

Prediction of parison formation using process data in extrusion blow molding

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Abstract. In the extrusion process for plastic fuel tanks, laminated molten polymeric material is extruded and is molded into a hollow cylindrical shape called a parison. Accurately predicting the shape of a parison made from material of inhomogeneous viscoelasticity is a challenging issue. In this study, a numerical simulation based on process data is developed that is capable of predicting the parison shape during production. The process data (extrudate swell, drawdown, and temperature distribution) are collected from the production process and is utilized to develop a simulation model. Comparison of parison shapes extruded by production equipment against numerical simulations verifies for prediction of the distributions of the diameter and thickness of the parison shape to within $\pm 20\%$ of measured values, even under conditions different from those under which the data is obtained except for the data around large and fast stroke changes. The results show the possibility to predict parison shapes close to the one in production without directly solving the complex flow of inhomogeneous viscoelastic materials.

Keywords: Blow molding / parison formation / finite-element method / process simulation

1 Introduction

Plastic fuel tanks have been adopted for use in automobiles for their low weight and the high degree of freedom of product form they allow. Plastic fuel tanks are produced in two stages: an extrusion process by which a hollow cylinder of molten polymeric material called a parison is extruded, and a blow molding process by which the parison is expanded inside a mold to give it the shape of the final product.

Plastic fuel tanks have to guarantee quality not only with respect to weight, but also with respect to rigidity, impact resistance, and flame resistance, resulting in the setting of strict standard values for thickness. Guaranteeing these standard values requires accurately predicting and controlling the length, diameter distribution, and thickness distribution of the parison shape formed in the extrusion process. Accordingly, there is a great need for a technology that enables prediction of the parison shape in the extrusion process.

To predict the parison shape (length, diameter distribution, and thickness distribution), numerical simulations have been employed. However, a simulation model capable of predicting parison shapes based on laboratory experimental equipment may yield results different from those for production equipment when applied to scaled-up medium and/or large parisons. Reasons for this may include variations in the molten polymers used in different pieces of production equipment and differences in scale between experimental and production equipment. Accordingly, even with extrusion conditions considered in advance, stable production is frequently not possible, and quality is often obtained through trial-and-error determination of extrusion conditions at the production site.

To predict parison shapes for specific production equipment, the following problems should be overcome. In the extrusion process, there occurs expansion of the polymeric material due to the viscoelasticity of the material at the end of the die during extrusion (extrudate swell) and elongation due to the material's self-weight (drawdown). As the parison is formed, the resin is cooled by surrounding air, while drawdown is affected by temperature change. Moreover, a plastic fuel tank has a laminated structure in which materials vary in the direction of thickness. An accurate rheological model for such inhomogeneous viscoelastic materials is practically impossible to describe,

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making prediction of parison shapes during production difficult. Accordingly, enabling the use of equipment-specific process data in the prediction model is necessary for overcoming problems in simulation-based prediction of parison shapes for plastic fuel tanks. Toward this end, an overview of previous research on simulation models for the parison molding process is provided.

Several prediction methods have been proposed for handling the extrudate swell and the drawdown. One type of method handles the extrudate swell and the drawdown separately. Ryan and Dutta [1] quantified swell from data in basic extrusion experiments, treated drawdown as a deformation due to unsteady uniaxial elongation, and superimposed these phenomena to simulate the parison molding process. Dealy and Orbey [2] developed a simple computational model for predicting parison shapes using data obtainable in the laboratory and reported that parison length can be predicted within an acceptable range. Diraddo and Garcia-Rejon [3] devised a non-contact method for measuring extrusion swell and drawdown in parison and reported that predicting thickness distribution based on the data is possible. Takimoto et al. [4] used an integral viscoelastic constitutive equation and calculated swell through steady viscoelastic flow analysis using a streamlined finite-element method and modeled drawdown as a uniaxial extension, and then superimposed the two to make predictions of the parison molding process. Early research has also shown that prediction of the parison molding process is possible using only modest computational resources.

Another prediction method involves numerically calculating viscoelastic flow up to the stage of parison molding, based on the flow inside the die. Terada et al. [5] reported that prediction can be achieved by calculating the flow inside the die using the finite-element method and calculating the parison molding process from the die outlet onward. Shinohara et al. [6] proposed a prediction method for the parison molding process that treats swell and drawdown in an integrated manner through differential viscoelastic constitutive equations and reported that the result agrees well with experimental values.

Under actual production conditions, the die gap changes during extrusion. When handling factors such as the effects of continuously changing flow in the die and the free surface of the material, the computational load of prediction calculations increases. However, computational resources are improving and continuous simulation through the inflation process following the parison molding process is now possible in some simple situations. Tanifuji et al. [7] reported that prediction accuracy can be improved by modeling the unsteady, non-isothermal flow with a free surface using the Lagrangian–Eulerian (LE) finite-element method and conducting an overall numerical simulation of parison molding and the inflation process. Laroche et al. [8] reported that, when using an integral viscoelastic constitutive equation to model drawdown and an empirical formula to model swell, the simulation results for the whole process are a close match for the experimental results. Recent years have seen further development of computational environments enabling practical prediction, including integral viscoelastic constitutive equations (K-BKZ models)

and calculations using ALE elements. Yousefi et al. [9] reported an overall simulation from parison formation to inflation using Blowparison[®], a finite-element method software, and compare the simulation results with experimental ones. Yousefi et al. [10] also reported the cases of high-density polyethylene materials of differing grades from Yousefi et al. [9], suggesting the positive results in a simulation of the parison molding process.

The above numerical calculations involve studies of homogeneous materials. By contrast, the material used in automobile plastic fuel tanks is laminate of inhomogeneous materials and thus involves multi-layer flow, making prediction by numerical simulation difficult. Even when assuming an approximate homogeneous material property, identifying valid rheological parameters is extremely difficult. Using hypothetical parameters identified from experimental equipment can lead to the accumulation of errors in the diameter, thickness distribution, and parison length because of the swell, drawdown, and ever-changing molding conditions, which directly leads to thickness diverging significantly from required values. When standard values cannot be guaranteed at the production site, the extrusion conditions need to be reset during production, with operators performing fine adjustment of the extrusion cycle, stroke adjustment, *etc.* on the spot.

For these reasons, there remains considerable demand for a simulation model that allows prediction of parison shape (length, diameter, and thickness distribution) during on-site extrusion and that further allows confirmation of effects when adjustments are made. Thus, using extrusion conditions (extrusion weight, die core shape, stroke, and equipment temperature) and parison deformation data measured in production equipment (hereinafter referred to as “process data”), we examined a method that enables predictions of parison shape (length, diameter distribution, and thickness distribution) that are close to that of actual production.

2 Material and methods

2.1 parison deformation model

Using parison molding process data, a simulation model is constructed that enables examination of actual parison molding. In the production process for plastic fuel tanks, a fixed amount (weight) of material is extruded in a given cycle at a constant flow rate to form a parison. The required weight of the parison is 10–15 kg, depending on the product shape. The cycle is set to 60–120 s per unit. The extrusion flow rate is typically set to 300–700 kg/h, depending on the product and the equipment capacity.

