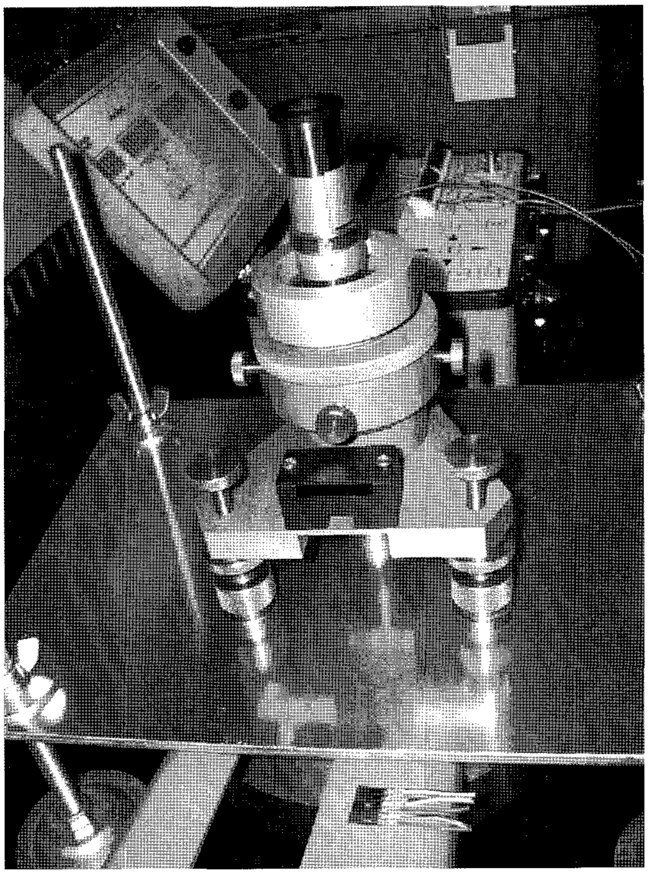

Fig. 1. Experimental set-up for the hole drilling method.

2.1. Measurement of residual stresses

A strain gauge, rosette (062UL type; Measurement Group, US), was attached at specific positions of the automotive part and then a hole was drilled precisely through the center of the rosette. The experimental set-up for the hole drilling is shown in Fig. 1. A precision milling guide was attached to the specimen and centered accurately over a drilling target in the rosette. The induced strain at each drilling step was measured by the rosette and the relationship between the principal stress and strain was considered to determine the residual stresses.

The RS-200 milling guide and rosettes were used for hole drilling method and strains were measured by following the ASTM procedure. While incremental drilling, the center of the drilled hole should be maintained and a proper type of drill must be selected. In this study, a double ended boring mill cutter and a hand drill were used to generate a flat-bottomed cylindrical hole. A three-wire temperature-compensating circuit was employed for calibration of the strain gage and the strain was displayed by using a commercial strain gage indicator with the resolution in the order of 10^{-6} Pa. Strains were measured for five times at every drilling of 0.2 mm from the surface by using the blind hole method. When the blind hole is drilled incrementally for 5 times at 2,000 rpm, each interval is sus-

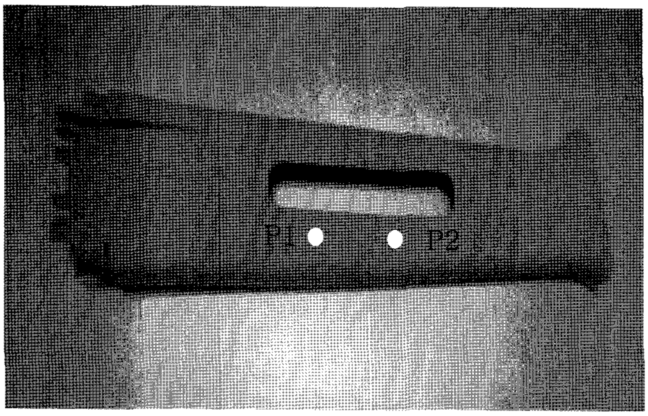

Fig. 2. Injection molded part with two points where the residual stress distribution is measured with respect to depth by using the hole drilling method.

tained for 45 seconds to stabilize the stress relaxation. Fig. 2 shows the injection molded part with two points where the residual stress distribution is measured with respect to depth by using the hole drilling method. The hole drilling method should be conducted carefully to obtain consistent raw data for calculation of residual stresses in an injection molded polymeric product. It is important to achieve perfect bonding of the rosette to the specimen. Sufficient amount of the adhesive should be applied as the rosette is attached and hardened for about 1 day for complete bonding. Soldering is required for wiring of the strain gage circuit and the soldering should be finished as soon as possible. Centering and fixing of the drill determine the quality of the hole drilled incrementally. After each incremental drilling, a time interval is needed for the residual stress to be stabilized before reading the signal from the strain gage amplifier.

