Residual Stress and Viscoelastic Deformation of Film Insert Molded Parts and Numerical Simulation for Film Insert Molding

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ABSTRACT

Simple tensile specimens and complex automotive parts were prepared by film insert molding (FIM). Residual stress and thermoviscoelastic deformation of the film insert molded specimens were investigated and processing of the specimens has been modelled numerically by using three dimensional flow and stress analyses.

INTRODUCTION

Polymeric materials have been used in automotive industry and the total amount has been increased significantly. Since they have low density and excellent mechanical properties, polymers are used as raw materials for automotive parts to improve the fuel economy without sacrificing safety. For last decades, lighter and tougher automotive interior parts have been produced by the automotive industry. Because emotional design concept requires automotive parts with fine details, some automotive interior products are manufactured by FIM.

FIM is a new injection molding method in which molten polymer is filled into the cavity after a film is attached to one side of the mold walls. The inserted film is preformed and attached to the cavity wall for decoration of the part instead of traditional screen printing or painting. Surface quality of the injection molded products can be improved by the decorated film. Moreover, adhesion between the film and the substrate may be enhanced because the injected hot molten resin can re-melt the film partially.[1] FIM is preferred to other surface decoration methods because it is a one-step process without extra post-processing that will increase the production cost. However, extreme warpage and non-uniform shrinkage can be generated in film insert molded parts due to an asymmetric residual stress distribution. Heat transfer perpendicular to the cavity wall can be retarded because the film is attached on one side of the cavity wall and two different polymers are used as the film and substrate.[2, 3]

Simple tensile specimens and automotive interior parts were prepared by FIM in order to investigate warpage of the specimens and were annealed to evaluate the thermoviscoelastic deformation. Three dimensional flow and stress analyses were performed to predict residual stresses in the specimens and to evaluate long-term viscoelastic deformation of the specimens by using time-temperature superposition principle. In the case of simple tensile specimen, it was observed that the film insert molded specimen was warped in the opposite direction after annealing. The peculiar observation, namely, 'warpage reversal phenomenon (WRP)' was also investigated.

EXPERIMENTAL

Materials

The film used for FIM has a laminated structure that consists of acrylonitrile -butadiene-styrene (ABS) substrate and polymethylmetacrylate (PMMA) film. Thickness of the PMMA layer was 0.05 mm and that of the ABS layer was 0.45 mm when supplied by the manufacturer (Nissha printing Co., Japan). It is expected that biaxial molecular orientation and residual stresses were developed in the film during manufacturing process. The polymeric resin used for injection molding was a blend (STAROY HP-1000X, Cheil industries, Korea) of polycarbonate (PC) and ABS and had the MFR of 27.0 g/10 min at 250℃ under the load of 10 kg according to ASTM D 128.

Characterization of materials

Dimensions of the received, thermoformed and annealed film treated at 80℃ were measured. Linear thermal expansion coefficient, α, of the film was determined by the following equation.

$$\alpha = \frac{\Delta l}{l_0 \Delta T} \quad (1)$$

where Δl is deformed length, l_0 is initial length, and ΔT is temperature difference. For modeling of viscoelastic properties of materials, relaxation moduli of the film, and substrate were measured by using the dynamic mechanical analysis (DMA 2980, TA instrument, USA). To obtain rheological property of the substrate at high shear strain rate region, a capillary rheometer (Rheograph 6000, Göttfert, Germany) equipped with a single bore die whose diameter is 1 mm was used in the shear strain rate region from 100 s^{-1} to 2000 s^{-1} at 250℃ and 260℃, respectively.

