Characterization of the biaxial response of a thermoplastic ABS Sheet using DIC-instrumented bubble inflation technique

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Abstract. During the forming of a product with the thermo-vacuum forming process, a heated thermoplastic sheet is subjected to a complex and dynamic multi-axial deformation mode. In order to measure the relevant mechanical response of the material during processing, an experimental method that applies the relevant modes of deformation during forming is required. The bubble inflation technique combined with digital image correlation (DIC) allows having a complete data set regarding displacement, principal strains as well as local thickness reduction for material characterization. Bubble formation as a function of temperature would be investigated to determine the nonlinear terms of a material constitutive model for numerical simulation.

Introduction

Thermoforming is a material processing technology in which a thermoplastic sheet is radiatively heated above its glass transition point. The heated sheet begins to sag under its weight when it is in its softening range. In order to compensate for sag deformation and also make a uniform biaxial pre-stretching before forming into the desired mold shape, positive air pressure is exerted. At the appropriate temperature, the sheet is stretched to get the shape of a mold using both mechanical loading and vacuum. The thickness of the thermoformed product is determined as a critical parameter for product quality definition. In order to predict the thickness distribution of the thermoformed product, it is essential to characterize the strain and temperature dependency of material under relevant modes of deformation when it is subjected to large rapid deformation. Currently, a proper prediction of the thickness is still a challenge, due to a lack of proper understanding of the material behavior and the need for a specific experimental test that applies large and rapid biaxial or multi-axial deformation mode. Experimental work shows that a uniaxial tensile test is not sufficient to characterize the material behavior while it is subjected to the mainly multi-axial direction [1,2] in the vacuum forming process. Therefore, it is essential to examine the extension behavior of the material in biaxial directions with a suitable experimental method. There are different classical experimental methods to determine the biaxial extension behavior of the material. A basic rheometer test is a squeeze-flow technique where the specimen is compressed between two discs with a lubricated surface [3]. This kind of rheometer is well-suited for liquid-like high viscous materials while the forming range of thermoplastic material in vacuum forming is far away from the melting point and it is close to a solid-like state. Moreover, it does not cover large deformations. The biaxial in-plane technique is another well-known displacement-controlled method to characterize the behavior of the material. But gripping the material at an elevated temperature, sag deformation during heating, and the complexity of the clamping introduce uncertainties to this test setup. The plug assist technique is the other common method that is used frequently to capture relevant large deformation at a high strain rate corresponding to the vacuum forming process. But this method has also a big drawback regarding the effect of friction and heat transfer through contact between plug and specimen. It could be concluded that a large biaxial extension can be achieved under pressurized air within another classical method named the bubble inflation test. This method seems to have the best fit to track the appropriate strain rates and large biaxial elongation deformations. This technique was initially applied by a British scientist, Treloar in 1944 [4]. A very simple conical glass tube was used in his test setup to purge by pressurized air to detect the natural rubber inflation with a thickness of 0.8 mm at ambient temperature. In 1951, Rivlin et al [5] utilized this method to calibrate directly the Neo-Hookean and Mooney-Rivlin rheological parameters of natural rubber by examining the equibiaxial state of the deformation at the pole of the inflated material using membrane theory. In 2001, Reuge et al [6] extracted the equibiaxial stress-strain data of elastomers at ambient temperature by measuring the elongation and curvature radius of the bubble of a specimen with 40 mm diameter at the pole using a 2D CCD video camera technique. In 2008, the bubble inflation test coupled with a 3D digital image correlation (DIC) device was adopted for the first time by Sasso [7] to capture the real-time strain field evolution of the rubbery-like material at ambient temperature. A similar effort was implemented to determine the stress field by computing the curvature tensor during inflating of the material at each surface point by Machado [8]. Cakmak et al. in 2013 [9] performed a biaxial bubble inflation test using a self-constructed test rig with a diameter of 120 mm over two different rubbery-like materials at -20°C, 20°C, and 60°C under low strain rate so that the stretch ratio near to 2 was reported at around 20 seconds. The main goal was to determine a master curve applicable to small and large deformations. To the best of the author's knowledge, the only research aiming to meet the extension modes relevant to vacuum forming process was performed by Turner et al. in 2019 [10] to investigate the biaxial response of 2 mm thickness PEEK in the temperature range between 130 to 160°C at the pole using a small size of bulge diameter 5 cm. Discrepancy reported on principal strain directions at the pole using DIC measurement was attributed to the extrusion process of the material. The tests at different temperatures and very high strain rates (less than 1 second) highlighted the nonlinear viscoelastic behavior of the material. However, the results were limited to the pole of the specimen and the shape of the bubble was not discussed.

