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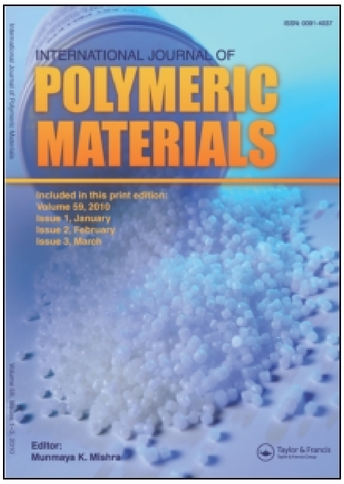

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Measuring Temperature Dependence of Secondary Forming Behavior of Cellular Polystyrene Sheets

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Foamed polystyrene extrusion sheet is often post-formed at reasonably warm temperatures for various final applications. Modified Erichsen testing apparatus with heating chamber is used for evaluating temperature dependence of post-forming ability of foamed polystyrene sheet. Circular sheets (90 mm diameter) of thickness (1.5 mm–2.4 mm) are used as test specimen in this experiment. The fracture of sheet specimen at hemi-spherical punch corner can be observed through upper glass plate during the punch penetration travel.

Profile of holding die, thickness of test specimen and clamping conditions (neat fit, press fit and clearance fit) of sheet specimen between dies are varied in this experiment and their effects on the fracture penetration depth are investigated at various working temperatures (30–100°C) with the interval of 10°C. In general, Erichsen fracture values increase greatly with working temperatures. While the effect of clamping conditions are not clear, Erichsen fracture values increase with the increase of inner diameter of holding die and thickness of foamed blank.

Erichsen recovery is measured as strain retentivity for complicated post-forming of foamed polystyrene. The test specimen was processed initially to fixed Erichsen depth (9 mm) at the temperatures of 70°C and 80°C, and then is free-annealed for 3 hours at the temperatures higher than the initially processed temperatures in order to cause strain recovery of the test specimen. The residual Erichsen depth after the annealing is measured and the Erichsen recovery percentage are calculated. As expected, the Erichsen recovery increases greatly with annealing temperature rise and is almost perfect at the annealing temperature of 100°C.

Finally, it is suggested that sheet profile of the penetration of hemi-spherical punch into a circular blank fixed rigidly with surrounding boundary, is analyzed theoretically on the basis of theory of rubber elasticity, assuming that the material is incompressive, isotropic and homogeneous, with fixed boundary condition of membrane, and further the central part of the circular blank is relaxed and set immediately after the contact with punch head.

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I. INTRODUCTION

From the viewpoint of academic study, new free surface elongational[1] flow processing including four main shapings: melt spun fiber[2,3] stretching, tubular inflation forming,[4] blow molding[5] and sheet thermo-forming,[6] is among current research topics in the field of polymer processing. This is rapidly replacing, as an important research subject, classical shear flow processing[7,8] with fixed boundary such as extrusion and injection, although shear flow processing still has some unsolved and very important problems such as "Residual stress and strain of injection-molded polymer products with dimensional stability and environmental cracking".[9] Among the four main shapings in elongational flow processing, the first three occur immediately after die extrusion and are concerned with primary shaping with continuous or cyclic behavior. On the other hand, the last one-sheet thermoforming[10,11] involves polymer sheets that have been extruded and solidified in a separate operation, and hence, is one of the most typical secondary shapings.

Foamed polystyrene sheet extruded is post-formed often and widely at reasonable warm[12] temperature for various applications.[13] However there have been few investigations in the field of processing behaviors of foamed[14] polymers. Hence it is very important for foamed polystyrene sheets of different grades to investigate experimentally optimum postforming conditions of temperature, working tool dimension with definite clamping boundary of sheet specimen, and to compare with the experimental data of ordinary polystyrene sheet and also with theoretical analysis.

2. MODIFIED ERICHSEN TEST AT WARM TEMPERATURES

Modified Erichsen testing apparatus with warm chamber, shown in the photograph of Figure 1, is employed for measuring simply, rapidly and easily the temperature dependence of post forming ability of foamed polystyrene extrusion sheet, comparing with the data on ordinary polystyrene extrusion sheet. The general view of the Erichsen testing apparatus is shown in Figure 2.