Film insert molding

The received film was preformed to fit the mold cavity. The film preformed to the tensile specimen was annealed at 80℃ for 20 days in order to minimize the effects of thermal shrinkage and residual stresses on the warpage of film insert molded parts. For the automotive parts, the film was prepared by using thermoforming at 150℃ because of complicate shape of the automotive part. The PC/ABS resin was dried at 80°C in a convection oven for 4 hours before injection molding to minimize the effect of moisture. The films were attached to one side of the mold wall before injection of the resin. The polymer resin was injected into the cavity by using an injection molding machine (Engel, Germany). After ejection, the molded specimens and parts were annealed in a convection oven at 80℃ and for various time periods of 10, 20, 30 minutes, 2 hours and 5 days in order to evaluate viscoelastic deformation of the tensile specimens and automotive parts, respectively. Two abbreviations were used for the automotive interior pars in this study, i.e., FIM-E and FIM-A represent film insert molded automotive part after ejection and after annealing, respectively. The warpage of the tensile specimens and the automotive parts was measured before and after annealing by scanning the specimens and parts with a scanner (Hewlett-Packard, U.S.A.) and a 3D scanner (3D NEXTUS, U.S.A.), respectively.

Measurement of residual stresses

The hole-drilling method is applicable to an object with a complex geometry and have been employed to evaluate residual stresses in complex automotive interior parts.[4] The hole-drilling method is a semi-destructive residual stress measurement technique which was first proposed by Mathar.[4] When a hole is drilled and the material is removed, a new stress equilibrium is established around the hole by the stress relaxation. Localized stress

relaxation is caused by deformation around the hole as soon as the stressed material is removal. Generation of the strain caused by the deformation can be measured by using a specially designed strain gage, rosette. The procedure is relatively simple and has been standardized as depicted in the ASTM Standard Procedure E 837. Details for the measurement were followed as the reference.[4]

NUMERICAL SIMULATION

Flow analysis

The governing equations for the flow analysis in the mold cavity are the conservation of mass, conservation of momentum, and conservation of energy equations[5] as shown below.

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot v) = 0 \tag{2}$$

$$\rho \frac{Dv}{Dt} = -\nabla P + \nabla \cdot \tau + \rho g \tag{3}$$

$$\rho C_p \frac{DT}{Dt} = \beta T \frac{DP}{Dt} + \eta \dot{\gamma}^2 + \nabla \cdot q \tag{4}$$

where ρ is density, v is velocity vector, P is pressure, τ is viscous stress tensor, g is gravity/body-force vector, C_p is specific heat at constant pressure, β is expansivity, η is generalized Newtonian viscosity, q is heat flux, and $\dot{\gamma}$ is the shear rate. The flow front in the cavity is tracked using a fluid concentration equation, which can be expressed as:

$$\frac{DF}{Dt} = 0 \tag{5}$$

where F is fluid concentration. Since inserts are treated as a rigid body with no deformation or displacement, mass and momentum conservation in inserts are ignored. However, heat exchange between the inserted film and mold or polymer melt needs to be evaluated. Hence energy balance in the process must be taken into account. The only equation relevant to the insert is the conservation of energy. Using the assumption that the insert is a rigid body, the conservation of energy equation for the cavity given in equation 5 can be simplified for inserts and is represented as,[5]

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot q \tag{6}$$

Three dimensional flow analysis was performed by assuming that rheological behavior of the polymeric melt satisfies the modified Cross model with the following Williams-Landel-Ferry (WLF) equation.[5, 6]

$$\eta = \frac{\eta_0}{1 + \left(\eta_0 \dot{\gamma} / \tau^* \right)^{(1-n)}}, \log \frac{\eta_0 \theta^* \rho^*}{\eta^* \theta \rho} = \frac{-C_1 (\theta - \theta^*)}{C_2 + (\theta - \theta^*)} \tag{7}$$

where η is viscosity, η_0 is zero shear rate viscosity, $\dot{\gamma}$ is shear rate, τ^* is shear stress at the transition between Newtonian and power law behavior, η^* is viscosity at reference temperature, ρ is density, ρ^* is density at reference temperature, θ is temperature and θ^* is reference temperature. Typically θ^* is chosen as the glass transition and C_1=17.44 and C_2=51.6 K for many polymers. Heat conduction through the mold polymer interface, convective heat transfer by the cooling liquid, and viscous heating during both filling and post-filling stages should be considered in the thermal analysis. The modified Tait equation is employed as the PVT relationship. The thermal and flow fields are calculated with the control-volume approach to handle the melt-front advancement by utilizing a hybrid FEM/ FDM scheme. An implicit numerical scheme

is employed to solve the discretized energy equation.[7]