In our simulation model, the deformation of the parison that occurs during the extrusion time t_{cycle} is considered for a parison of the required weight. To examine the deformation of the parison, the deformation of a small cylinder volume extruded in the time $\Delta t = t_{cycle}/N$ is modeled. Overall deformation of the parison is calculated by iterating the deformation of the consecutive small cylinder volumes over N steps. At the k th time step $t = k \Delta t$, k small cylinders ($n=1, \dots, k$) constitute the extruded parison. The unit time is set to $\Delta t = 1$ s. The extrusion

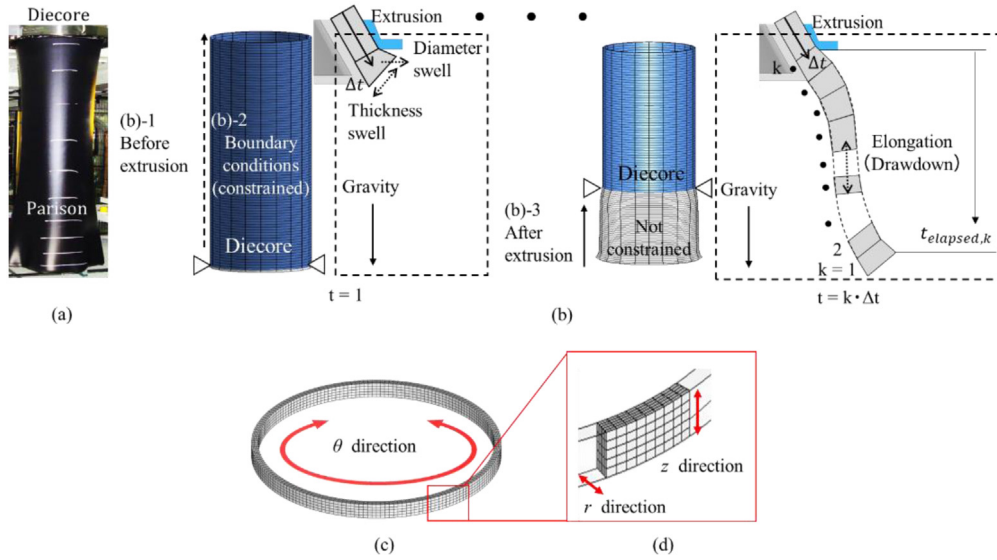


Fig. 1. Calculation model and mesh division for parison shape prediction: (a) entire extruded parison; (b) cylindrical calculation model for calculating the parison molding process; (b-1) state of the calculation model before extrusion; (b-2) constraints set in the model before extrusion, while in the model after extrusion, sequential calculations are performed with constraints released at each Δt ; (b-3) state of the calculation model after extrusion; (c) mesh division of the calculation model extruded during unit time Δt ; and (d) enlarged figure. Here, r is thickness direction and z is extrusion direction.

length during Δt is 15–30 mm. The cylindrical volume extruded during Δt is divided into five in the radial (r) direction and five in the extrusion (z) direction, and 180° in the circumferential (θ) direction, as shown in Figure 1. This division of elements is roughly the same as the model divisions used by Funatsu et al. [5].

Elongational strain ε_i in the i th direction ($i = r, \theta, z$) of each element is described by the Maxwell model with elongational modulus E dependent on temperature and elongational viscosity η dependent on temperature and elongation rate:

$$\varepsilon_i = \frac{\sigma_i}{E(T)} + \frac{\sigma_i}{\eta(T, \dot{\varepsilon})} \Delta t \quad (1)$$

In extrusion, the material is extruded above its melting point and crystallization temperature. The extruded molten polymers are normally assumed to be an incompressible fluid. In this study, the swell during extrusion is calculated by inputting the measured stress data. Therefore, it is a calculation model that can tolerate volume changes due to deformation. The reason for this is that it is difficult to determine accurate rheological parameters of the material, and it was necessary to propose a model that could simply calculate elongation deformation. Additionally, the effect of volumetric shrinkage due to crystallization is reduced above the melting point and crystallization temperature. Volumetric shrinkage is not considered in the proposed model.

Deformation is calculated by applying normal stress σ_i in three directions, following equation (1). Two stresses are considered: tensile stress σ_g in the vertical direction due to the self-weight of the parison, and stress σ_{swell} responsible for extrudate swell immediately after

extrusion:

$$\sigma_i^n = \sigma_{g,i}^n \delta_{iz} + \sigma_{swell,i}^n \delta_{nk} \quad (i = r, \theta, z, n = 1, \dots, k) \quad (2)$$

Swell stress is applied only to the single time step immediately after extrusion. Stress with respect to swell is estimated from experimentally measured swell data. Estimated swell stress is distributed inside the cylinder volume of Δt . Based on the velocity distribution inside the die channel, swell stress $\sigma_{swell,il}$ is added to the cylinder model:

$$\sigma_{swell,il} = E(T) \varepsilon_{swell,i} \frac{v_{max}^k}{v_l^k} \quad (i = r, \theta, z, l = 1, \dots, 5) \quad (3)$$

where v_l^k, v_{max}^k are defined as the flow velocity at die exit at the l th radial position and maximum flow velocity at the k th time step, respectively. Swell stress is not uniform in the direction of parison thickness. Accordingly, a weight based on extrusion flow distribution is included in equation (3) to calculate the distribution of the stress. This is because the flow field developed in the die channel vanishes at the wall if slippage near the wall is ignored and takes its maximum value at the center of the channel. Funatsu et al. [5] reported that the normal stress difference related to swell has its minimum at the point of maximum flow velocity and they confirmed an inversely proportional correlation to extrusion flow rate.

While the measurement of the extrusion flow distribution in production equipment is difficult, Soeda et al. [11] reported the agreement on the velocity distribution of polymer solutions in concentric double cylinders with analytic equation. In our study, estimation using an analytic equation for steady flow velocity in concentric

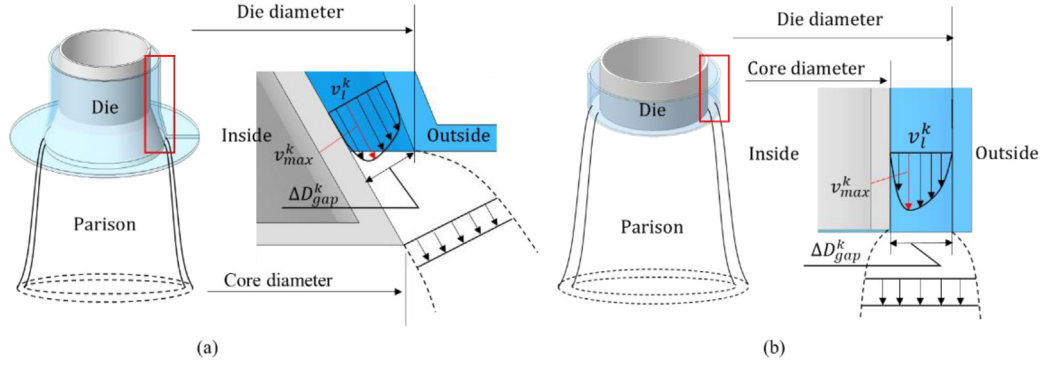


Fig. 2. Schematic diagrams of extrusion flow velocity distribution before extrusion: (a) in the die channel and (b) in the concentric double cylinder model. The extrusion flow distribution calculated from equation (4) is set as the velocity distribution v_l^k in the die.

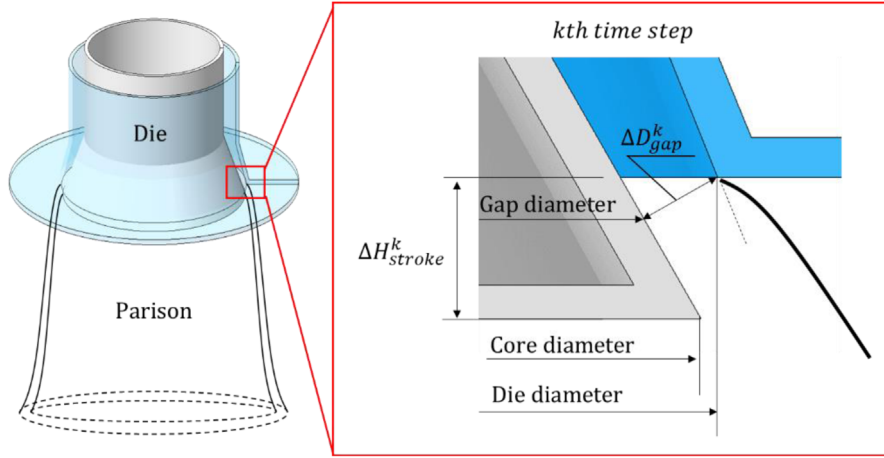


Fig. 3. Schematic diagram of the die gap ΔD_{gap}^k at k th time step.

double cylinders [12] is used as shown in Figure 2.

$$v_l^k = \frac{\Delta P R_{Die}^k}{4\mu L} \left[1 - \left(\frac{r_l^k}{R_{Die}^k} \right)^2 + \left(\frac{1 - \kappa^2}{\ln(1/\kappa)} \right) \ln \left(\frac{r_l^k}{R_{Die}^k} \right) \right] \quad (4)$$

$$r_l^k = R_{core} + \frac{2l-1}{10} \cdot \Delta D_{gap}^k (l = 1, \dots, 5) \quad (5)$$

where ΔP is the pressure difference between the die inlet and outlet, R is the die radius, μ is the viscosity, L is the channel length, and r_l is the discretized l th radial position in the channel. Here, $\kappa = R_{Core}/R_{Die}$ and expresses the ratio of core radius to die radius.