As shown in Figure 3, the constant temperature chamber in which the circular sheet test specimen of 90 mm diameter and the working tools are located, is heated by circulating hot air from a blower with electric heater. The temperature of the hot air is varied by controlling an electric heating source. A thermoregulator connected to a relay circuit is inserted near the test specimen and provisions are made so that the temperature of the test specimen in the chamber is kept accurately at a constant temperature. A baffle plate is provided at the hot air inlet in the chamber in order to cause turbulent flow of the hot air which in turn will provide uniform temperature distribution in the

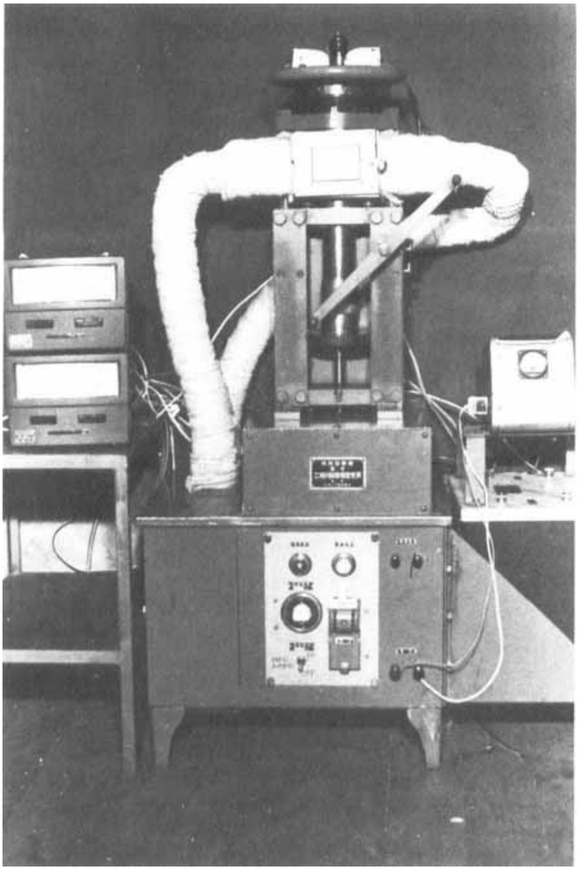

FIGURE 1 Modified Erichsen testing apparatus with warm chamber (photograph).

chamber. At the same time, auxiliary Nichrome wires are wound the upper and lower dies to maintain the temperature variation in the test specimen as small as possible.

A hemi-spherical punch is penetrated into the centre of the sheet specimen at a constant rate of stroke, as shown in detail in Figure 4. The stroke was designed with a tolerance of approximately 60 mm in consideration of the large deformation of sheet specimen at elevated temperatures. The fracture of test specimen at the hemi-spherical punch corner is observed through the upper glass plate. Profile of holding die, thickness of test specimen and clamping conditions (neat fit, press fit and clearance fit) of sheet specimen between upper and lower dies are varied in this experiment and their effects on