Residual stresses were calculated by using the hybrid model.[5]

$$\sigma_e^{//} = b_1\sigma_P + b_2\tau + b_3,\ \sigma_e^{\perp} = b_4\sigma_P + b_5\tau + b_6 \quad (8)$$

where $\sigma_e^{//}$ and $\sigma_e^{\perp}$ are the corrected principal stresses in the directions parallel and transverse to flow respectively, σ_P is the predicted residual stress, $b_i's$ (where $i = 1,...,6$) are constants to be determined and τ is a measure of orientation in the material.[5] The laminated film was treated as a homogeneous film by neglecting the PMMA layer because the PMMA layer is relatively thin. Properties of ABS (techno ABS 545, techno polymer) were employed as properties of the film and those of the polymer resin (Lupoy HR5007AB, LG Chemical) whose rheological property was the same as that of the substrate resin as shown in Fig. 1 were selected as properties of the injected resin for flow analysis. Molding conditions for the numerical predictions are the same as the experimental conditions. At the end of the flow analysis, the output data including in-mold stress condition of the part were exported to the stress analysis program and used as the initial condition for stress analysis of the film insert molded part.

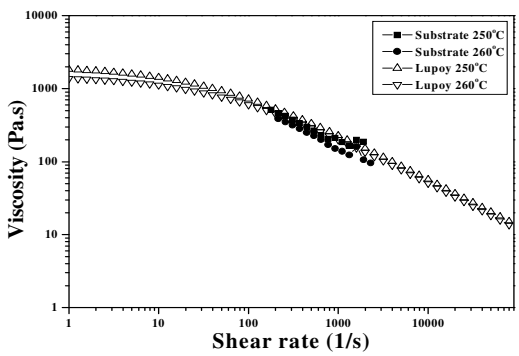

Figure 1. Viscosity variation of the substrate resin and Lupoy HR5007AB with respect to shear strain rate at 250 □ and 260 □.

Stress analysis

Residual stress distribution and deformation of the ejected film insert molded parts were predicted by applying elastic properties of the solid polymer. However, it is well known that viscoelastic properties must be applied to predict time-dependent deformation of polymeric parts which are exposed to various environmental conditions. For prediction of long term viscoelastic behavior of the polymeric part, it was assumed that the viscoelastic polymer material was isotropic and the temperature effect on material behavior was explained by the thermo-rheological simplification.

Constitutive equation of the generalized Kelvin model was selected as the constitutive equation for the linear thermoviscoelastic material. The linear thermoviscoelastic constitutive equation is represented by hereditary integrals and the effect of temperature is considered by the following equation.[8, 9]

$$\tau(t) = G_0(\theta)\left(\gamma - \int_0^t \dot{g}_R(\xi(s))\gamma(t-s)ds\right) \quad (9)$$

where the instantaneous shear modulus G_0 is temperature dependent and γ is the shear strain.

$$\dot{g}_R(\xi) = dg_R / d\xi,\ g_R(t) = G_R / G_0 \quad (10)$$

where $G_R(t)$ is the time dependent shear relaxation modulus that characterizes the material's response and $g_R(t)$ is dimensionless relaxation modulus. ξ (t) is the reduced time defined by the following equation.

$$\xi(t) = \int_0^t \frac{ds}{A(\theta(s))} \quad (11)$$

where A(θ(t)) is a shift function at time t. Temperature dependence of the reduced time is usually referred to as the thermo -rheologically simple (TRS) temperature dependence. The shift function is often approximated by the WLF form.