The equation employed to calculate elastic strain (ε_{rr}) which is measured by the rosette (Fig. 3) at the periphery of the hole is given as

$$\varepsilon_{rr} = (\bar{A} + \bar{B}cos2\beta)\sigma_{max} + (\bar{A} - \bar{B}cos2\beta)\sigma_{min}$$
$$\bar{A} = -\bar{a}(1+v)/(2E)$$
$$\bar{B} = -\bar{b}/(2E) \tag{1}$$

where β is an angle measured counterclockwise from the maximum principal stress direction to the axis of the strain gage, $\bar{A}$ and $\bar{B}$ are calibration constants, and σ_{max} and σ_{min} are principal stresses (Turrnbull *et al.*,1999; Youn *et al.*, 2005)

2.2. Measurement of the geometry before and after annealing test

The molded specimen was heat treated at elevated temperature to release the residual stresses present in the part. Annealing of the part was conducted in a convection oven at 90°C for 5 days. Three dimensional geometry of the part was measured by using a 3-D scanner before and after the annealing. Dimension of the part predicted by the numerical stress analysis should be examined by comparing it with the measurement results obtained by the Exyma 3D Scanner (3D NEXTUS^{TM}). Dimension of the molded part geometry is also compared with that of the cavity geometry obtained by the mold design supplied by the CATIA^{TM} file.

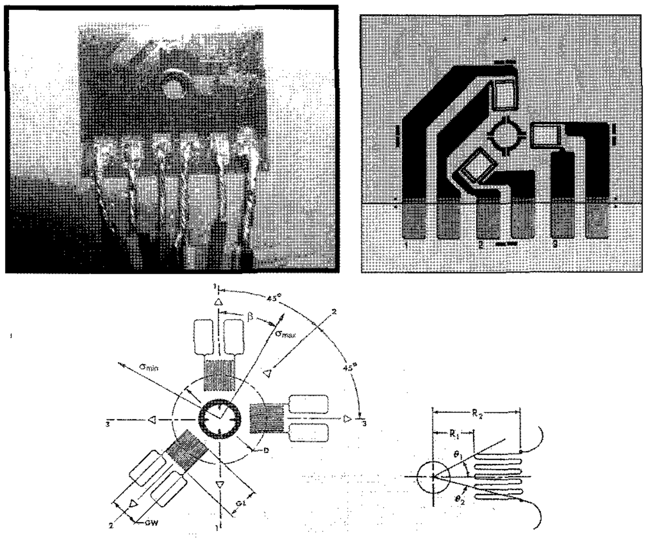

Fig. 3. A rosette (CEA-XX-062UL-120) attached to the specimen.

3. Numerical simulation of residual Stresses

3.1. Mesh generation

Hypermesh, a commercial program, was selected as a preprocessor to modify the three dimensional mold cavity design provided as a CATIA file and generate finite element mesh. Two dimensional triangular fusion mesh was generated by the preprocessor and transferred to Moldflow as an input file that was modified to generate three dimensional tetrahedral mesh. The 3D mesh was employed to model filling, packing, and cooling stages of the injection molding. The molding analysis results were transported to ABAQUS where four noded tetrahedral 3D elements (C3D4) were modified to generate ten noded tetrahedral 3D elements (C3D10MT) for thermal stress analysis. The ten noded tetrahedral 3D elements are needed to perform thermo-viscoelastic stress analysis of the polymeric part.