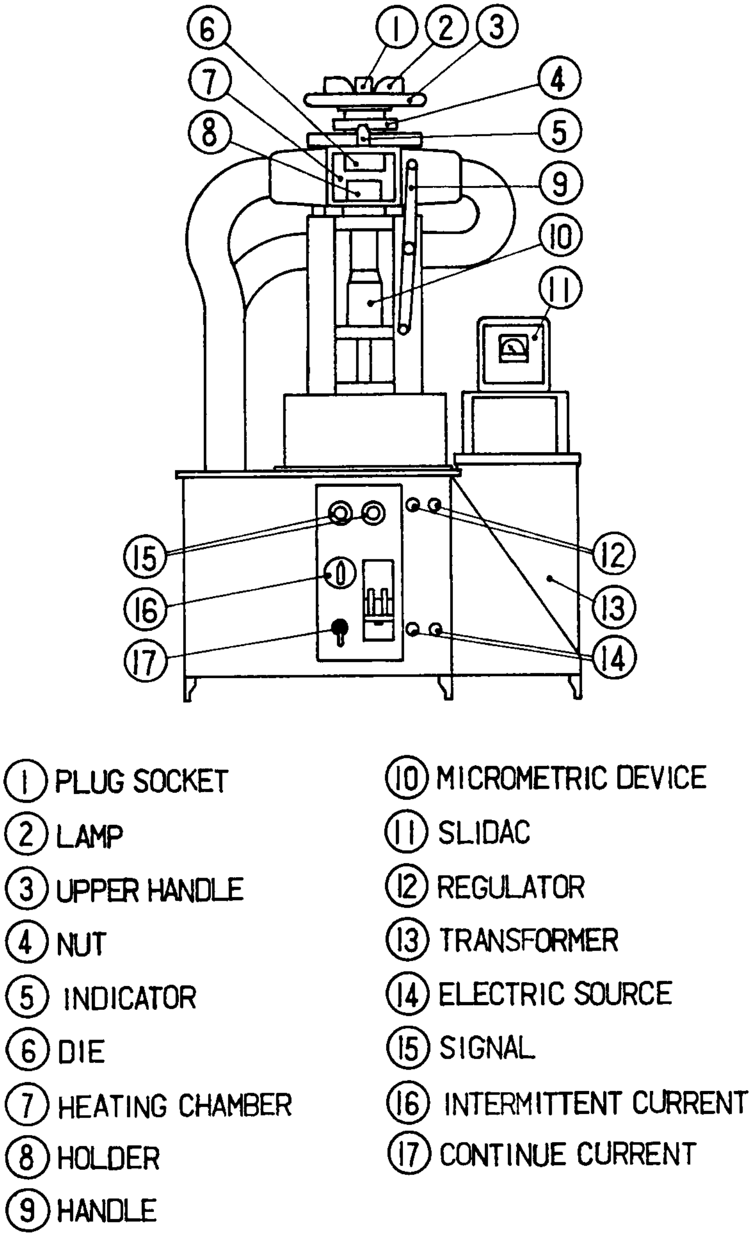

FIGURE 2 General view of modified Erichsen testing apparatus with warm chamber.

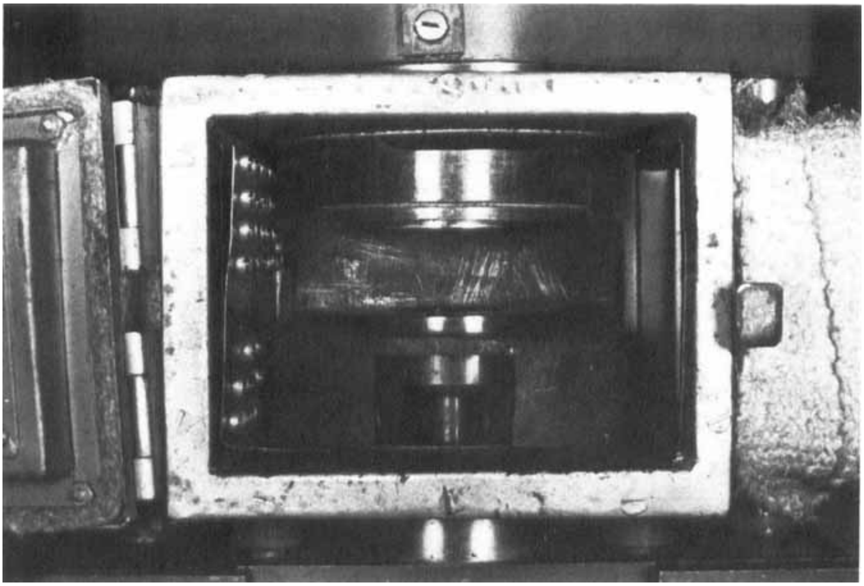

FIGURE 3 Inside of warm chamber in modified Erichsen testing apparatus (photograph).

the fracture penetration depth (Erichsen fracture value) are investigated at various elevated temperatures (30–100°C) with the interval of 10°C.

3. EXPERIMENTAL RESULTS ON ERICHSEN FRACTURE TEST

Erichsen fracture values of foamed polystyrene sheet increase greatly with working temperature rise. At the temperatures higher than about 100°C, foamed polystyrene sheet used in this study is likely to be in rubber elasticity and can not be fractured by the punch penetration. Typical Erichsen fracture samples worked at various warm temperatures are shown in Figure 5.

Several influencing factors concerning the relationship between Erichsen fracture value and working temperature were investigated to determine optimum condition of solid tool forming of foamed polystyrene sheet. The influence of blank thickness is established first at various working temperatures and the result is illustrated in Figure 6. The detailed information on test specimens with different thicknesses is indicated in Table I. The Erichsen fracture values increase with the thickness of sheet specimen. This is caused by the fact that tensile fracture of sheet blank at the punch corner is more probable with the decrease of sheet thickness than bending fracture of which