As outlined previously, the bubble inflation technique combined with the optic method provides valuable real-time datasets including displacement, strains at different locations as a function of time as well as the local thickness reduction to fully understand the material behavior during the vacuum forming process. The objective of this work is to characterize the biaxial behavior of the Acrylonitrile Butadiene Styrene (ABS) material in the range of thermo-vacuum forming process. ABS is well suited for vacuum forming process fabrication. Formability at relatively low temperature, impact resistance, strength, and stiffness of this material makes it to be a good choice for economical engineering applications, especially for prototyping. In this work, ABS Epsotech single layer (AB AN2 V0, Tg=105°C) was used [11]. Forming temperature range of this material is 140°C up to 180°C. Although the aforementioned literature has provided a comprehensive understanding of the fundamental biaxial deformation behavior of mostly elastomers and PEEK materials, to the best of the author's knowledge, no studies exist concerning the extension behavior of ABS in more than one axis at forming temperatures. In the present work, a specific instrumented bubble inflation test setup with a 300 mm inner diameter was developed. The inner effective diameter is large enough to let the specimen expand avoiding any border effect. Moreover, It helps to investigate the shape of the bubble formation when it is subjected to large deformation at elevated temperatures which is helpful to calibrate the non-linear terms of the material constitutive model as a subsequent step of this work. Two different temperatures in the forming range (140°C and 150°C) were selected to examine the temperature-strain dependency of the material.

Instrumented Bubble Inflation Experimental Test Setup
A schematic view of the custom-made bubble inflation test rig is presented in Fig. 1. A circular ABS disc material with a diameter of 340 mm and thickness of 3 mm is mounted between two metal disks flanges, slightly clamped around the circumference providing an effective diameter of 300 mm of the material to inflate. Thinning of the material underneath the flange due to excessive clamping pre-load must be avoided since the thermoplastic material softens at elevated temperatures.

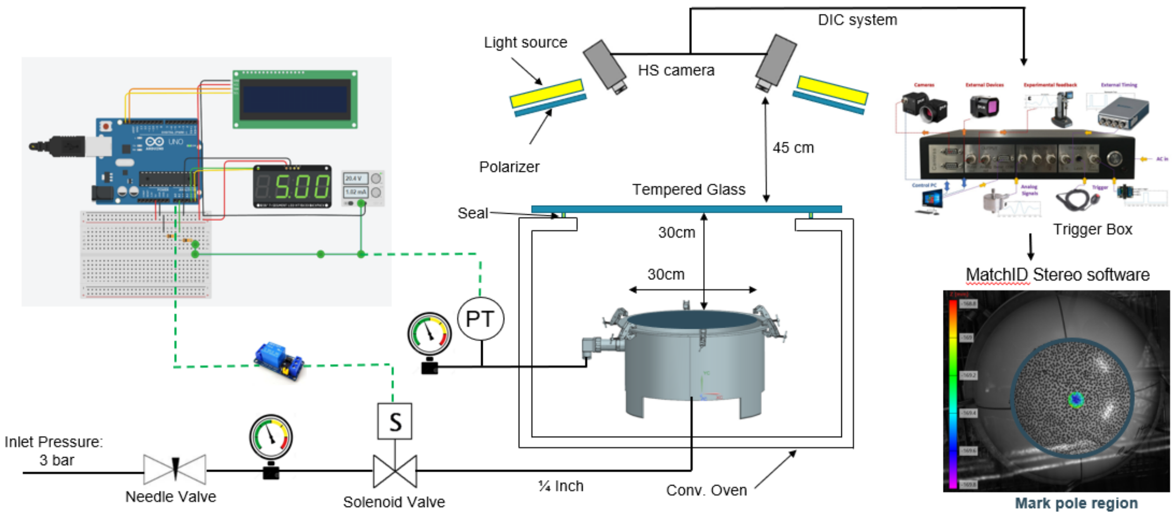
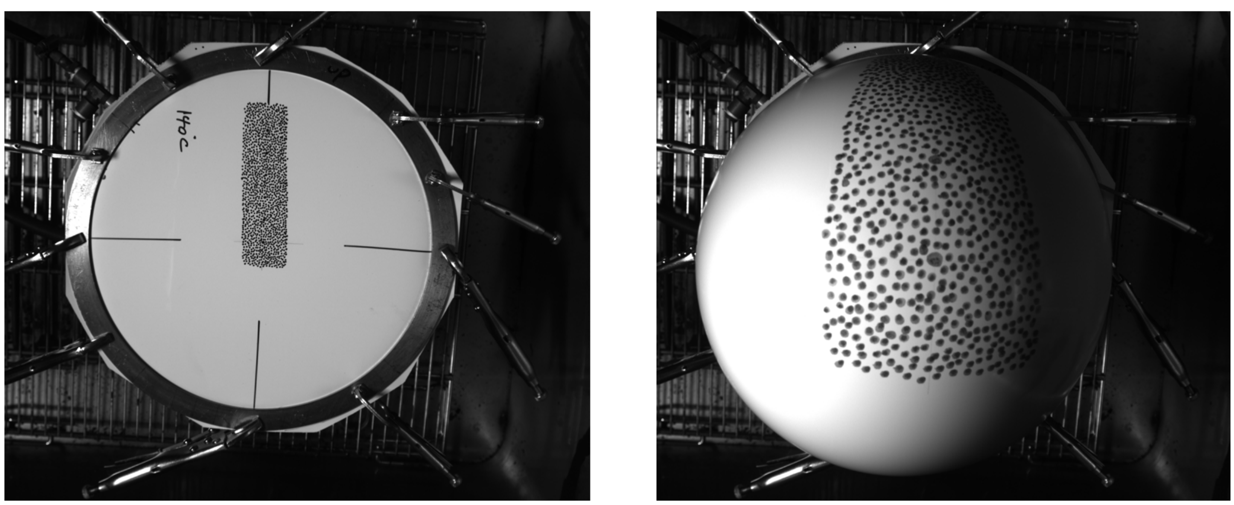