Swell data including the thickness swell and the diameter swell is measured as a function of average extrusion flow velocity v_{ave} . The average extrusion flow velocity v_{ave}^k at the k th time step is estimated as follows. Based on extrusion weight W per unit time, and mass density $\rho(T)$ at the extruded resin temperature, the extrusion volume ΔV per unit time is, according to

Equation (6):

$$\Delta V = \frac{W}{\rho(T)} \quad (6)$$

The cross-section S_{gap}^k at the die exit is calculated based on the distance between the die core surface to the apex of the outer wall, ΔD_{gap}^k and the circumference of the Die diameter and Gap diameter at the k th time step, as in the enlarged diagram in Figure 3. The average extrusion velocity $v_{ave}(k)$ is estimated from:

$$v_{ave}(k) = \frac{\Delta V}{S_{gap}^k} \quad (7)$$

The thickness swell $\varepsilon_{swell,r}^k$ is calculated from the experimentally measured thickness $t_{thickness}^k$ and ΔD_{gap}^k at the k th time step:

$$\varepsilon_{swell,r}^k = \frac{t_{thickness}^k}{\Delta D_{gap}^k} \quad (8)$$

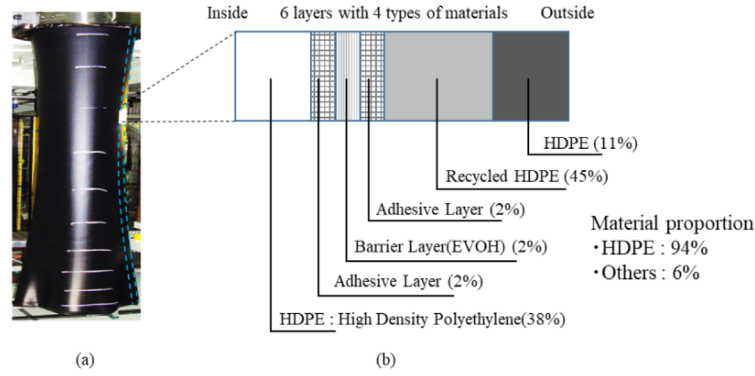


Fig. 4. The actual parison considered in this study: (a) the photo of whole extruded parison and (b) cross-sectional composition of the parison (six layers of four different materials).

The diameter swell $\varepsilon_{swell,\theta}^k$ is calculated from the experimentally measured parison diameter $D_{parison}^k$ and die diameter D_{die} at the k th time step:

$$\varepsilon_{swell,\theta}^k = \frac{D_{parison}^k}{D_{die}} \quad (9)$$

The vertical normal stress σ_{gz}^n of n th small cylinder ($n=1, \dots, k$) is derived from the self-weight of the parison:

$$\sigma_{gz}^n = \frac{\rho g(n-1)\Delta V \Delta t}{S_n} \quad (10)$$

where g is the gravitational acceleration, S_n is the cross-sectional area after extrusion at the n th small cylinder. The cross-sectional area S_n is calculated sequentially within the model. $E(T)$ and $\eta(T, \varepsilon)$ are estimated so as to reproduce experimental drawdown.

Next, to calculate the change in temperature of the parison, the temperature of the element is set to follow thermal conduction and heat transfer with air according to Fourier's law:

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \right) T \quad (11)$$

$$q_{out} = h(T_{resin} - T_{outair}) \text{ at the parison surface boundary} \quad (12)$$

where q_{out} is the heat flux from the surface of the parison to the surrounding air, λ is the thermal conductivity of the parison material, h is the heat transfer coefficient possibly considering natural convection of the surrounding air, T_{resin} is the temperature of the surface of the parison, and T_{outair} is the ambient temperature surrounding the parison [13]. LS-DYNA R8.1.1 software from the Livermore Software Technology Corporation (LSTC; currently Ansys, Inc.) was used for the calculation.

2.2 Materials of parison

The parison examined in this study is inhomogeneous, with a structure of multi-layer composite material (six layers of four different materials), as shown in Figure 4.

Table 1. Variable stroke extrusion conditions for verification. The stroke profiles are shown in Figure 5.

Item	Range of experiment
Die diameter, mm	Φ360
Flow rate, kg/h	536
Stroke, %	40–80 change
Die gap, mm	9.4–18.6
parison length, mm	1200–1500
Temperature, °C	210

As shown in Figure 4, the main material is HDPE (HR111 from Japan Polyethylene Corporation, Tokyo, Japan). In this study, the rheological parameters are corrected according to the elongation of the target inhomogeneous material from the process data, and the parison deformation model is calculated.

Therefore, the rheological parameters of HDPE were measured as initial parameters. That data was then modified to match the extrusion process data.

3 Results and discussion

3.1 Estimation of model parameters from extrusion experiment

To reproduce the deformation during parison molding in actual production equipment without explicitly considering the internal structure, the rheological parameters for the parison deformation model given in equations (1)–(12) are estimated based on the process data. For the elongational viscosity and modulus identified here, temperatures between 150 and 210 °C, as used in production, are considered.

During extrusion, the die gap (ΔD_{gap}^k) changes to control the thickness profile in the product. The amount of movement of the die core is expressed as a percentage based on the maximum open position of the die gap, which is called the stroke. In this study, the estimation of the model parameters are done from experimental process data under constant strokes (fixed die core position). Next, for the verification, the model predictions are compared with the

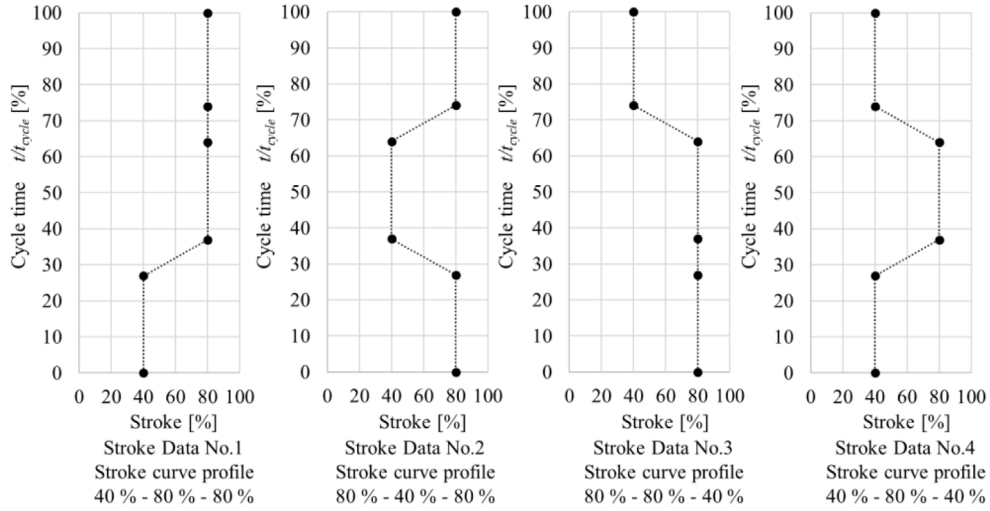


Fig. 5. Stroke profiles used in verification. Each graph depicts stroke for the relative extrusion time t/t_{cycle} .