3.2. Numerical analysis of injection molding

Numerical simulation of injection molding was carried out by using Moldflow that consists of modules for filling, packing, and cooling stages. A set of unified governing equations for the flow field in the cavity, which is based upon the generalized Hele-Shaw model of a compressible viscous fluid under nonisothermal conditions, is used throughout the filling and post-filling stages. Convective

Table 1. Material properties of the resin used for injection molding

Elastic modulus	1.385E+9
Poisson's ratio	0.408
Thermal conductivity(220°C)	0.11 W/m°C
Thermal expansion coefficient	9.05E−5
Specific heat	2723 J/kg°C
Solid density	741.25 kg/m^3
Melt density	906.95 kg/m^3

Table 2. Molding Conditions

Filling time	3.247 s
Cooling time	20.0 s
Packing / holding time	10 s
Packing / holding pressure	7.5 MPa
Melt temperature	220°C
Mold temperature	40°C

Table 3. Finite element employed for molding simulation

Mesh	Tetrahedral
Type	C3D4
Number of elements	387455

heat transfer by the cooling liquid, viscous heating during both filling and post-filling stages, and heat conduction through the mold-polymer interface are accounted for in the thermal analysis. Specific volume is represented by the modified Tait equation. The coupled thermal and flow fields are solved with the control-volume approach to handle automatic melt-front advancement by using a hybrid FEM/ FDM scheme. An implicit numerical scheme is employed to solve the discretized energy equation (Santhanam *et al.*, 1991/1992). Material properties of the polymer resin and the molding conditions employed for numerical simulation are listed Tables 1 and 2. Type of finite element mesh used for mold filling analysis is specified in Table 3.

3.3. Viscoelastic stress analysis

Residual stresses are developed in the injection molded part due to non-uniform cooling and pressure distribution. In the present analysis, it is assumed that the polymer material is transversely isotropic with viscoelastic stress-strain behavior, where the dependence of material behavior

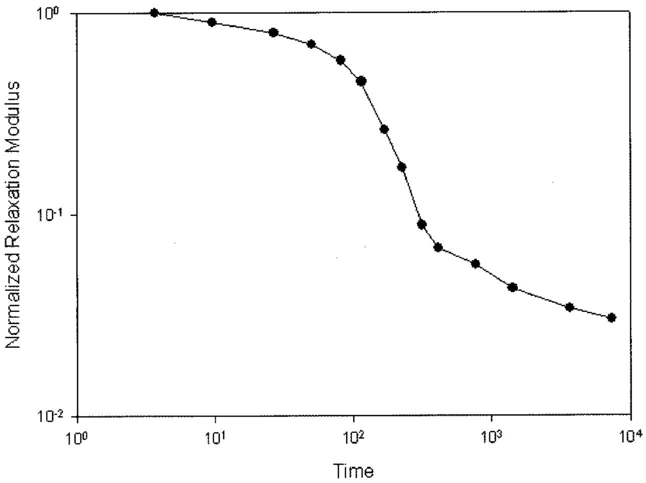

Fig. 4. Normalized relaxation modulus of the resin obtained by DMTA.

on temperature is accounted for though the assumption of the thermo-rheological simplicity. The constitutive equation for the linear viscoelastic material is expressed as follows.

$$\tau(t) = G_o(\theta)(\gamma - \int_0^t \dot{g}_R(\xi(s))\gamma(t-s)ds)$$
$$\dot{g}_R(\xi) = dg_R/d\xi \tag{2}$$

where the instantaneous shear modulus G_o is temperature dependent and $\xi(t)$ is the reduced time.

$$\xi(t) = \int \frac{ds}{A(\theta(s))}, \tag{3}$$

where $A(\theta(t))$ is a shift function at time t. The reduced time concept for temperature dependence is usually referred to as thermo-rheologically simple (TRS) temperature dependence. The shift function is often approximated by the following WLF form.

$$\log(A) = -\frac{C_1(\theta-\theta_0)}{C_3+(\theta-\theta_0)}, \tag{4}$$

where θ_0 is the reference temperature at which the relaxation data are given, and C_1 and C_2 are calibration constants obtained at the temperature. If $\theta \leq \theta_0 - C_2$, elastic deformation will occur based on the instantaneous moduli (Mlekusch, 2001). Normalized shear relaxation modulus of the polymer melt measured by the DMTA is shown in Fig. 4 and used for the viscoelastic stress analysis.