$$\log(A) = \log\left(\frac{t}{t_0}\right) = \frac{-C_1'\left(\theta - \theta^*\right)}{C_2' + \left(\theta - \theta^*\right)} \qquad (12)$$

where θ^* is the reference temperature at which the relaxation data are provided and C_1' and C_2' are calibration constants obtained at the temperature.

$$C_1' = \frac{C_1^g}{1 + \left(\theta^* - \theta_g\right)/C_2^g},\ C_2' = C_2^g + \theta^* - \theta_g \quad (13)$$

where C_1^g and C_2^g are universal constants, which are 17.4 and 51.6 K, respectively.

RESULTS AND DISCUSSION

Tensile specimen

Warpage of VITS and FITS specimens before and after annealing are shown in Fig. 2 (a) to (d). The molded VITS specimens had little warpage before or after annealing as shown in Fig. 2 (a) and (b) because the specimens were molded without the film while the same temperature was maintained at both core and cavity sides of the cavity. On the other hand, FITS specimen in Fig. 2 (c) was bent after ejection such that the film side was protruded because shrinkage of the solid film side was lower than that of the other side where polymer melt had been solidified by the cold surface of the mold. Fig. 2 (d) showed that FITS specimen annealed at 80℃ for 2 hours was bent such that the opposite side of the film was protruded. This interesting behavior is named 'warpage reversal phenomenon (WRP)'.

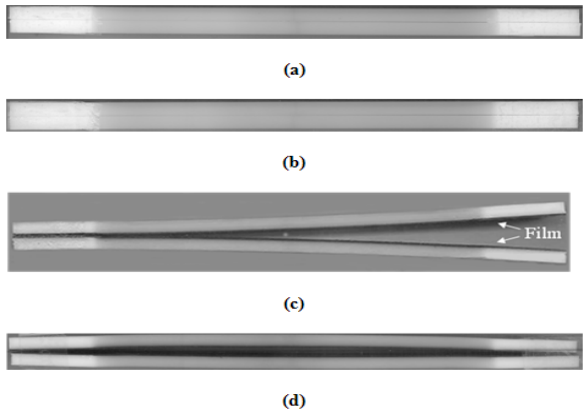

Figure 2. Warpage of molded specimens without the film (VITS) and with the inserted film (FITS): (a) VITS before annealing, (b) VITS annealed at 80□ for 2 hours, (c) FITS before annealing, and (d) FITS annealed at 80□ for 2 hours.

The residual stress distribution of the FITS specimen after ejection and that of the FITS specimen annealed at 80℃ for 12 hours was shown in Fig. 3. Compressive residual stresses were confirmed in the film region of the ejected FITS specimen due to the solidification of injected hot molten resin. Residual stress distribution in the film region of the FITS specimen annealed at 80℃ for 12 hours was varied as tension and compression from the PMMA layer to the ABS layer. As shown in Fig. 4, thermal shrinkage of the film was observed in the early stage of annealing. Since the shrinkage of the film would be larger than that of the other part during annealing, it is expected that the thermal shrinkage of the film will impose larger effect on deformation of the specimen during annealing than the relaxation of residual stresses. Therefore, WRP occurs due to thermal shrinkage of the film and relaxation of residual stresses in the entire part.

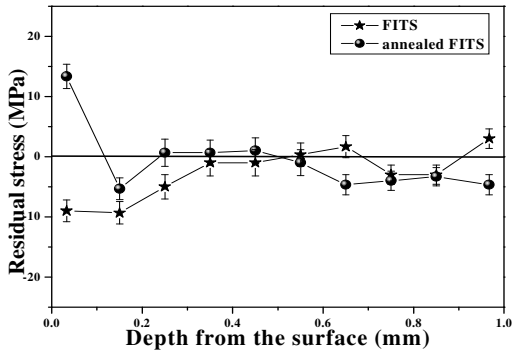

Figure 3. Residual stress distribution with respect to the depth from the surface of the FITS after ejection and after annealing at 80□ for 12 hours.

