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Direct Observation and Simulation of Blow Molding Process

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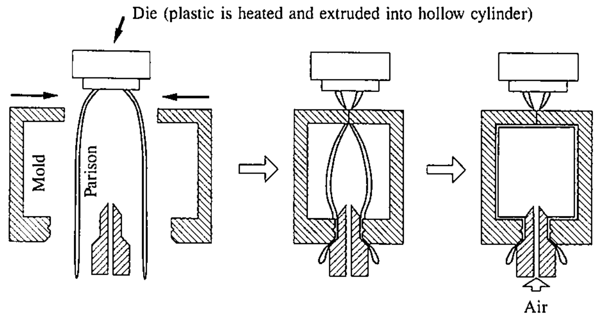
Abstract:

A technique was developed to directly observe with a fiberscope the inside of the parison (hollow plastic cylinder) used in the blow molding process. It was confirmed that the parison rarely slips on the mold surface during the inflation phase but deforms in the portions where it is not in contact with the mold. It was directly observed that the parison ruptures when stretched where it is not in contact with the mold. From the changes in the surface temperatures of the parison and mold, the heat transfer coefficient at the interface between the parison and mold was calculated to be 100 to 260 W/m²K. Based on these experimental results, the inflation phase was simulated by the general-purpose structural analytical program ABAQUS. The wall thickness distribution predicted by the simulation agreed closely with the measured wall thickness distribution.

1. Introduction

The blow molding process can produce parts light in weight and with high stiffness, or complex shape by making the most of double-walled structures and the geometrical freedom. Because of these advantages, blow molding has been highlighted in recent years as the superior technology for forming large structural parts and functional parts for automobiles, transport machinery, and office automation equipment, among other applications[1,2]. The blow molding process involves placing a hollow extruded plastic cylinder (parison) in a mold and inflating the parison with air (**Fig. 1**). Air is blown into the parison to force its free surface against the mold. The difficulty of controlling the shape and wall



(a) Parison extrusion (b) Mold closing (c) Parison inflation

Fig. 1 Schematic illustration of blow molding process (sectional views)

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thickness of the parison was one disadvantage of the blow molding process. Compared with injection molding, blow molding is considered to have a higher need for computer-aided engineering (CAE) to aid in product design and fabrication. The behavior and deformation mechanism of the parison in the mold have not been clarified in many respects. In terms of development and application of CAE software, the blow molding process is way behind the injection molding process.

In recent years, the blow-molded parts market has expanded, and the products have increased in size, complexity and functionality, yet product delivery lead time has shrunk. Under these circumstances,CAE is essential for product development and fabrication when using the blow molding process. For this reason, great efforts are being focused on the development of CAE software for blow molding[3].

To clarify the blow molding process, the authors developed a technique for directly observing the parison in the mold[4] and elucidated the slip, rupture, and other behavior of the parison in the mold. (The slip of the parison on the mold surface is the most important issue concerning the development of CAE software, because the wall thickness distribution of the blow-molded part mostly depends on whether or not the parison slips on the mold surface.) Several experiments were carried out using "glass molds"[5,6]. Since parison contact with the glass mold is different from parison contact with the "metal mold" in terms of friction coefficient and other factors, there is a possibility that the parison may develop phenomena unlike those observed with the metal mold. The thermal conductivity and other heat transfer phenomena between the parison and metal mold were also studied experimentally[7].

Based on the results of these direct observations and heat transfer experiments, the present authors performed simulation not by two-dimensional viscoelastic models[8,9] and elastic models[10-13] which have been reported previously, but by a rarely reported three-dimensional viscoelastic model considered to be most accurate[14-18]. The detailed results of this simulation work are presented in another report[19].

2. Experimentation

2.1 Direct observation of blow molding

2.1.1 Experimental method

The behavior of the parison in the mold was directly observed by inserting a fiberscope into the parison as shown in **Fig. 2**. The fiberscope was sealed in a glass tube against the inflating air pressure and designed to move up and down and to rotate.

We used polypropylene (PP) as the material. The parison was marked with a grid pattern extruded on the outer surface as shown in **Fig. 3**. When air was blown into the parison, the slip and other behavior of the parison were observed. The molded part was a bottle, a rectangular parallelepiped (300 × 190 × 140 mm in size, **Photo 1**.)