Data files obtained from the injection molding simulation contains information on geometry, temperature, pressure, and stress distribution of the part which is still in the cavity. The date files were transported to ABAQUS for three dimensional numerical stress analysis. Type of the finite element mesh used for the thermo-viscoelastic stress analysis is specified in Table 4. Residual stress distribution and deflection of the molded part was predicted for different

Table 4. Finite element employed for thermo-viscoelastic stress analysis

Mesh	Tetrahedral
Type	C3D10MT
Number of elements	387,255
Initial condition	25°C
Annealing condition	90°C for 5 days
Viscoelastic property	Relaxation test by DMTA

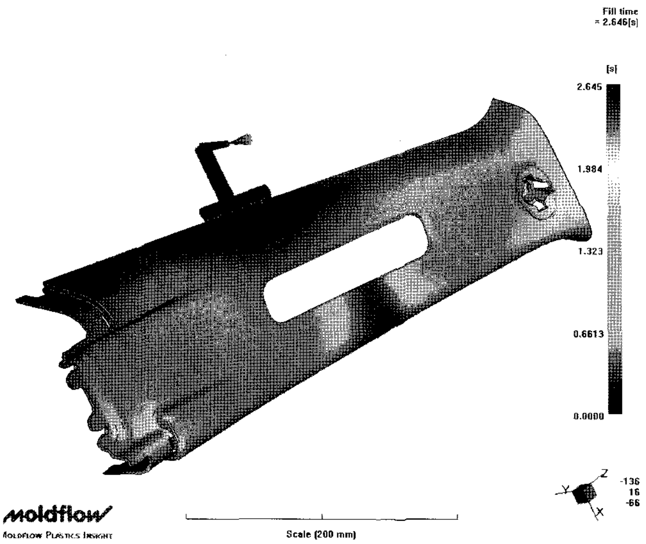

Fig. 5. Predicted filling time of the part.

environmental conditions, *i.e.*, 1) sudden elastic deformation at ejection due to removal of the constraints imposed by the solid mold wall, 2) viscoelastic deformation when stored at room temperature for 5 days, 3) viscoelastic deformation when annealed at elevated temperature for 5 days, and 4) viscoelastic deformation when stored at room temperature for 5 hours after annealing.

4. Results and discussions

4.1. Injection molding analysis

Flow front advancement is calculated as a function of time and shown in Fig. 5 which indicates that the mold is filled in 2.646 seconds. Fig. 6 presents temperature distribution of polymer resin at the end of filling that varies from 224°C to 184.6°C. It is anticipated and shown in the figure that temperature of the flow front is decreased due to heat transfer through the mold wall and cold air in cavity (Zhang *et al.*, 2002). Non-homogeneous temperature distribution is developed and causes uneven solidification that affects residual stresses of the injection molded part. Pressure profile is shown in Fig. 7 at 2.580 seconds that is right

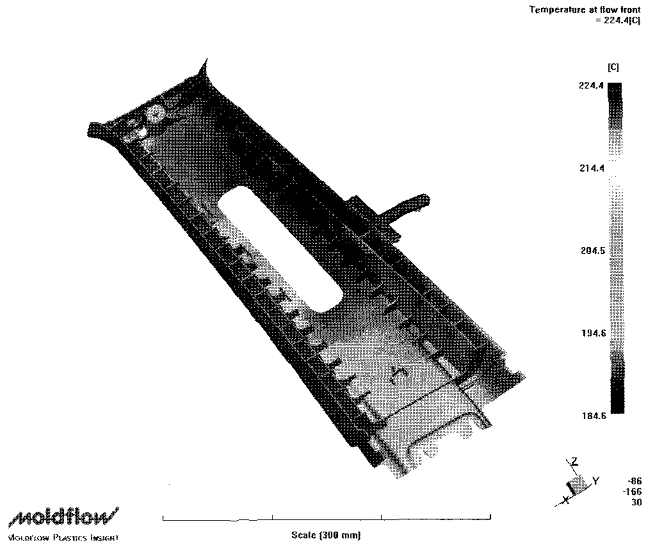

Fig. 6. Temperature distribution in the part at the end of filling.