Fig. 1. Schematic annotated diagram of custom-made bubble inflation test rig.



(a) (b)

Fig. 2. 3 mm ABS Epsotech disk with a diameter of 300 mm speckled by permanent marker mounted between flanges using 10 adjustable clamps inside the convection oven, a) reference state, b) deformed state after 3 seconds of applying pressurized air.

This can be troublesome, particularly when conducting high strain rate tests at higher temperatures due to the excessive formability of the material. To avoid this, it needs to balance the clamp pre-load force in such way to avoid the tearing failure of the specimen during inflation. Moreover, the material shows sufficient friction with the steel flanges at elevated temperatures to avoid slippage. It is noted that the polymeric material here works itself like a seal at high temperatures, the application of an additional sealant O-ring is thus unnecessary. A temperaturecontrol convection oven is used to heat the material to reach the desired temperature. The upstream pressure behind the solenoid valve was fixed at 0.3 MPa for all the tests. This pressure allows a large rapid deformation in less than 3 seconds. It is possible to increase the upstream pressure to 0.7 MPa to meet a higher value of strain rate in case of need. A voltage-type pressure transducer in the range of 0 to 25 kPa (0.5 to 4.5 V RSPRO) with an accuracy of ± 0.25 % is applied to measure the air pressure inside the cavity during inflation. It sends the analog voltage signal to the microcontroller to regulate the solenoid valve condition on 20 kPa as a default triggering set point. Pressure data is then synchronized to the actual DIC data for each image frame for stress calculation during time evolution. The full field surface deformation of the material during inflation is optically measured using two high-contrast 5 Megapixels cameras (Fujinon HF-SA) supports with 3.45μm sensor size with 12.5 mm focal length lenses under MatchID system platform [12]. The cameras are mounted at a 75 cm distance from the disc specimen ensuring that the whole region is under the Field of View (FOV). There is a tempered ultra-clear glass with a thickness of 5 mm in between. The distance between the glass and the specimen is 310 cm. A dotted random, non-repetitive, with high contrast speckle pattern with an average size of 3.7 pixels is made on the Region Of Interest (ROI) with dimensions of 40 x 140 mm using a permanent marker in each test (Fig. 2a). The minimum speckle size adapted by MatchID system is 3 x 3 pixels per speckle [12]. A surface of a combination of 3 to 5 pixels that represents a unique signature so-called subset, is utilized to correlate between the reference state and deformed state per each updated reference. Digital pair images are taken with 20 frames per second during all the following tests. The correlation settings adopted in MatchID stereo software can be found in Table 1. Moreover, in order to enhance the quality of the record images and make uniform light conditioning on the region of interest, a light source was employed. However this light conditioning is valid for the reference state, it makes a shiny reflection on a curved surface during the inflation of the material which moves from the corner to the center of the specimen. This issue is particularly annoying for DIC correlation and post-processing. To avoid this, cross-polarized filtration techniques were implemented by applying linear polarizers in front of camera lenses and light sources.

Table 1. Correlation setting using MatchID stereo software.