2.1.2 Experimental results and discussion

In the parison inflation phase, the movement of the grid pattern on the parison surface (**Fig. 3**) was observed before and after the parison came into contact with the mold surface, as shown in **Fig.4** When observed with the fiberscope, the movement of the grid marking after the contact of the parison with the mold was extremely small as shown in **Photo 2**. (The molding temperature was 200°C, the mold temperature was 20°C, the air flow rate was 0.015 Nm³/s, and the air pressure was 0.25 MPa.)

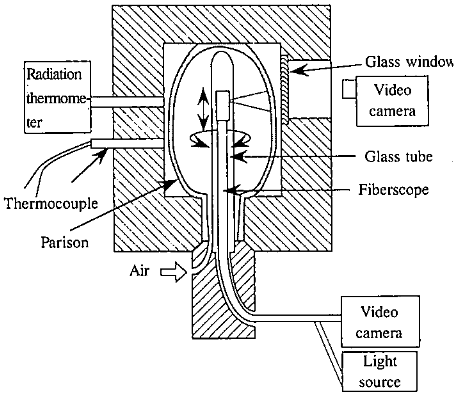


Fig. 2 Experimental apparatus for direct observation of blow molding (sectional view)

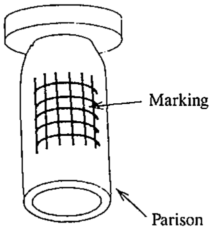


Fig. 3 Grid Marking of parison

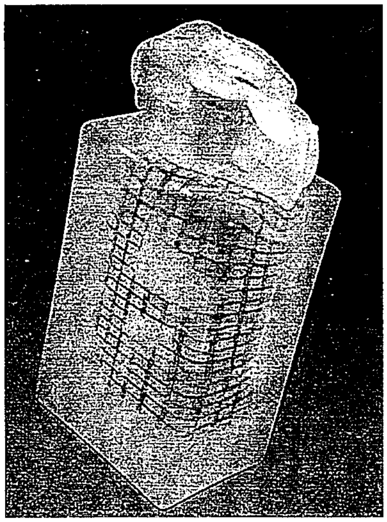


Photo 1 Blow molded bottle of rectangular parallelepiped shape

These results indicate that parison slip on the mold surface during the inflating phase is small enough to be practically ignored. Little or not slip of the parison was observed either when the mold surface was coated with silicone oil, machine oil, stearic acid, or other lubricants.

Most of the blow molding simulation reports[8-13] to date have handled the contact between the plastic and mold as complete contact without slip. The present experiment supported this contact condition for the first time.

2.2 Heat transfer phenomena in blow molding

2.2.1 Experimental method

To verify the heat transfer phenomena in the parison extru-

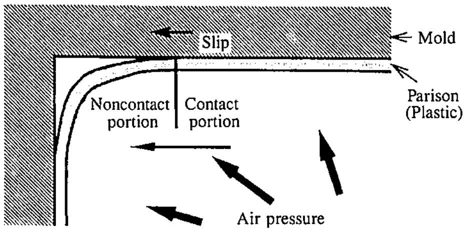


Fig. 4 Schematic illustration of slip

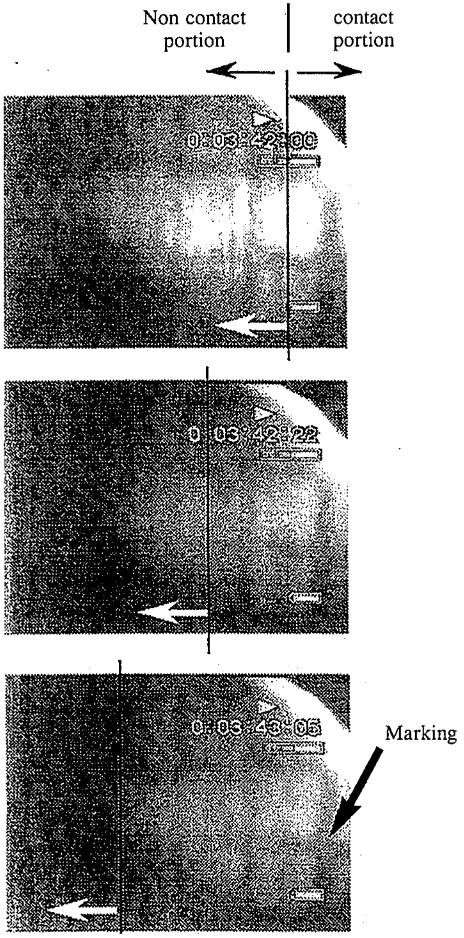


Photo 2 Slip of parison on mold surface as observed with fiberscope

sion phase, a parison was extruded by a certain amount, and the change with time in the outer surface temperature of the parison in this condition was measured with an infrared radiation thermometer. Using the mold for the bottle shown in **Photo 1**, the parison was blow molded by inflating it with an air pressure of 0.5 MPa, and changing the cooling time. The change with time in the surface temperature of the molded part immediately after the mold was opened was also measured with the infrared radiation thermometer.