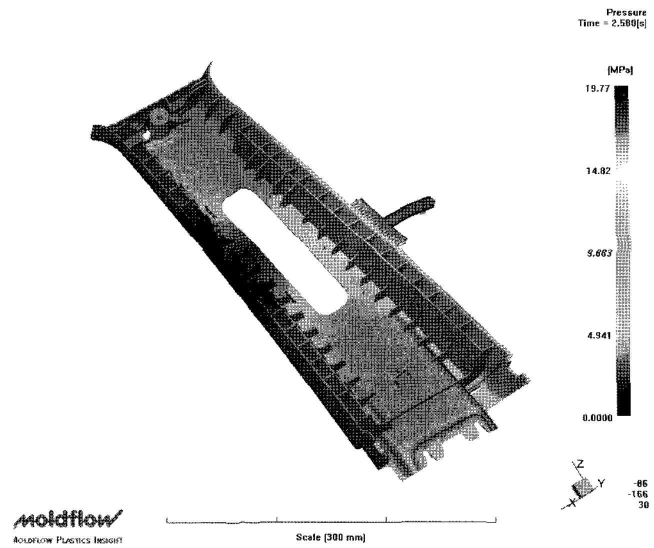

Fig. 7. Pressure distribution in the part at the end of filling.

before complete filling. Deflection of the part right after ejection from the mold is predicted by assuming isotropic elastic sold and shown in Fig. 8. The molded part shows considerable shrinkage right after ejection compared with the dimension of the mold cavity.

4.2. Three dimensional viscoelastic stress analysis

Residual stresses in the part which is in the cavity at the end of cooling are predicted and only tensile stresses are present because of the solid boundary conditions. After ejected from mold, a new stress equilibrium is achieved yielding residual stress distribution of tensile, compressive, and tensile modes from the surface to the center of the part. The molded polymeric part begins viscoelastic deformation as soon as it is ejected from the mold.

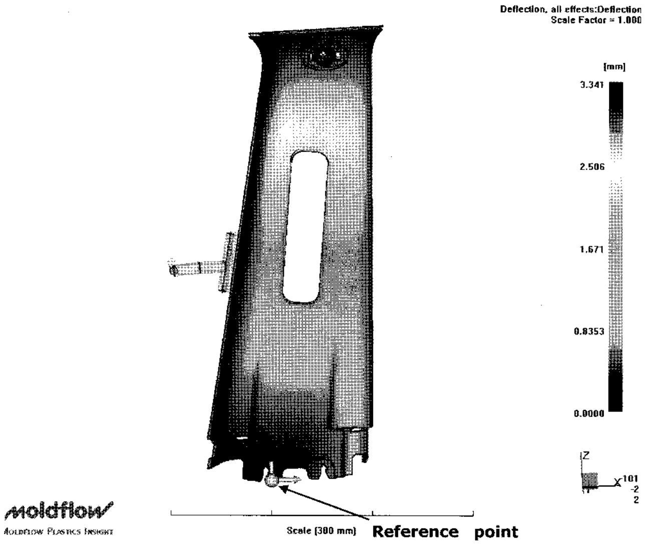

Fig. 8. Predicted deflection of the part after ejection.

Residual stress distribution of the part is calculated by the viscoelastic stress analysis when the ejected part is stored at room temperature for 5 days and displayed in Fig. 9. As shown in the figures, the specimen has a complex shape with a number of ribs and undergoes complicated temperature and pressure distribution resulting in complicated stress contours. A reference length, a distance between two specific points, is defined and displayed as an arrow in Figs . 9 and 10, and will be compared with the measured value. Residual stress distribution and deformation of the part are predicted in Fig. 10 when annealed at elevated temperature for 5 days and stored at room temperature for 5 hours after annealing. The molded part undergoes slight shrinkage when it is stored at 25°C for 5 days and substantial shrinkage when it is heat treated at 25°C for 5 days and cooled to room temperature for 5 hours.

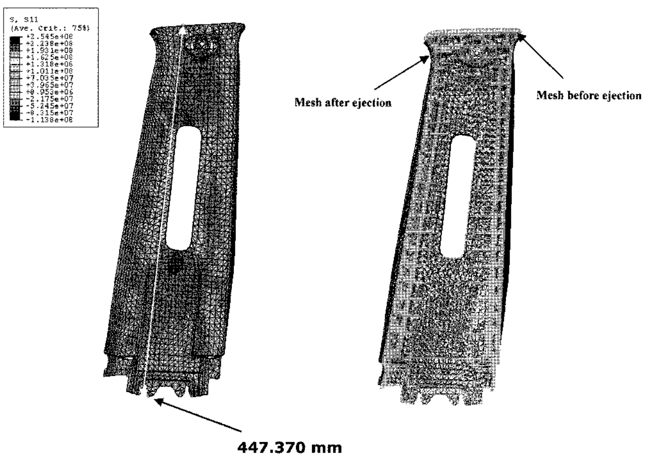

Fig. 9. Predicted residual stress distribution and deflection of the part before annealing after stored at 25°C for 5 days.