Parameters	Method
Correlation algorithm	Zero-Normalized sum of squared differences
Interpolation	Local Bicubic Spline Interpolation
Stereo transformation	Affine
Correlation progress	Spatial + update reference
Subset weight	Uniform
Subset size	45x45
Step size	3
Strain window [pixels]	15
Strain Tensor	Green Lagrange

Results and Discussion

Fig. 2a shows the ABS disc at the reference state which is subsequently inflated beyond the hemispherical stage shown in Fig. 2b at 140°C. It is done under instantaneous purging of 0.3 MPa pressurized air into the cavity by the quick opening action of the solenoid valve. The material was heated inside the oven for 90 minutes to make sure about temperature uniformity distribution across the specimen and through the thickness. The material starts to sag under its weight when it

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gets the formability temperature range. The out-of-plane sagging displacement of the material measured using the DIC system is 2.8 mm and 14.93 mm for 140°C and 150°C, respectively at the pole of the material. Then, the 3D displacement of the specimen was incrementally correlated for 3 seconds of evolution time of inflation for all the following tests. Fig. 3 shows a typical contour plot of the out-of-plane correlation images of ABS material at 140°C. Fig. 4a shows the variation of the pressure inside the cavity during the inflation of the material at two different temperatures. The peak pressure value for 140°C and 150°C are 12.68 kPa and 9.66 kPa which occurs after 1.36 and 1.28 seconds of the test, respectively. After that, the pressure value decreases due to the continuous thickness reduction of the material while inflation is still ongoing even at a higher rate. Fig. 4b shows the out-of-plane pole deflection at these two selected temperatures. It is 238 mm and 273 mm at 140°C and 150°C, respectively. It is expected that the bubble deformation is to be truly biaxial only at the pole region [6]. In order to check the equibiaxiality behavior of the material at the pole, the correlation was first performed at the pole region to extract the strain variation of the material. Here, strain is calculated by applying a polynomial fit on the displacement data using MatchID post-processing stereo software. The Green-Lagrange strain was selected due to the large strain field for strain definition. The principal green strain in both directions at the pole at 140°C and 150°C are shown in Fig. 5a. Discrepancy between strains in the principal directions at 140°C is more pronounced which could be attributed to anisotropy generated during extrusion process manufacturing. By enhancing the temperature to 150°C, this effect is less pronounced and the material tends to behave like a truly biaxial extension. For a strain value less than 1, the material extends in the same manner at different temperatures. Strain dependency of the material begins particularly at strain higher than 1 so that the maximum principal strain reaches 11 at 150°C while it is 6 at 140°C. The strain gradient in Fig. 5b reveals how the rate of elongation begins to grow up from 1.5 seconds of the test to be doubled at the same time for higher temperatures.

Upon knowledge of the pole extension behaviour of the material at different temperatures, it is of particular important to detect the shape of the bubble formation during inflation by knowing the extension behavior of the material at different locations. It enhances the accuracy of the curve-fitting process afterward to find the non-linear terms of the mathematical models. The ultimate goal of this work is to calibrate the potential viscoelastic constitutive model using an inverse approach based on Finite Element Model Updating (FEMU).