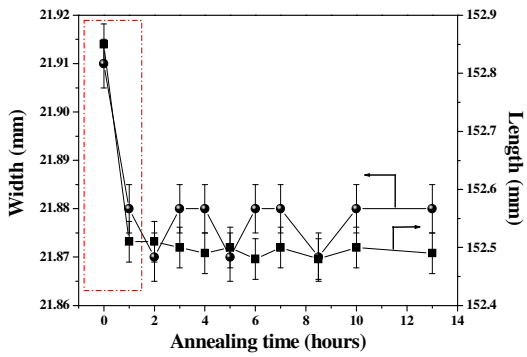

Figure 4. Variation in the dimension of the film annealed at 80□ with respect to annealing time.

Warpage of FITS and AFITS (with pre-annealed film) specimens after both ejection and annealing is shown in Fig. 5 for various annealing time. FITS and AFITS specimens were bent after ejection such that the film side was protruded. It was also observed in Fig. 5 (a) that the warpage of AFITS with the annealed film which had been shrunken and relaxed sufficiently by the pre-annealing was larger than that of FITS after ejection. This behavior can be explained by the fact that the unannealed film inserted into the FITS specimen was shrunken thermally by the hot injected resin during filling stage. As the two tensile specimens were annealed at 80℃, the gap between the two FITS specimens shown in the Fig. was decreased with annealing time and the WRP occurred for annealing time between 10 and 20 minutes. After the WRP, the reversed gap between the two specimens was increased further as shown in Fig. (d). However, on the contrary to the case of FITS, the gap between the two AFITS specimens was not decreased after annealing and the WRP was not observed. Fig. 6 shows the predicted warpage of FITS and AFITS specimens and it was almost similar to the experimental results.

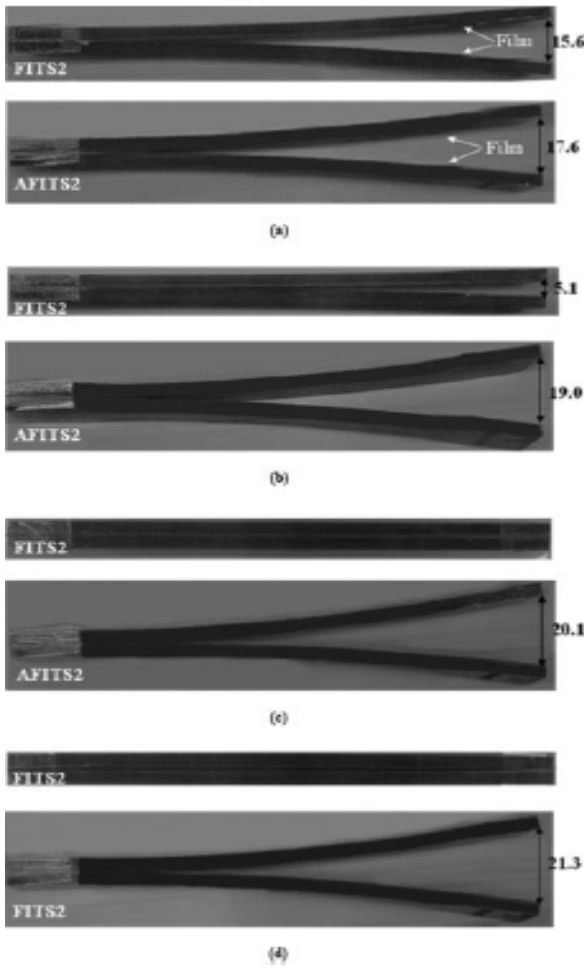

Figure 5. Warpage of FITS and AFITS specimens observed after ejection and annealing at 80□ with increasing annealing time: (a) after ejection, (b) for 10 min, (c) for 20 min, and (d) for 30 min.