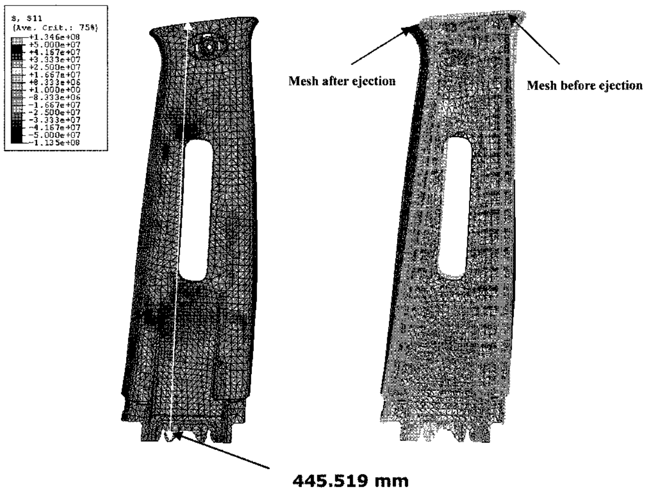

Fig. 10. Predicted residual stress distribution and deflection of the part after annealing at 90°C for 5 days and cooling at 25°C for 5 hours.

4.3. Three dimensional measurement of the geometry

Surface shape of the molded part was scanned by the 3D Scanner (NEXTUS™) right after ejection. Geometry of the part was also measured after annealing at elevated temperature for 5 days and stored at room temperature for 5 hours. Fig. 11 presents the shape of the part before and after annealing: darker specimen represents before annealing and brighter one represents after annealing. As mentioned before, the annealing temperature was 90°C compared with the transition temperature of 165°C (Courtney, 1999). The reference length is measured from the scanned geometry to identify the effect of annealing on dimensional change of the part.

4.4. Measurement of residual stresses

Residual stresses are measured by the incremental hole drilling method and compared with the predicted results as shown in Figs. 12 and 13. Residual stress distribution

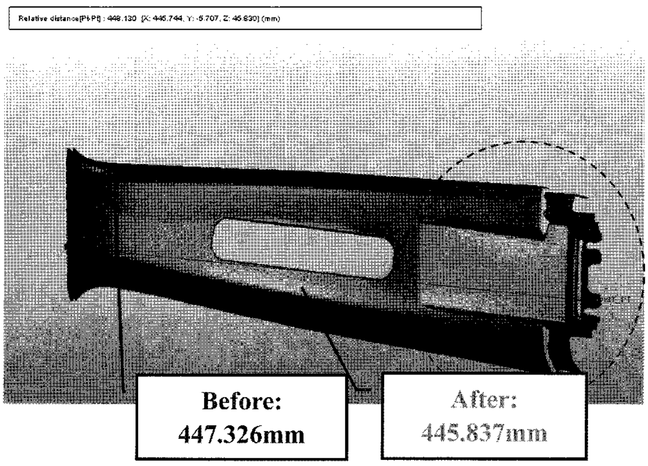

Fig. 11. Geometry of the part measured by the 3D Scanner before and after annealing.

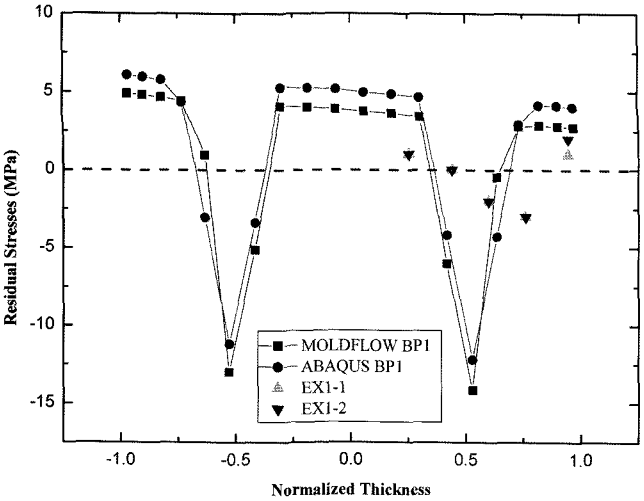

Fig. 12. Comparison of residual stresses predicted by numerical simulation with experimental results obtained at position 1.