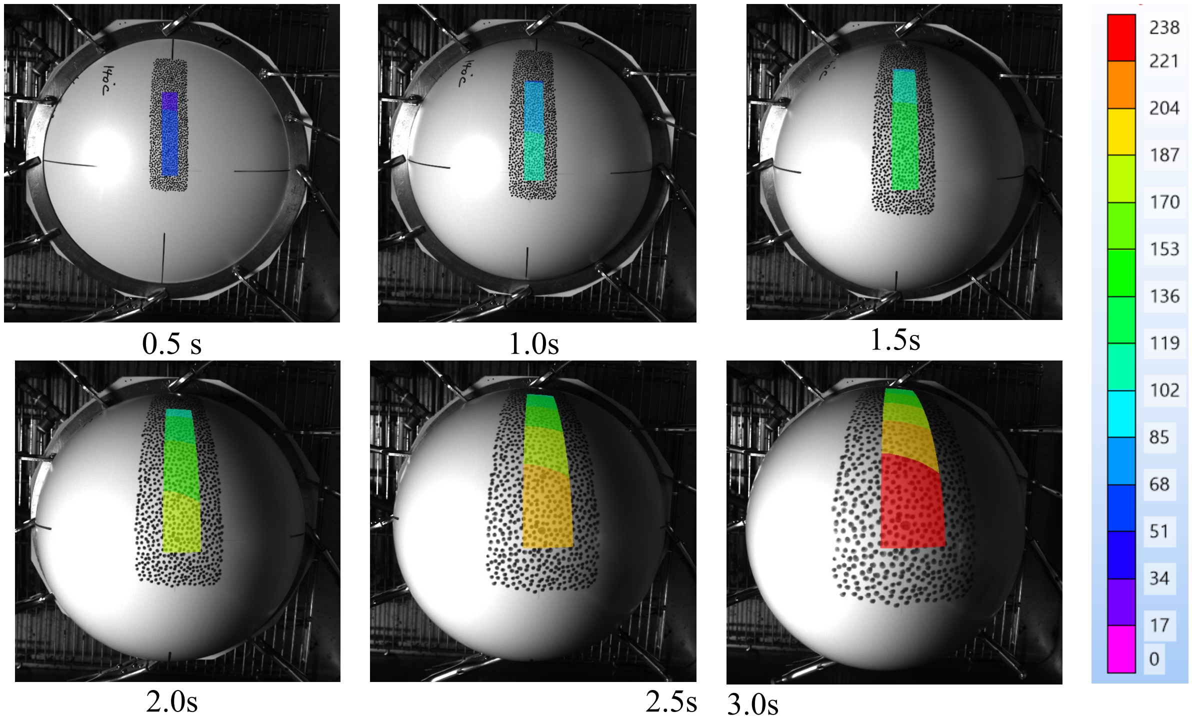

Fig. 3. Displacement magnitude [mm] of DIC inflation images sequence at 140°C during the time evolution.

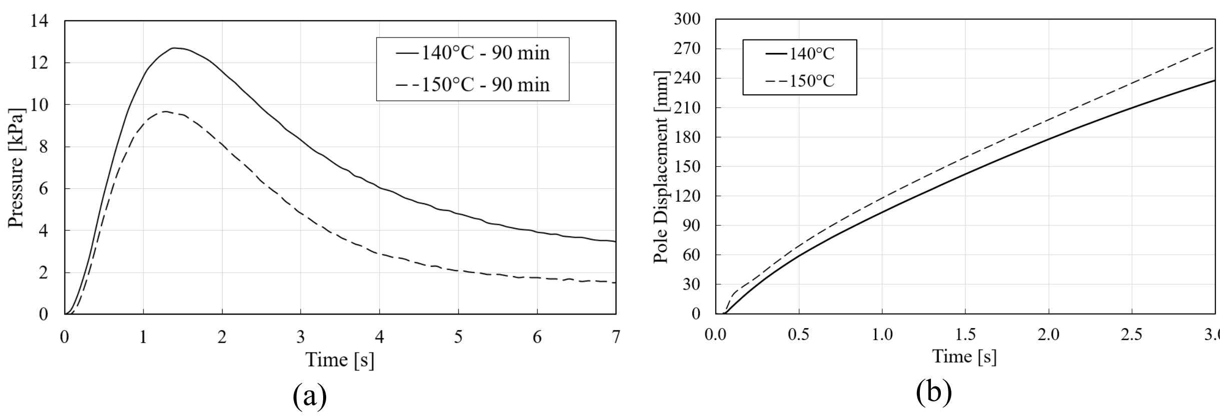

Fig. 4. (a) Pressure profile during inflation of the ABS material at 140°C and 150°C, (b) pole displacement within 3 seconds recording with 20 frames/sec using DIC cameras.

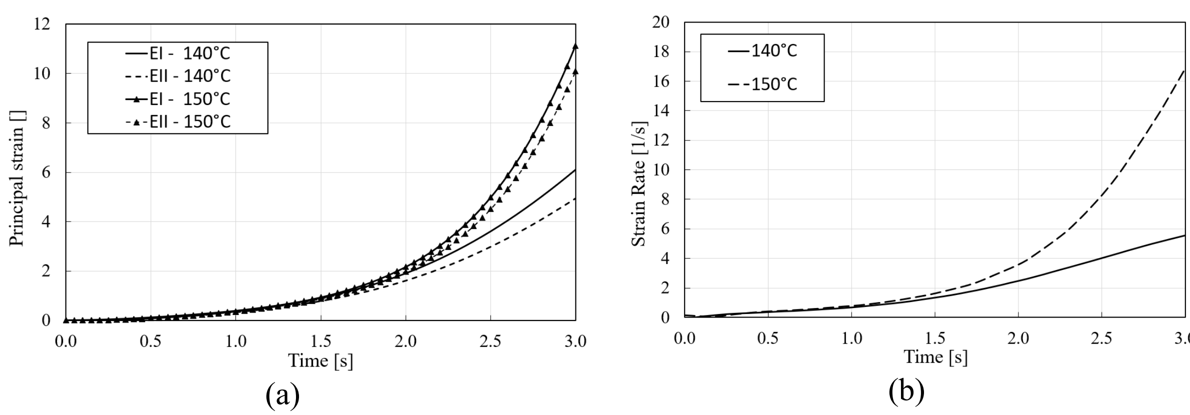

Fig. 5. Strain and strain rate variation at the pole against time during 3 seconds of inflation of 3 mm ABS at 140°C and 150°C, (a) maximum and minimum principal strains (b) strain rate.