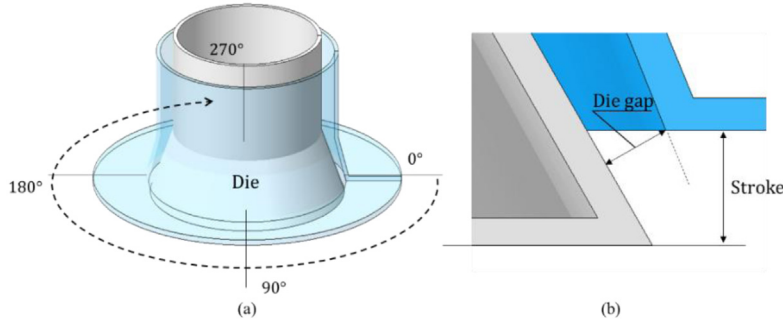


Fig. 6. Measurement of the die gap: (a) measurement positions and (b) the schematic diagram of the die gap and the stroke.

extrusion data under non-constant stroke profiles close to actual production conditions, as shown in Table 1 and Figure 5.

To calculate the cross section of the die exit from the stroke, the die gap as a function of stroke is measured using a taper gauge at positions of 0°, 90°, 180°, and 270° in the circumferential direction, as shown in Figure 6, and plotted in Figure 7.

To compare the prediction results with experimental ones, the extruded parison shape is measured. However, online measurement of the shape of a continuously extruded parison (total length, diameter distribution, and thickness distribution) is difficult to perform. Previous studies have measured the parison shape in various ways, as follows. Eggen and Sommerfeldt [14] applied points of ink to a parison and measured its shape using the distance between points in images captured by a camera. Swan et al. [15] proposed a method of measuring thickness from the reflection of irradiation by a non-contact laser. Huang and Li [16] reported measuring the shape of a parison by using continuous imaging combined with image processing technology. In the present study, the total length and diameter of the parison were measured from captured images and the thickness distribution was measured by cutting the parison and using a non-contact laser displacement meter.

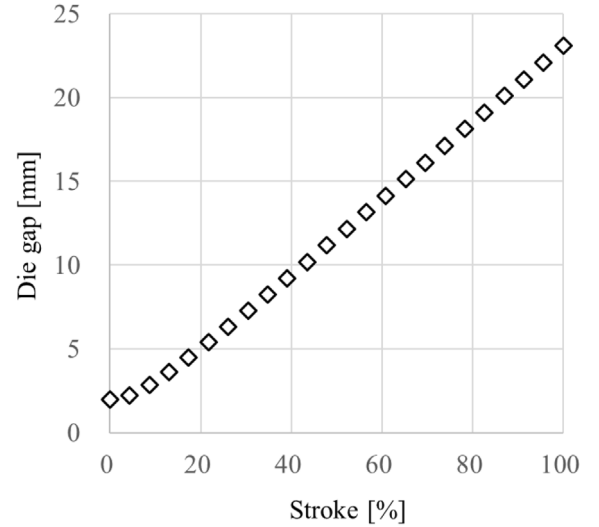


Fig. 7. Average measured die gap (ΔD_{gap}) of four points shown in Figure 6 as a function of stroke.

3.1.1 Parameters for the heat equation

The parameters needed to estimate temperature change in the parison are identified. Kikuchi et al. [17] reported that no temperature- and pressure-dependence of thermal

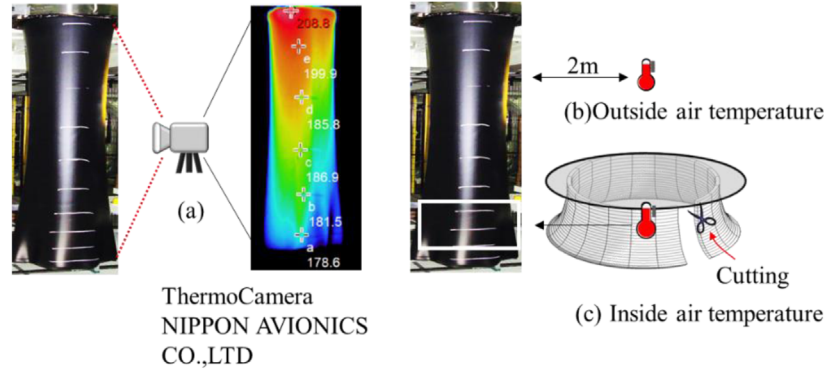


Fig. 8. Measurement of temperature. (a) The temperature distribution on the outer surface of the parison was measured using a thermal camera (manufactured by Nippon Avionics Co., Ltd.). (b) The temperature at 2 m or farther from the parison was measured as the ambient temperature. (c) The ambient temperature inside the parison cylinder was measured by making a cut in the direction of extrusion of the parison and using an infrared thermometer.

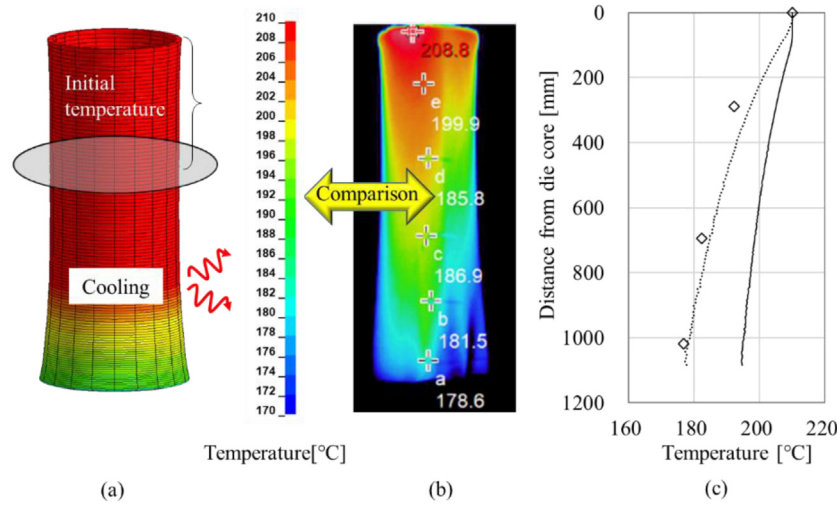


Fig. 9. Estimation of the heat transfer coefficient: (a) model for calculation of parison temperature distribution, (b) measured parison temperature distribution, and (c) Comparison of calculated (lines) and measured (diamond) temperature distribution as a function of distance from die core at the stroke of 30%. The solid and dotted lines indicate calculation results for a heat transfer coefficient of $9.8 \text{ W/m}^2\text{K}$, and $19.6 \text{ W/m}^2\text{K}$, respectively.

conductivity of high-density and low-density polyethylene were observed under conditions of pressures of 0.1 to 150 MPa and temperatures of 70–200 °C. We assume the thermal conductivity of the parison is the same as that of high-density polyethylene, and thus λ is set to 0.46 W/mK .

The heat transfer coefficient between the surrounding air and the parison is then identified in order to consider cooling of the parison. To estimate it, the heat transfer coefficient is fitted so as to reproduce the measured parison temperature distribution. The method of measuring ambient temperature and extruded parison temperature is as follows. Two constant stroke conditions based on the range used in production are set, as shown in Table 2. Figure 8 shows the method of measuring temperature on the outer surface, internal air, and surrounding area of the parison.

The extruded parison shape is then modeled to perform heat transfer analysis. A heat transfer coefficient is determined so as to yield the temperature distribution

Table 2. Extrusion conditions for identification of the heat transfer coefficient.