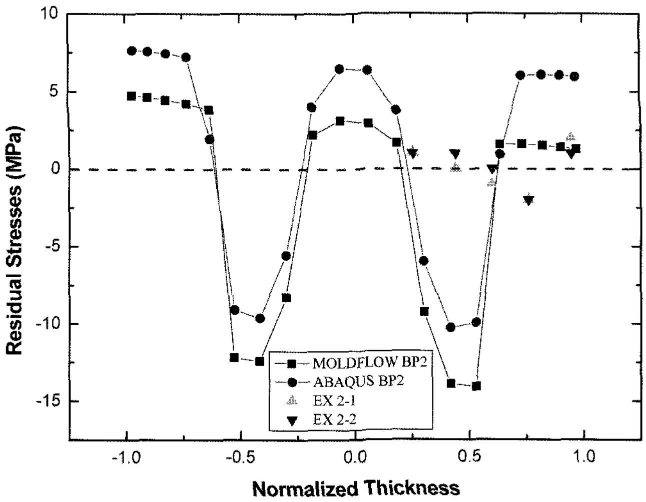

Fig. 13. Comparison of residual stresses predicted by numerical simulation with experimental results obtained at position 2.

shows the same trend at the two different points: tension, compression, and tension from the surface to the center of the specimen. There is discrepancy between measured and predicted values. It is believed that the discrepancy is caused by slipping of polymer molecules at the mold surface, viscoelastic stress relaxation during cooling, stress relaxation after ejection from the mold, stress relaxation during destructive measurements, and simulation errors. In the case of the hole drilling method, forces are applied to the specimen locally and additional strain can be generated due to contact between the milling cutter and the specimen. For more reliable numerical simulation and measurement results, slip conditions on the mold surface must be considered in the numerical simulation and viscoelastic stress relaxation must be minimized before and during measurement.

4.5. Comparison of the reference length

A reference length was selected to compare the dimension of the part before and after annealing with the cavity dimension. Prediction of the geometry at ejection, before, and after annealing will contribute to design of the part and cavity geometry prior to production of the mold. As shown in Table 5, the reference length of the ejected part predicted by the molding simulation is 451.690 mm compared with the cavity length of 455.337 mm. The length of the spec-

Table 5. Comparison of the reference length between two points of the part predicted by numerical simulation and obtained by measurements (the measured length is displayed as the arrow in Figs. 9 and 10)

Measurement / Prediction		Reference Length
Mold cavity geometry designed by CATIA		455.337 mm
Prediction by elastic stress analysis at ejection		451.690 mm (−0.80%)
Viscoelastic stress analysis of the part before annealing after stored at 25°C for 5 days		
Prediction by viscoelastic stress analysis before annealing		447.370 mm (−1.75%)
Measurement before annealing	by 3D scanner	447.326 mm (−1.76%)
	by using a string	448 mm
Viscoelastic stress analysis of the part after annealing at 90°C for 5 days		
Prediction by viscoelastic stress analysis after annealing and cooling		445.519 mm (-2.13%)
Measurement after annealing and cooling	by 3D scanner	445.837 mm (−2.01%)
	by using a string	446 mm

imen measured before annealing is 447.326 mm and in good agreement with the length (447.376 mm) predicted by the viscoelastic analysis when the specimen is stored at 25°C for 5 days. The reference length was measured by the 3D scanner and was verified with the measured length by using a string. Thermo-viscoelastic stress analysis was performed for annealing and the reference length was predicted as 445.519 mm after annealing and cooling. The length of the annealed specimen is measured to be 445.837 mm. The predicted length is in excellent agreement with the measured value considering that a complete and time consuming analysis of the part is performed from mold filling simulation to thermo-viscoelastic stress analysis. It is shown that the molded part produced at processing conditions employed in this study will experience considerable shrinkage upon ejection and further substantial shrinkage if it is used for a long time. Viscoelastic deformation of a polymeric part which is exposed to cyclic temperature loading can be evaluated by applying the simulation schemes used in this study.