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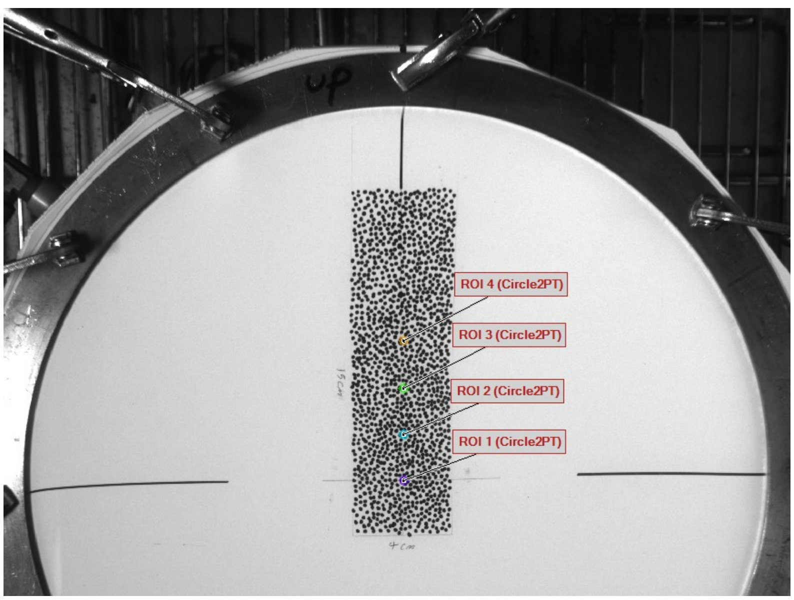
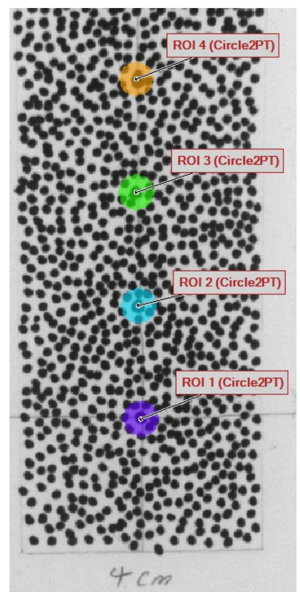
To meet this aim, 3 more points have been marked across the centrelines at a distance of 2 cm from each other as shown in Fig. 6(a). DIC data were averaged over a circle with a 5 mm diameter around each marked point shown in the zoomed view in Fig. 6(b). Fig. 7 shows the extension of the material on selected points at different temperatures. It is apparent that temperature increment induces the extension of the material, especially near the pole (ROI 2) which is in agreement with the aforementioned equal biaxial extension in two directions at the pole region versus the off-center location which is mostly unbalanced biaxial extension. It seems that by increasing temperature, a large amount of strain localizes disproportionately in a small region at the pole, resulting in prominent thickness reduction. This kind of extension distribution at higher temperatures tends to make a peaky bubble shape and eventually necks at the pole until failure. Fig. 8 indicates the rate of extension at 150°C versus 140 °C as evidence of the nonlinear behavior of the material. While the specimen at 150°C is softer, this also results in the material deforming at a higher rate than the material tested at 140°C; a maximum strain rate of 3.83 s-1 is observed at ROI 2 in comparison to rates of 10.8 s-1 seen in 150°C. The strain value at ROI 4 varies from 2 to 2.8 when the temperature shifts from 140°C to 150°C. The rate of extension at the locations far away from the pole is less influenced by temperature increment. In fact, thickness reduction at the pole region increases by a greater proportion than the material strain hardening at elevated temperatures.



(a)



(b)

Fig. 6. (a) Extracting averaged DIC data over circle with 5 mm diameter around the points every 2 cm across the center line, (b) Zoomed view of 4 small circle Region of Interests (ROI).