Item	Range of experiment
Die diameter, mm	$\Phi 340$
Flow rate, kg/h	400
Stroke, %	30, 80
Die gap, mm	7.2, 18.6
parison length, mm	1200
Temperature, °C	210

on the outer surface at the time of completion of extrusion. A parison model was created from the process data (parison length, diameter and thickness distribution), and the parison shape model is discretized into meshes in the same manner as in the extrusion simulation as shown in Figure 9a. Calculations were performed with the ambient

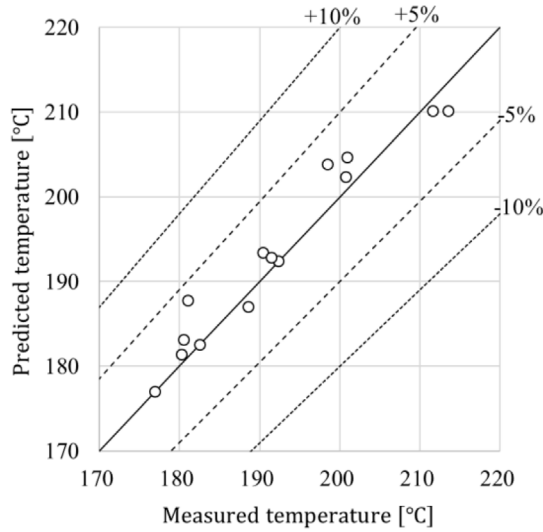


Fig. 10. Comparison of measured and predicted values of parison temperature under the variable stroke conditions in Table 1 and Figure 5. The predicted temperature is plotted against the measured temperature at the same position. The dashed and dotted lines indicate accuracy within $\pm 5\%$, and $\pm 10\%$, respectively.

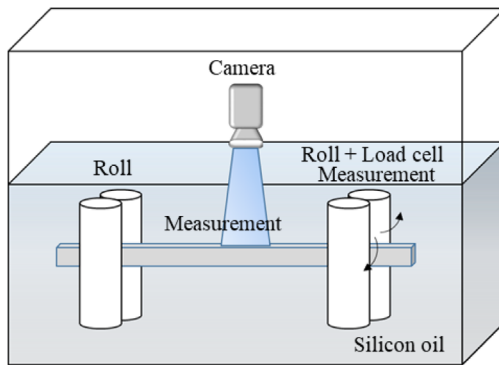


Fig. 11. Schematic diagram of the elongational viscosity measurement apparatus.

temperature around the parison set to 30°C and the internal ambient temperature set to 80°C , as based on measurements. Figure 9c shows the Comparison with the measured parison temperature shown in Figure 9b to estimate the heat transfer coefficient.

The predicted temperature distribution becomes closer to the measured values when the heat transfer coefficient is set to $19.6\text{ W/m}^2\text{K}$. For reference, when natural convection between the parison surface and air is assumed, the heat transfer coefficient h between the surface of high-density polyethylene and surrounding air was reported as approximately $3\text{--}10\text{ W/m}^2\text{K}$ [18]. The reason that the estimated heat transfer coefficient is several times greater than the values reported in the literature is thought to be the decrease in temperature caused by radiation from the parison to the outside and the differences in materials. The estimated heat transfer coefficient is an effective value that takes these effects into account.

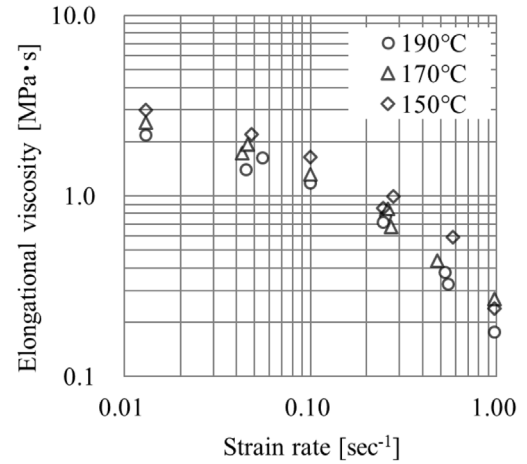


Fig. 12. Elongational viscosity η of HR111 at 190°C (circle), 170°C (triangle), and 150°C (diamond).

Table 3. Extrusion conditions for drawdown measurement.

Item	Range of experiment
Die diameter, mm	$\Phi 300$, $\Phi 410$
Flow rate, kg/h	450, 600
Stroke, %	10, 20
Die gap, mm	3.2, 5.1
parison length, mm	1500
Temperature, $^\circ\text{C}$	210

In Figure 10, the measured and predicted values in the numerical simulation are also compared under variable stroke conditions described in Table 1 and Figure 5. The discrepancy between measured and predicted values is found to be less than 5%.

3.1.2 Parameters for elongational rheology

Next, rheology parameters are estimated based on drawdown measurements. The elongational viscosity of the high-density polyethylene (HR111 from Japan Polyethylene Corporation, Tokyo, Japan) used in a portion of the parison was measured in order to use it as an initial data curve for elongational viscosity. Figure 11 shows a schematic diagram of the method for measuring elongational viscosity. The measuring device shows in Figure 11 using a Meissner-type elongational rheometer (Melten Rheometer, Toyo Seiki Seisaku-sho, Ltd., Tokyo, Japan). This device holds both ends of the specimen in an oil bath kept at a constant temperature, and pulls the specimen by rotating a roll at a constant speed for measuring elongational viscosity.

Elongational viscosity is obtained at elongation rates of 0.01, 0.05, 0.3, 0.5, and 1.0 s^{-1} and temperatures of 150, 170, and 190°C shown in Figure 12.

Next, the actual drawdown is measured to estimate the elongational viscosity and modulus that reproduce the drawdown. The measurement is done as follows.

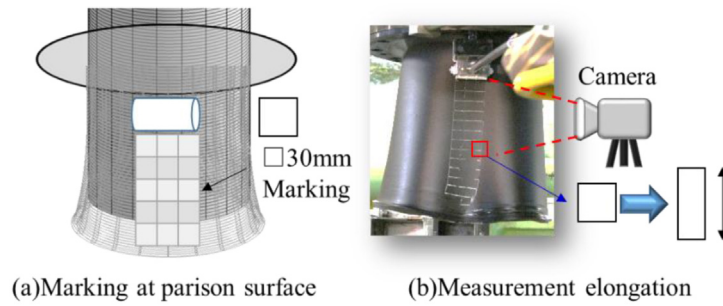


Fig. 13. Method of measuring elongation due to drawdown: (a) Markings are made on the outer surface of the parison just after extrusion, (b) the drawdown elongation is measured in images of the parison from deformation of the markings.

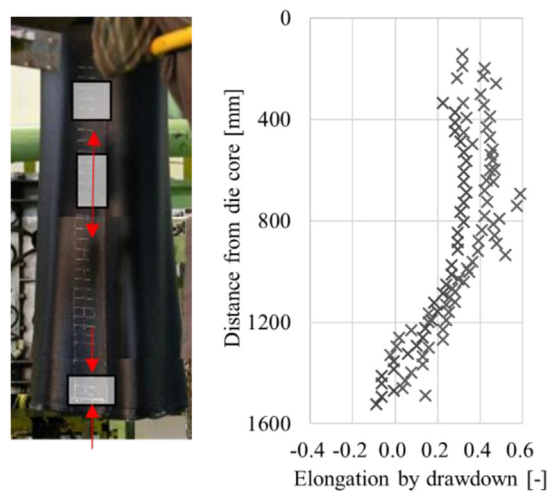


Fig. 14. Distribution of measured drawdown elongation as a function of distance from the die core at the condition of die diameter 410 mm, stroke 20% and flow rate 450 kg/h.