2.2.2 Analytical method

The interfacial heat transfer coefficient h was calculated as a heat transfer evaluation index.

$$Q = h\,(T_h - T_c)\,A \qquad \cdots\cdots(1)$$

where Q = rate of heat flow; T_h = temperature of high temperature side; T_c = temperature of low temperature side; and A = surface area. The heat transfer coefficient h_a at the interface between the inner surface and air and the heat transfer coefficient h_m at the interface between the plastic outer surface and mold, both of which correspond to h as expressed by Eq. (1), were also obtained.

These heat transfer coefficients were calculated by fitting the results of one-dimensional unsteady-state heat transfer analysis to the experimental results.

2.2.3 Experimental results and discussion

According to the results of the experiment and calculation in the parison extrusion phase, the heat transfer coefficient between the parison and air was h_a = 10 W/m^{2}K. As shown in **Fig. 5**, the calculated and measured changes with time in the outer surface temperature of the parison roughly agreed with each other. This value of h_a was practically the same as the heat transfer coefficient of a flat sheet surface at room temperature reported in the literature[20]. In the inflation and cooling phases, the molded part had a temperature gradient in the thickness direction. When the cooling time was short, the internal molded part temperature was higher than the outer surface temperature (on the mold side). The outer surface temperature of the molded part rose after the mold was opened. When the cooling time was short, only the molded part on the outer surface was cold.

The results obtained when polypropylene was used as the plastic are shown in **Fig. 6**. When calculated from the results of several experiments conducted under different conditions, the heat transfer coefficient h_a between the inner surface and air was 20 to 90 W/m^{2}K, and the heat transfer coefficient h_m between the outer surface and mold was 100 to 200 W/m^{2}K. The calculated and measured rises in the outer surface temperature of the molded part did not completely agree with each other as shown in **Fig. 6**. The flow velocity and other conditions of air in the molded part change during molding. This in turn changes the heat transfer coefficient h_a between the inner surface and air and makes it impossible to completely match the calculated values to the measured values (see **Fig. 7**). The heat transfer coefficient h_a between the inner surface and air is thus considered to change with such factors as inflation time (change in air velocity in the molded part), air pressure, air flow rate, product shape, and air nozzle shape. The heat transfer coefficient h_m between the outer surface and mold is also considered to change with such factors as the type of plastic, air pressure, and surface nature of plastic.

When calculated from the heat transfer coefficient h_a between the inner surface and air, the average through-thickness temperature change of the plastic was small. This means that the parison can be isothermally analyzed in the mold closing and inflation

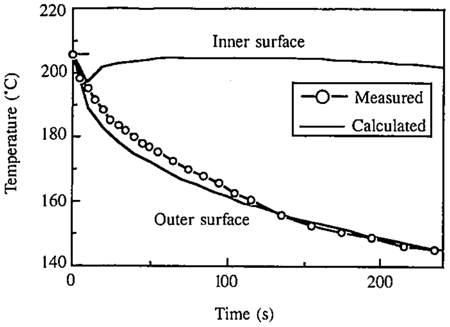


Fig. 5 Temperature change on the outer surface of parison (extrusion phase)

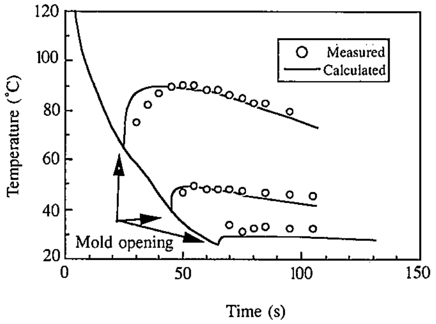


Fig. 6 Temperature change on the outer surface of a molded part after mold opening (inflation and cooling phase)

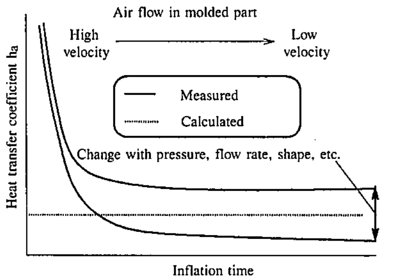


Fig. 7 Shematic curves for heat transfer coefficient (h_a) change during blowing

phases. (In this experiment it took about two seconds to inflate.)