To make it more tangible, the thickness reduction during the real-time inflation test is calculated considering the Green-Lagrange strain definition through the following formula [13]:

$$t_f = t_i\left(\frac{1}{\sqrt{(1+2\varepsilon_1)(1+2\varepsilon_2)}}\right) \quad (1)$$

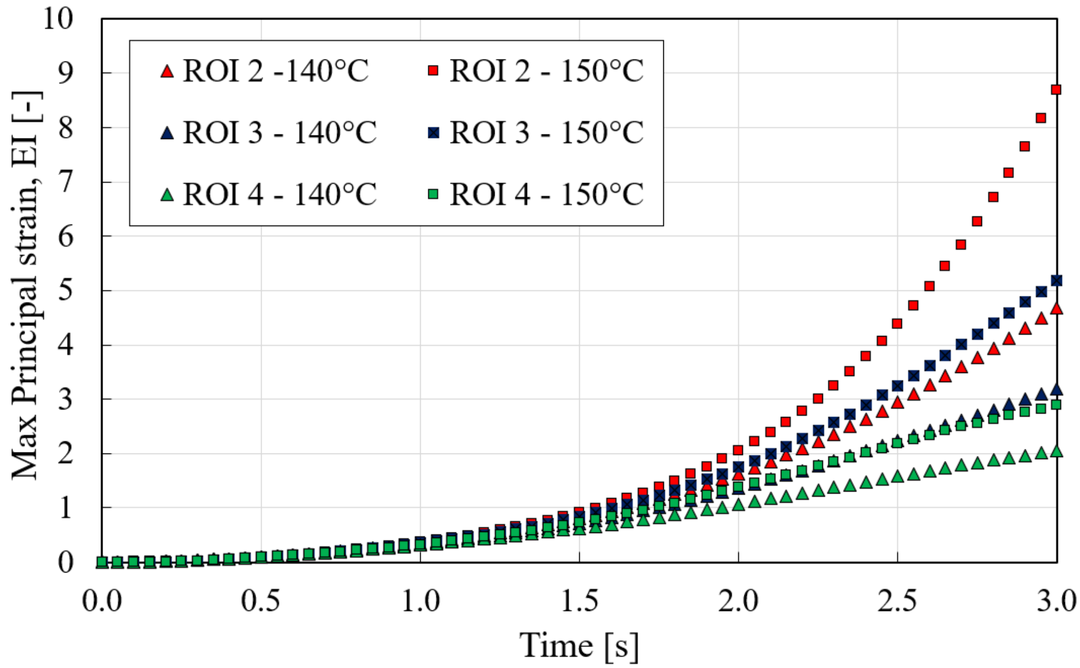


Fig. 7. Average strain of ABS material at three probes across the line with 2 cm distance to each other at 140°C and 150°C.

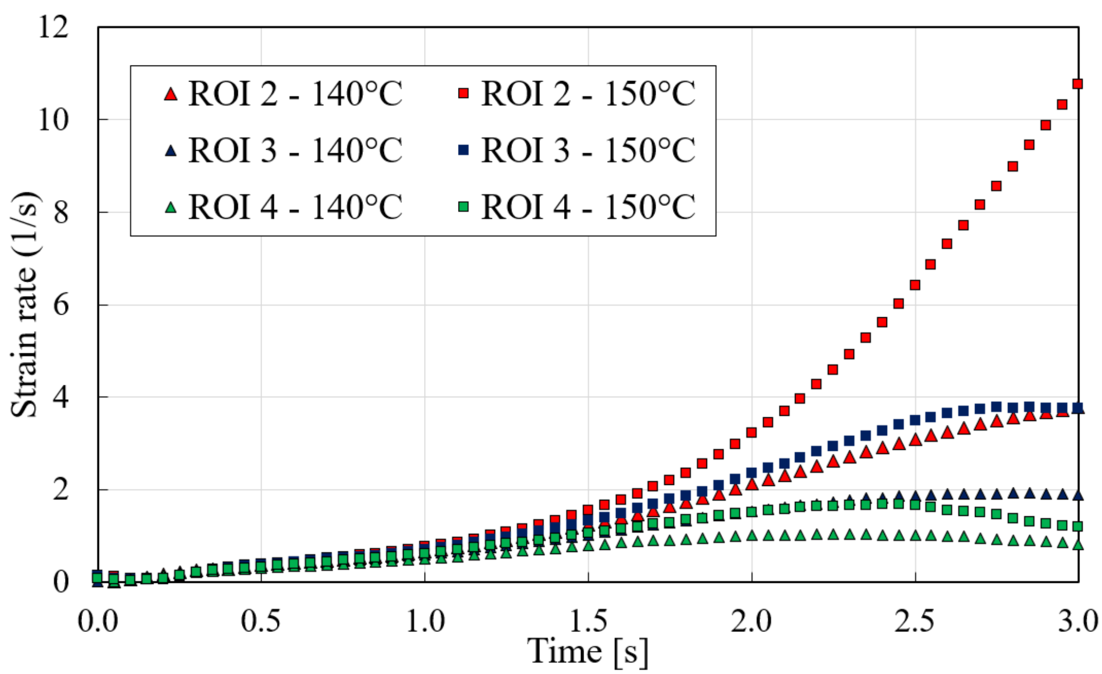


Fig. 8. Strain rate ABS material at three different locations across the line with 2 cm distance to each other at 140°C and 150°C.