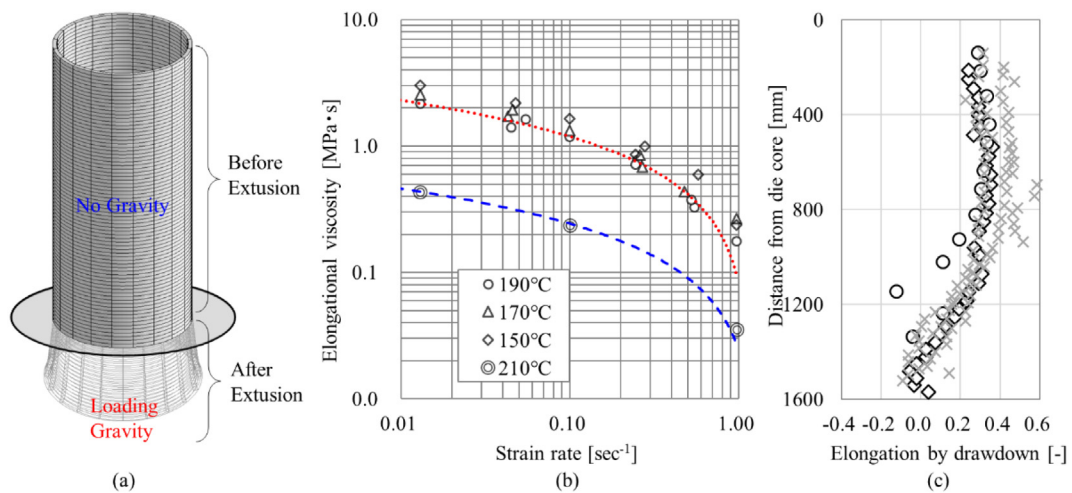


Fig. 15. Estimation of the elongational viscosity: (a) calculation model of drawdown in a parison; (b) elongational viscosity modified to fit the measured drawdown elongation, where the red dotted line indicates measured data at 190 °C and the blue dashed line indicates viscosity curve data at 210 °C; (c) Comparison of calculated drawdown elongation and measured elongation (cross) as functions of distance from the die core at the condition of die diameter 410 mm, stroke 20%, and flow rate 450 kg/h: the calculation results with the elongational viscosity of HR111 (circle), and the one with the fitted elongational viscosity (diamond).

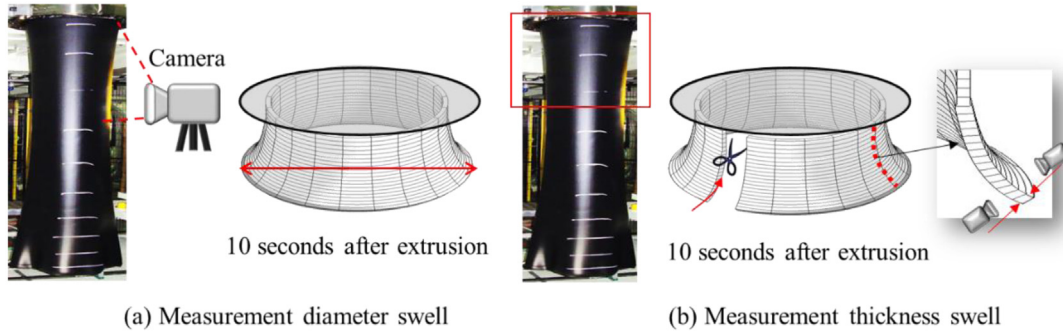


Fig. 16. Measurement of (a) diameter swell, and (b) thickness swell.

Table 4. Extrusion conditions for swell measurement.

Item	Range of experiment
Die diameter, mm	$\Phi 360$, $\Phi 410$
Flow rate, kg/h	310, 400, 536, 600
Stroke, %	15, 20, 35, 50, 60, 75
Die gap, mm	4.0, 5.1, 8.3, 11.7, 14.1, 17.6
parison length, mm	1100–1800
Temperature, °C	210

Table 5. Constant stroke extrusion conditions for verification of the model.

Item	Range of experiment
Die diameter, mm	$\Phi 360$, $\Phi 410$
Flow rate, kg/h	400, 536, 600
Stroke, %	10, 15, 37
Die gap, mm	3.2, 4.0, 8.7
parison length, mm	1100–1800
Temperature, °C	210

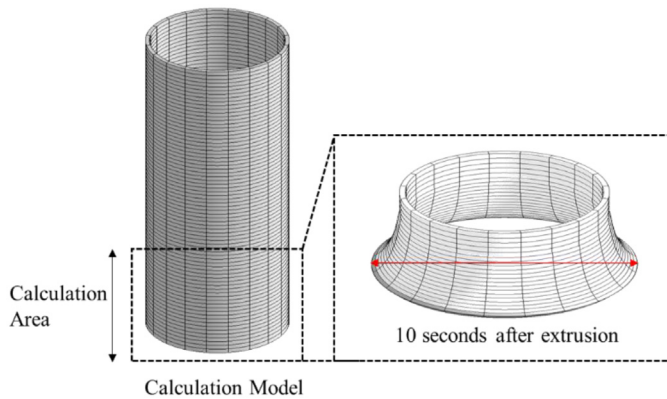


Fig. 17. Calculation model used in swell verification.

Contiguous 30 mm rectangle markings are made on the parison surface immediately after extrusion (Fig. 13a). Images of the entire parison are captured when extrusion is complete (Fig. 13b). The relative deformation in the 30 mm markings is calculated from the images as the drawdown elongation. Extrusion conditions for drawdown measurement are set to close to the actual production conditions (Tab. 3). Figure 14 shows an experimental drawdown, from which it is observed that drawdown is pronounced in the region close to the die.

Next, an analysis of drawdown without swells in thickness or diameter is conducted using a cylindrical parison model that is created based on the experimental extrusion conditions. As initial values for the parameters to be estimated, the viscosity was interpolated with the measured values of 150–190 °C, and was set to that at 190 °C for temperatures above 190 °C that is close to

extrusion temperature. The elongational modulus was estimated from the measured viscosity and the relaxation time from Funatsu et al. [5] as 0.44 MPa at 190 °C and higher, 0.49 MPa at 170 °C, and 0.536 MPa at 150 °C which were linearly interpolated for the simulation model. With these parameters, simulated drawdown elongation was smaller than the experimental one (Fig. 15c).

To reproduce the actual elongation, the assumed viscosity at 210 °C set to 0.1–0.5 times of the viscosity at 190 °C is used to calculate the drawdown. The best results are obtained when the viscosity at 210 °C is shifted to 0.15 times of that at 190 °C (Fig. 15b). As shown in Figure 15c, this yields an elongation close to the measured values (correlation coefficient with measured values is 0.78). With the obtained rheological parameters, the simulation model was found to be capable to reproduce experimental drawdown.

3.1.3 Stress for extrudate swell

Finally, estimation of swell stress is performed. The extrudate swells in thickness and diameter are measured and the corresponding stress values required for swell deformation are estimated. Swan et al. [19] used a camera capable of motion synchronized with parison extrusion to measure diameter swell. In the present study, however, it is necessary to measure the both swells in the parison diameter and thickness, which is performed as shown in Figure 16.

The parison is imaged 10 s after extrusion, at which time the measurement of extrudate swell is feasible, and the parison diameter is measured. During extrusion, a portion of the parison is cut vertically and thickness at a measurement position 45 degree away from the cutting

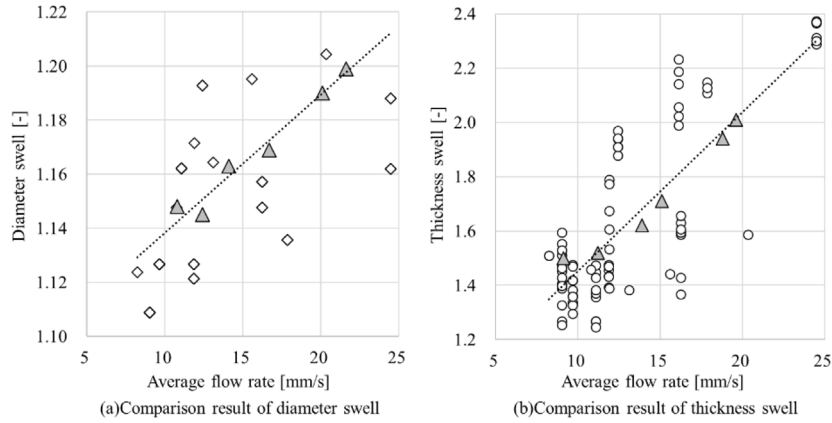


Fig. 18. Comparison of predictions (closed symbols) of swells in the parison against the experimental data (open symbols) as functions of average extrusion velocity v_{ave} under the extrusion conditions in Table 4; (a) diameter swell, and (b) thickness swell. The dotted lines indicate the linear fit of the experimental data of equation (13) for diameter swell and equation (14) for thickness swell, respectively. The simulation data are for the die diameter of 400 mm and the flow rate of 400 kg/h at the constant stroke of 18, 20, 25, 30, 35, and 40%.