The heat transfer coefficient h_m between the outer surface and mold is 1,000 to 30,000 W/m^{2}K for injection molding. It is clear that blow-molded parts cooled more slowly than injection-molded parts. The blow molding pressure used was 1 MPa or less as compared with an injection molding pressure of about 100 MPa. This pressure difference caused the contact condition between the mold and plastic to vary between blow molding and injection molding.

3. Analysis (Blow Molding CAE)

3.1 Analytical method

Based on the results of the blow molding, direct observation and the heat transfer experiments, the inflation phase was simulated by using a highly-accurate three-dimensional viscoelastic model rarely reported to date. The general-purpose structure analytical program ABAQUS was used for this analysis.

Molded part: Rectangular parallelepiped-shaped bottle as shown in **Photo 1**

Analytical model: Three-dimensional shell model-one-eighth of the bottom portion with considerations for symmetry

Initial condition: Parison with diameter of 100 mm and uniform thickness of 5 mm (measured on extruded parison)

Plastic material: High-density polyethylene (HDPE)

Plastic property: Viscoelasticity[21] (generalized Maxwell model)

Plastic temperature: 190°C (parison temperature change during inflation time was small enough to be ignored)

Contact between plastic and mold: Friction coefficient ranging from 0 to ∞(complete slip to complete contact without slip complete contact)

3.2 Analytical results

Fig. 8 shows the simulation results of parison deformation during the mold closing and inflation phases. In **Fig. 9**, the thickness distributions of the molded part obtained by simulation are shown in comparison with the measured thickness distribution. When the friction coefficient was 1, the simulated thickness distribution agreed closely with the measured thickness distribution. This relationship did not appreciably change when the friction coefficient was set at a value greater than 1.

It was thus found that the thickness distribution of the molded

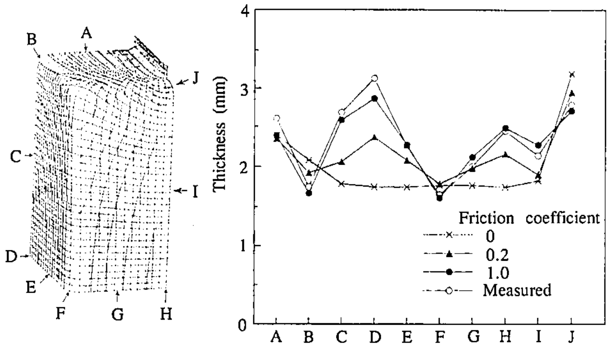
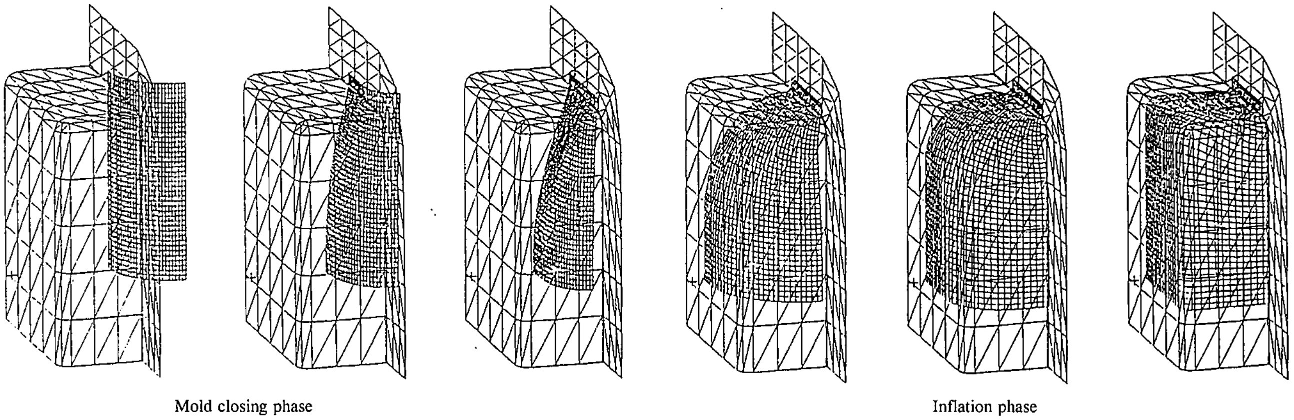