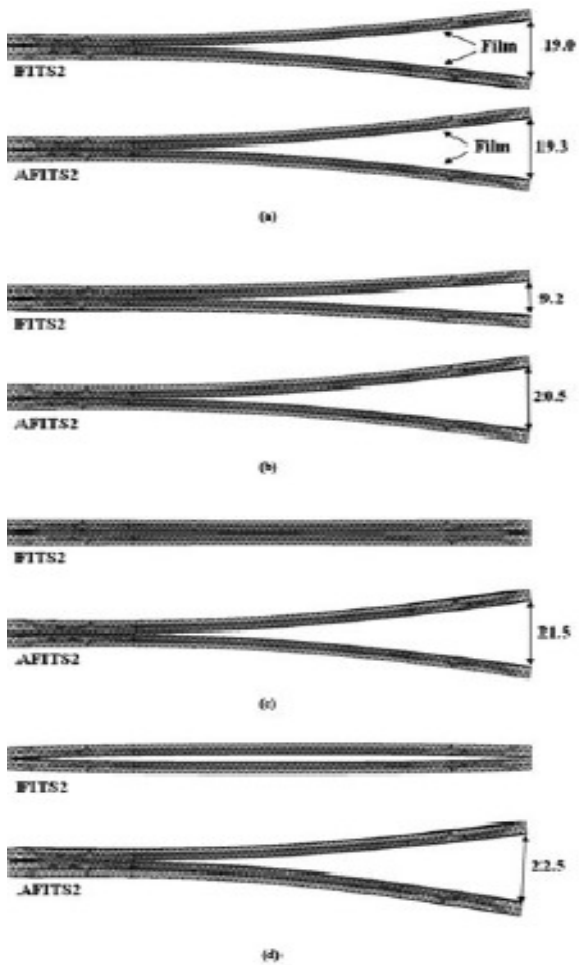

Figure 6. Predicted warpage of FITS and AFITS specimens numerically molded after ejection and annealing at 80□ with increasing annealing time: (a) after ejection, (b) for 10 min, (c) for 20 min, and (d) for 30 min.

Automotive Interior Part

Fig. 7 shows both measured and predicted residual stress distributions of the ejected automotive interior parts and the annealed parts treated at 80°C for 20 days. Residual stress distribution of the unannealed part was varied as tension, compression, and tension from the PMMA layer to the upper PC/ABS layer and the residual stress distribution of the annealed part was varied as tension and compression from the surface. Large tensile stresses were observed at the surface of the annealed part due to the relaxation of remained biaxial molecular orientation in the PMMA layer of the thermoformed film. Residual stresses in the film and substrate had been relaxed during annealing and the measured residual stress distribution was in good agreement with the predicted results.

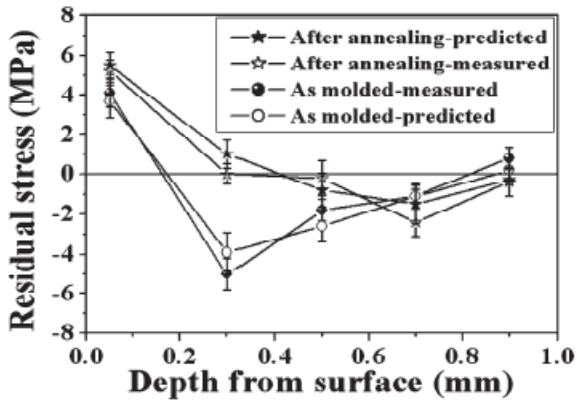

Figure 7. Residual stress distribution of the molded automotive part and the annealed part treated at 80□ for 20 days.