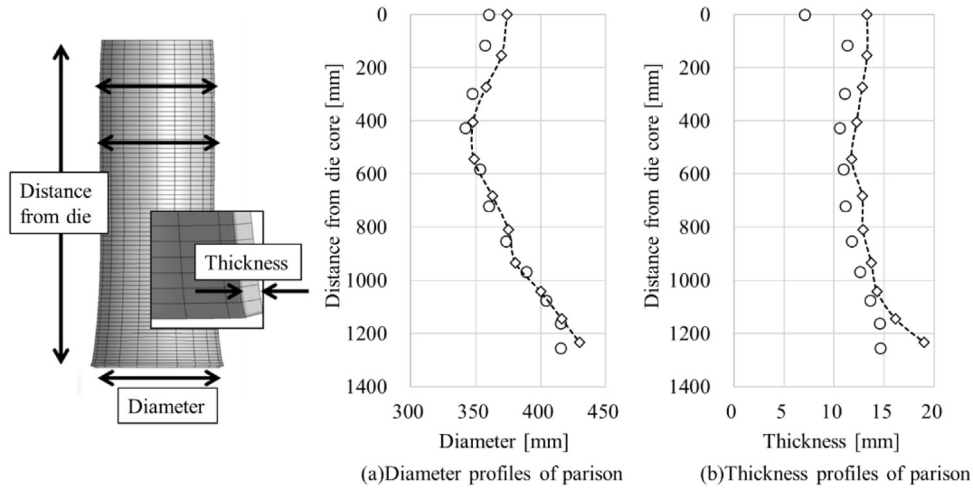


Fig. 19. Comparison of predicted (diamond) and measured values (circle) of the parison shape under constant stroke of 37% at the die diameter of 360 mm, and flow rate of 400 kg/h.; (a) the parison diameter distribution against the distance from the die core, and (b) the parison thickness distribution against the distance from the die core. Lines are guides to the eye.

position is measured 10 s after extrusion via insertion of a non-contact displacement meter. The extrusion conditions for the swell measurement are described in Table 4.

The measured diameter swell and thickness swell as functions of the average extrusion velocity are shown in Figures 18a and 18b, respectively. Linear approximation of the relationship between swell and average extrusion velocity v_{ave} is performed using the least-squares method:

$$\varepsilon_{swell,r} = 0.0585 \cdot v_{ave} + 0.8692 \quad (13)$$

$$\varepsilon_{swell,\theta} = 0.0051 \cdot v_{ave} + 1.0874 \quad (14)$$

The swell stress is estimated from the linear fit of experimental data equations (13) and (14) with the model equations (3), (8), and (9), and then the prediction of swell is performed for verification. The calculations are done up to the measurement time (10 seconds) as shown in Figure 17.

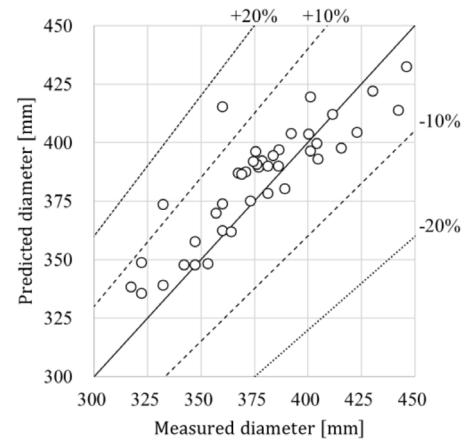


Fig. 20. Prediction accuracy of the parison diameter against the experimental data under constant stroke conditions. The dashed and dotted lines indicate prediction accuracy within $\pm 10\%$, and $\pm 20\%$, respectively.

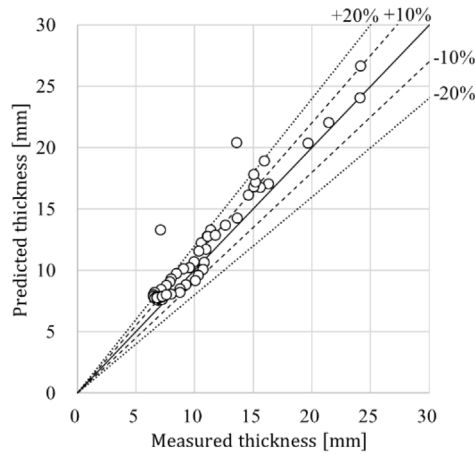


Fig. 21. Prediction accuracy of the parison thickness against the experimental data under constant stroke conditions. The dashed and dotted lines indicate prediction accuracy within $\pm 10\%$, and $\pm 20\%$, respectively.

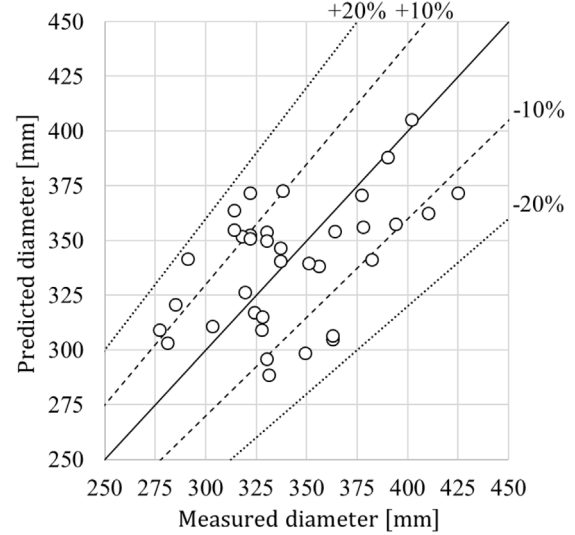


Fig. 23. Prediction accuracy for the parison diameter against the experimental data under variable stroke conditions in Table 1 and Figure 5. The dashed and dotted lines indicate prediction accuracy within $\pm 10\%$, and $\pm 20\%$, respectively. This Comparison does not include the data at the upper and lower ends of the parison.

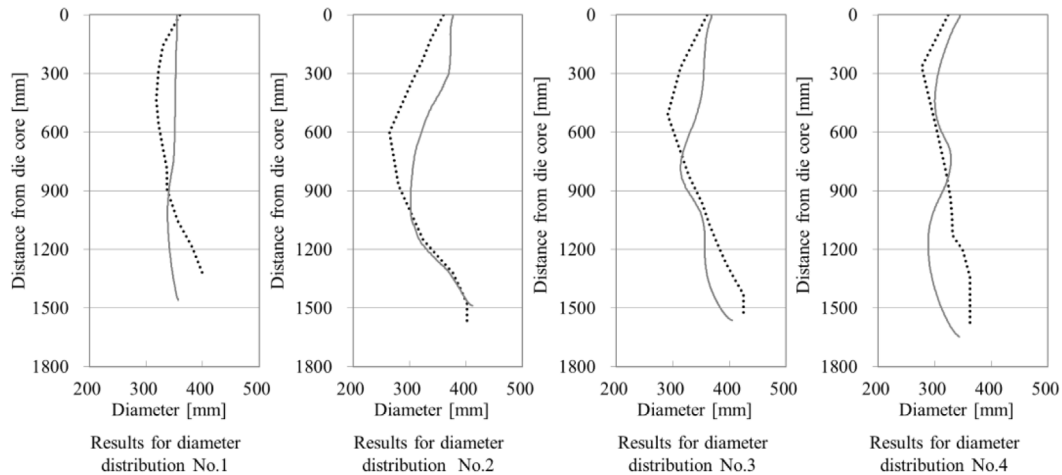


Fig. 22. Comparison of predicted (solid line) and measured (dotted line) parison diameter as functions of distance from the die core under variable stroke conditions described in Table 1 and Figure 5. The stroke pattern of each panel indicated by number is shown in Figure 5.

From Figure 18, the simulation model is found to be capable of reproducing both swells in diameter and thickness. For further verification, the entire parison shape was calculated under constant stroke conditions described in Table 5.

From Figure 19, it is confirmed that the distributions of the parison shape (length, thickness distribution, and diameter distribution) are successfully predicted.