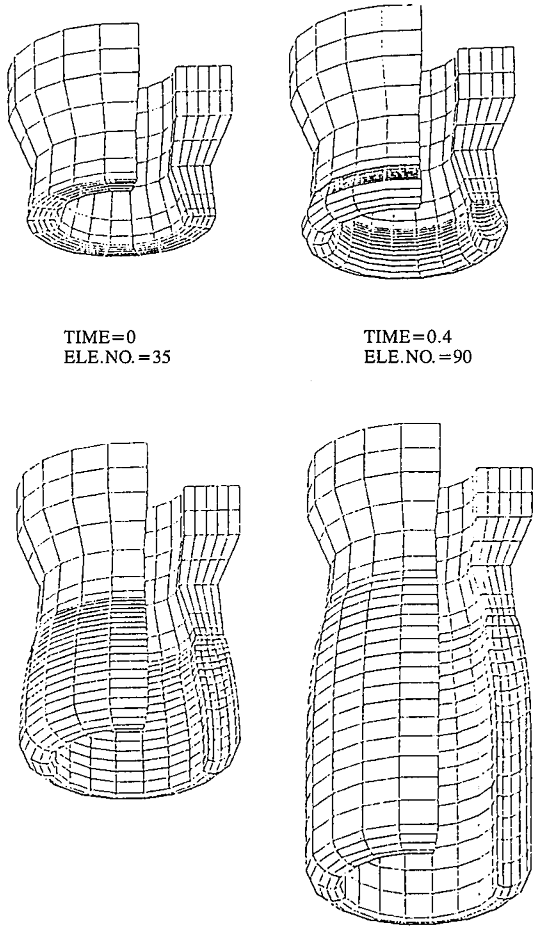
Fig. 9 Comparison of calculated and measured thickness distribution of blow-molded part



Mold closing phase

Inflation phase

Fig. 8 Simulation of parison in mold closing and inflation phases part can be accurately predicted from the conditions (shape, thickness, and temperature) of the parison immediately before mold closing and from the mold geometry by simulating the mold closing and parison inflation phases under the analytical conditions that were obtained from direct observation and the heat transfer experiments.



TIME=0
ELE.NO.=35

TIME=0.4
ELE.NO.=90

Fig. 10 Simulation of parison in extrusion phase

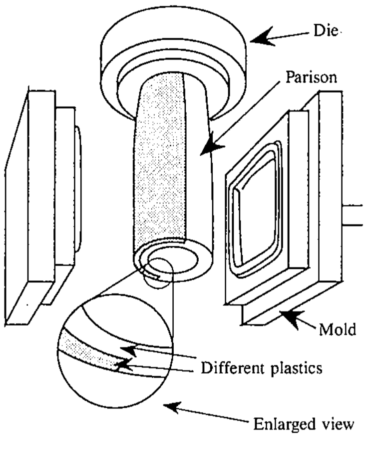


Fig. 11 Schematic illustration of ASM blow molding process

4. Conclusions

The blow molding process was observed directly, and the heat transfer phenomena during blow molding were experimentally and analytically investigated. Based on the experimental and analytical results, the mold closing and parison inflation phases were simulated. The following findings were obtained:

1) The deformation of the parison in the mold closing and parison inflation phases was directly observed from the inside of the parison. It was clarified that parison slip on the mold surface was extremely small and that the parison did not slip on the mold surface in most cases.
2) The heat transfer coefficient between the plastic and mold and between the plastic and air were calculated from the analytical and experimental results of the heat transfer phenomena in the blow molding process.
3) Based on the above results, the mold closing and parison inflation phases were simulated by using a three-dimensional viscoelastic model. The model succeeded in accurately predicting the thickness distribution of the blow-molded part when the friction coefficient was 1 or above.

The elucidation and simulation of the mold closing and parison inflation phases during blow molding were discussed earlier. Although not described here, a parison extrusion phase model (called SIMBLOW) is under joint development (**Fig. 10**)[22,23]. In the near future, highly-accurate CAE software will be developed and applied as a technological aid for product design and fabrication in the blow molding process in the same way as CAE software is presently used for the injection molding process.

Another objective of the authors is the development of new plastic molding processes. For example, the ASM blow molding process[24,25] is the molding process the authors developed while performing process clarification. The ASM molding process can separately layer two different types of plastics in the circumferential direction of the molded part as shown in **Fig. 11**. In this way, the advancement of blow molding technology is expected to accelerate, as represented by multilayer and three-dimensional blow molding processes. In line with this trend, it will be possible to make blow-molded parts larger, and more complex and functional. Furthermore, blow molding process elucidation and simulation technology will assume ever increasing importance.

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