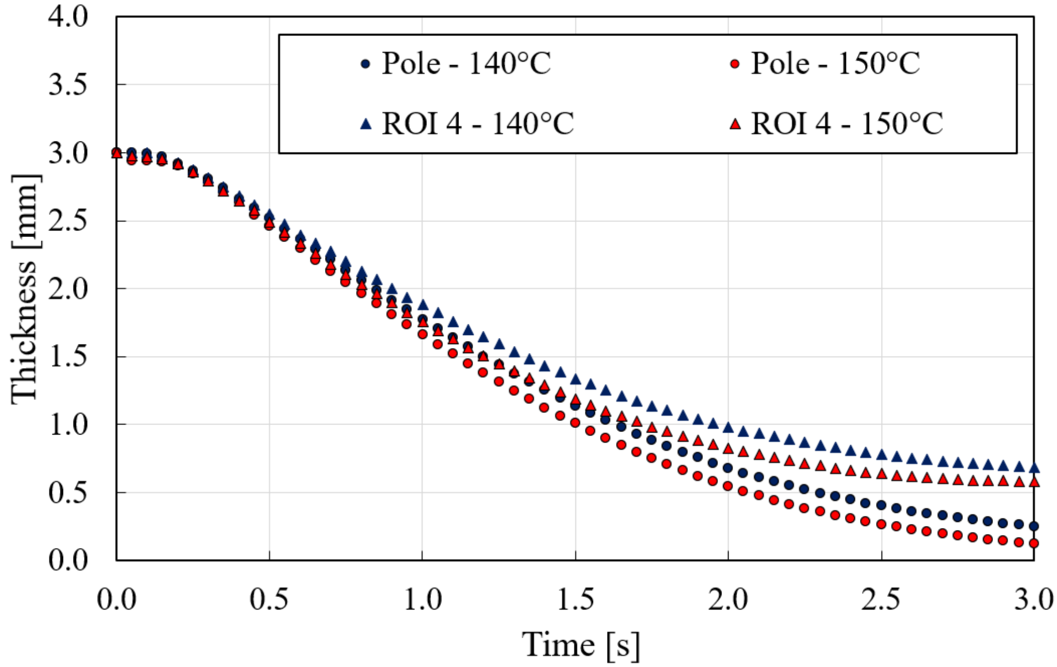


Fig. 9. Thickness variation against real-time at 140°C and 150°C.

Where t_f is the final wall thickness, t_i is the initial thickness, ε_1 and ε_2 are maximum and minimum principal strains, respectively. Equation 1 is only valid with the volume conservation of the sheet during inflation. Fig. 9 shows the effect of temperature increment on thickness variation at pole and ROI 4 (the last and furthest point from center) against time evolution. 52% thickness reduction (From 0.24 mm to 0.12 mm) at pole against 14% at the ROI 4 (From 0.67 mm to 0.57 mm) indicates the tendency of the material behavior to generate a narrow peaky bubble shape formation at elevated temperature. In other hands, strain hardening behavior at lower temperature leads to have more uniform stretching which is exhibited by delaying neck failure while at higher temperature strain hardening is drastically reduced which might be attributed to increasing mobility of the polymer matrix leading to have non-uniform deformation indicated by excessive thickness reduction at the pole.

Summary

In this study, the biaxial extension behaviour of a heated ABS sheet was examined using a custom-made bubble inflation test rig. DIC measurements were focused across the centreline to detect the bubble-shaped formation of the material as a function of temperature during inflation. It was exhibited that increasing the forming temperature results in an overall decreasing pressure level with larger material stretching at a higher strain rate. Biaxial strain discrepancy at the pole, attributed to anisotropy produced during the extrusion process of the sheet, is more prevalent at a lower forming temperature. Increasing the temperature from 140°C to 150°C reduces this effect resulting in a nearly equibiaxial extension in the two principal directions. Real-time strain values at different points across the centreline revealed a large amount of strain localized disproportionately in a small region at the pole by temperature increment, resulting in prominent thickness reduction. This kind of extension distribution tends to make a narrow peaky bubble shape at higher temperatures. The strong dependence of bubble shape as a function of temperature shown in this work is suggested as a convenient representative to calibrate the material non-linear model parameters aiming to elaborate the numerical simulation accuracy.

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