The prediction and measurement are compared for the parison diameter in Figure 20 and for the parison thickness in Figure 21. The prediction results are of accuracy within 10% for the diameter swell (Fig. 20), and within 20% for the

thickness swell (Fig. 21) except for the two data points. Large errors are observed at the die exit and the lower end of the parison. The large overestimation near the die is because the extrudate swell is calculated instantaneously in the first single time step in our model. The large error at the bottom is due to the cutting of the parison in the experiment that is not considered in the calculation model. In the production equipment, the parison in the previous shot is chucked and cut by a jig, the thickness of the parison is compressed by the jig. It is likely that the measured diameter and thickness at the lower end of the parison become smaller than their actual values. In the practical viewpoint, the upper and lower 10% of

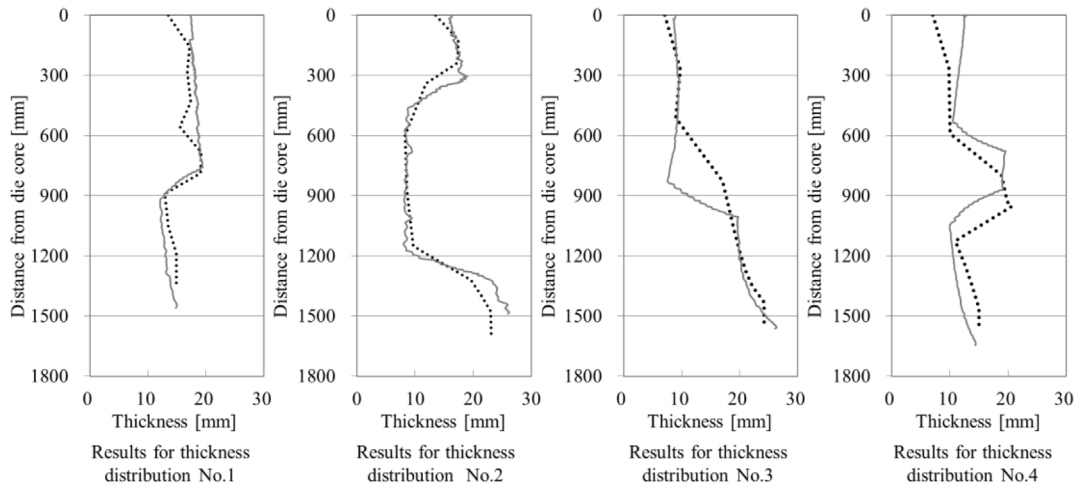


Fig. 24. Comparison of predicted (solid line) and measured (dotted line) parison thickness as functions of distance from the die core under variable stroke conditions described in Table 1 and Figure 5. The stroke pattern of each panel indicated by number is shown in Figure 5.

the parison are not used as burrs in the product, the errors in these parts are not substantial problem in the prediction. For the other part than the upper and lower ends, the constant stroke extrusion conditions allow prediction with an accuracy of $\pm 20\%$ overall.

3.2 Verification of the parison deformation model

In the previous sections, the model parameters are determined based on the process data under constant stroke extrusions. In this section, verification of the parison deformation model is performed under conditions by which stroke varied to simulate the extrusion during actual fuel tank molding.

Comparison between experimental and predicted values under variable stroke conditions in Table 1 and Figure 5 are shown in Figures 22 and 23 for parison diameter and Figures 24 and 25 for parison thickness. The quantitative Comparison in Figures 23 and 25 exclude data from both ends of the parison, as physically accurate predictions are not expected, as discussed in the previous section. By changing the stroke during extrusion, the parison diameter (Fig. 22) and thickness profiles (Fig. 24) are modified from those under constant stroke conditions shown in Figure 19. The predictions qualitatively reproduce the trend of shape change observed in the experimental results (Figs. 22 and 24). However, the discrepancy between the experimental and the predicted values increases especially around the points where the stroke changes. This is supposed to be because our model does not take into account changes in flow due to stroke changes. In general, the flow of a viscoelastic fluid depends on the history of deformation. Actually, Tanoue and Iemoto [20] reported that swell is affected by the deformation history in flow. Due to the lack of unsteady flow effects in our model, the cumulative error is supposed to result in the substantial error in the prediction for the parison diameter and thickness. In the variable stroke conditions used in this section, the observed thickness changes are about 50% due to

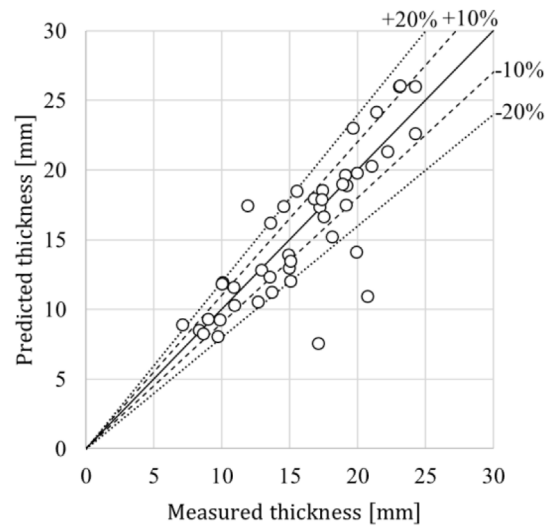


Fig. 25. Prediction accuracy for parison thickness against the experimental data under variable stroke conditions in Table 1 and Figure 5. The dashed and dotted lines indicate prediction accuracy within $\pm 10\%$, and $\pm 20\%$, respectively. This Comparison does not include the data at the upper and lower ends of the parison.

the 40% stroke change in ten seconds (Fig. 24). More accurate prediction under such harsh conditions is a future issue. Except for such points, the parison shape can be predicted within an accuracy of $\pm 20\%$ even in the variable stroke conditions.

4 Conclusions

This study developed a model that uses process data to predict the shape of parison formed from laminated material during the extrusion molding process for the

manufacturing of automotive plastic fuel tanks. Prediction of a parison shape close to that being produced is necessary in order to avoid trial-and-error based fine adjustments of extrusion conditions (extrusion cycle, stroke adjustment, etc.) by workers on-site. The difficulty in simulating laminated materials is identifying the rheology of an inhomogeneous material and resolving its viscoelastic deformations.

This study examined a model for predicting parison shape based on measurable process data from production equipment without a priori knowing complex rheology of multi-layered polymeric materials or solving internal deformation of multi-layer flow. In our method, first, the measurable process data in the parison molding are collected, and then a set of parameters for the parison deformation model are estimated from the process data, and finally the parison shape is calculated by the parison deformation model with the parameters based on the process data in different general extrusion conditions. To the extent of the authors' knowledge, this marks the first success in predicting parison molding with the laminated material used in plastic fuel tanks. The accuracy of prediction of the parison shape was at most $\pm 20\%$ for both diameter distribution and thickness distribution in variable stroke conditions except for the data around large and fast stroke changes. With this degree of accuracy, our prediction model can be used to assess trends in parison shape change due to changes in extrusion conditions. In validation, a large decrease in prediction accuracy turned out to occur primarily when the stroke changed. Therefore, dealing with the effects of stroke changes to improve the parison shape prediction is a future issue.

It is still difficult to reproduce the flow and deformation of multi-layer viscoelastic materials through direct numerical simulation, and therefore it is difficult to accurately predict the shape of the parison of laminated materials. In view of this situation, the successful prediction by the proposed model combined with process data is of significance for actual production process. By utilizing the process data, we were able to calculate the parison shape for different extrusion conditions. The application of machine learning and other AI (artificial intelligence) technologies as a way to utilize accumulated process data associated with extrusion conditions in production equipment is accelerating. By extending this work, to develop a parison shape prediction method that combines measurement data and machine learning techniques is an important future issue.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

Data will be made available on request.

Author contribution statement

Tomohiro Tokunaga: Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Writing – Original Draft Preparation. **Toshihisa Kajiwara:** Supervision. **Yasuya Nakayama:** Supervision, Funding Acquisition, Writing – Review & Editing.

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