5. Conclusions

Residual stresses in a molded polymeric part were predicted by numerical simulation and the deflection of the part was calculated right after ejection from the mold by assuming an isotropic elastic solid. Residual stress distribution in the ejected part was measured by the incremental hole drilling method and compared with the predicted results. Thermal stress analysis was carried out to predict creep deformation and residual stress distribution after annealing of the part by considering isotropic viscoelastic properties of the polymeric material. Geometry of the annealed part was measured by using a three dimensional scanner and compared with the predicted geometry of the part. A complete analysis of an injection molded part was performed from mold filling simulation to thermo-viscoelastic stress analysis and it can be utilized for design of plastic parts, injection molds, processing conditions, and long-term performance of the part. The viscoelastic stress analysis can be applied to the prediction of thermo-viscoelastic deformation of the injection molded polymeric parts when they are used in real world.

Acknowledgements

This study was financially supported by the Hyundai-Kia Motors and the Korea Science and Engineering Foundation through the Applied Rheology Center (ARC) at Korea University.

References

Bushko, W. C. and V. K. Stokes, 1995, Solidification of thermo-viscoelastic melts. part II: effects of processing conditions on shrinkage and residual stresses, *Polym. Eng. Sci.*, **35**, 365-383.

Bushko, W. C. and V. K. Stokes, 1996, Solidification of thermo-viscoelastic melts. part III: effects of mold surface temperature differences on warpage and residual stress, *Polym. Eng. Sci.*, **36**, 322-335.

Chiang, H. H., K. Himasekhar, N. Santhanam and K. K. Wang, 1993, Integrated simulation of fluid flow and heat transfer in injection molding for the prediction of shrinkage and warpage, *J. of Engineering Materials and Technology*, **113**, 37-47.

Courtney, T. H.., 1999, *Mechanical behavior of materials*, McGraw-Hill, International Editions.

Jansen, K. M. B., D. J. Van Dijk and M.. H.. Husselman, 1998, Effect of processing conditions on shrinkage in injection molding, *Polym. Eng. Sci.*, **38**, 838-846.

Jung, J. H., S. W. Lee and J. R. Youn, 1999, Characterization of deformation in injection molded parts after packing and cooling, *Macromolecular Symposia*, **148**, 263-283.

Kim, S. K., S. W. Lee and J. R. Youn, 2002, Measurement of residual stresses in injection molded short fiber composites considering anisotropy and modulus variation, *Korea-Aust. Rheol. J.* **14**, 107-114.

Manzione, L. T., 1987, *Application of computer aided engineering in injection molding*, Hanser Publishers, Munich.

Mlekusch, B., 2001, Calculation of residual stress development in injection molding using a nonlinear viscoelastic model, *Mechanics of Time-Dependent Materials*, **5**, 101-118.

Santhanam, N., H. H. Chiang, K. Himasekhar, P. Tuschak and K. K. Wang, 1991/1992, Postmolding and load-induced deformation of plastic parts in the injection molding process, *Advances in Polymer Technology*, **11**(2), 77-89.

Sweeney, J., T. L. D. Collins, P. D. Coates and R.A. Duckett, 1999, High-temperature large strain viscoelastic behavior of PP modeled using an inhomogeneously strained network, *J. Appl. Polym. Sci.*, **72**, 563-575.

Treuting, R.G. and W. T. Read, 1951, A mechanical determination of biaxial residual stress in sheet materials, *J. Appl. Phys.*, **22**, 130-134.

Turnbull, A., A. S. Maxwell and S. Pillai, 1999, Residual stress in polymers - evaluation of measurement techniques, *J. of Materials Science*, **34**, 451-459.

Youn, J. R., C. Kim, S. H. Kim and H. Oh, 2005, Residual stress in injection molded polystyrene parts, *Theories and Applications of Rheology, Proceedings of the Fall Meeting of the Korean Society of Rheology*, **9**(2), 15-18, Seoul National University.

Zhang, X., X. Cheng and K. A. Stelson, 2002, Approximate model of thermal residual stress in an injection molded part, *J. of Thermal Stresses*, **25**, 523-538.

Zoetelief, W. F., L. F. Douven and A. J. Ingenhousz, 1996, Residual thermal stresses in injection molded products, *Polym. Eng. and Sci.*, **36**, 1886-1896.