Deformed geometry of the ejected part can be predicted by considering residual stresses developed in the part and viscoelastic stress analysis can be carried out by applying the deformed geometry and time-temperature superposition principle. Deformed geometry of the molded part after ejection (FIM-E) and that of the part annealed at 80°C for 5 days (FIM-A) are shown in Fig. 8 (a) and (b), respectively. The FIM-E was deformed such that the surface at the film side was protruded because shrinkage of the solid film was lower than that of the other side where polymer melt had been solidified by the cold surface of the mold. However, shape of the FIM-A was bent in the opposite direction such that the film surface was intruded. In Fig. 8 (c), difference in the longitudinal length of the part between FIM-E and FIM-A samples is displayed in one figure to identify annealing effect and the difference was 7.228 mm. Deformed geometry of the FIM-E and FIM-A specimens was calculated

numerically as shown in Fig. 9 (a) and (b), respectively. Although the automotive interior part is large and has a complex shape, the numerically predicted shape showed almost the same geometry as the experimental one.

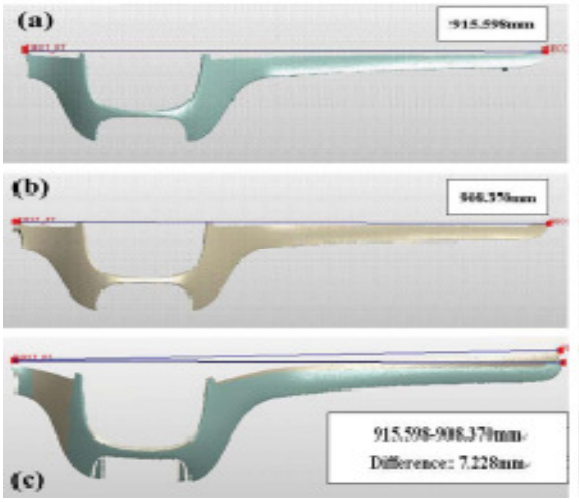

Figure 8. Deformed geometry of (a) the FIM-E part after ejection, (b) the FIM-A part annealed at 80□ for 5 days, and (c) longitudinal length difference between FIM-E and FIM-A specimens.

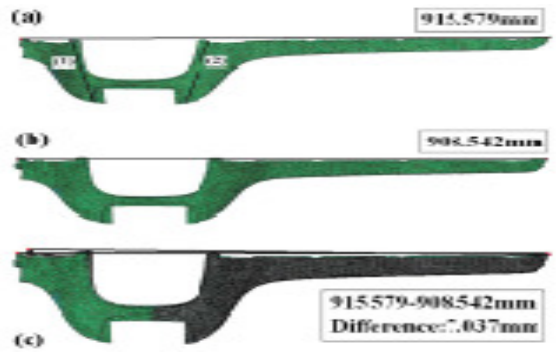

Figure 9. Numerically predicted geometry of (a) the FIM-E part after ejection, (b) the FIM-A part annealed at 80℃ for 5 days, and (c) longitudinal length difference between FIM-E and FIM-A specimens.

CONCLUSION

Simple tensile specimens and complex automotive interior parts were prepared by the FIM to investigate development of residual stresses and effects of viscoelastic deformation on warpage of the parts. Three dimensional flow and stress analyses were performed for the parts to predict residual stresses, viscoelastic deformation, and warpage. Both experimental and numerical results showed that the film insert molded tensile specimen with unannealed film was bent such that the film side was protruded after ejection and it was gradually bent in the opposite direction during annealing. The WRP is caused by the combined effect of thermal shrinkage of the inserted film and relaxation of residual stresses in the specimen during annealing. Also, thermal shrinkage of the inserted film and relaxation of the residual stresses imposed significant effect on the viscoelastic deformation of the automotive interior part during annealing. Although WRP is complicate, and the film insert molded part is large and has complex geometry, residual stresses, viscoelastic deformation, and warpage of the part were predicted and the numerical results showed good agreement with experimental results.

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