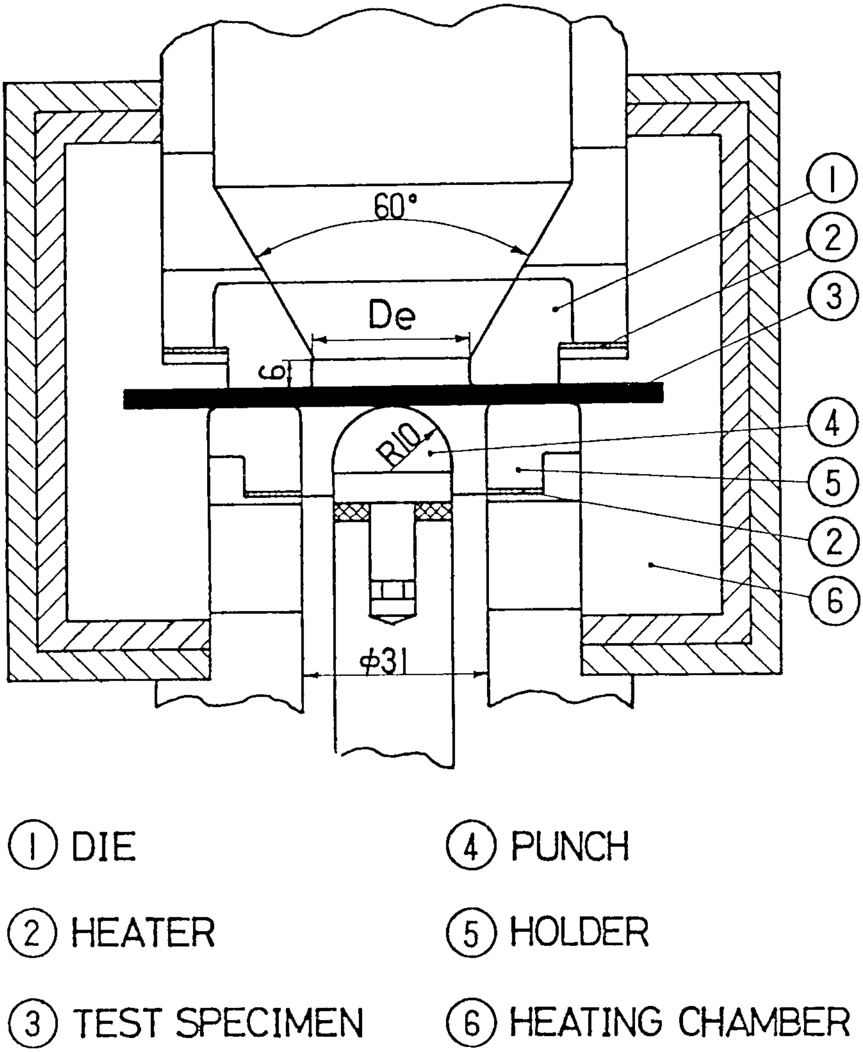

FIGURE 4 Arrangement of blank and working tool in warm chamber of modified Erichsen apparatus.

the resistance is larger due to non-uniform stress distribution. The experimental result on the effect of inner diameter of holding die is shown in Figure 7. In the case of neat fit of blank clamping, as expected, the bigger holding die allows easier and freer deformation of sheet and hence results in better Erichsen values at all the working temperatures tested.

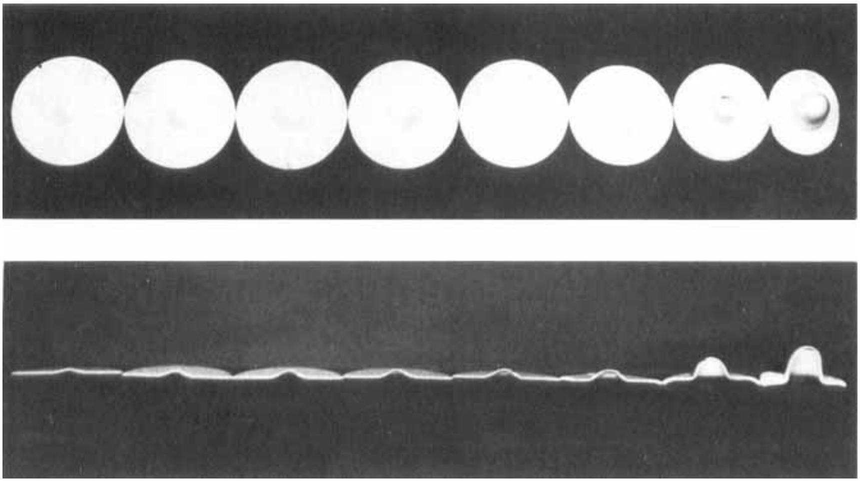

FIGURE 5 Typical Erichsen fracture specimens of foamed polystyrene and their cross sections, experimented at various temperatures (specimens from left are in the order of processing temperatures 30, 40, 50, 60, 70, 80, 90 and 100°C) (photograph).

Further the initial clamping conditions of sheet blank between upper and lower dies were varied in neat fit, press fit and clearance fit. Typical result in this experiment is shown in Figure 8. The influence of various clamping conditions was not clear, probably due to the fact that foamed polystyrene sheet is compressed easily under clamping pressure.

TABLE I

Test specimens of foamed polystyrene with different thicknesses.

Test specimen		
Seat mark	Thickness mm	Density g/cm^3
A	1.48	0.093
B	1.58	0.092
C	2.38	0.113

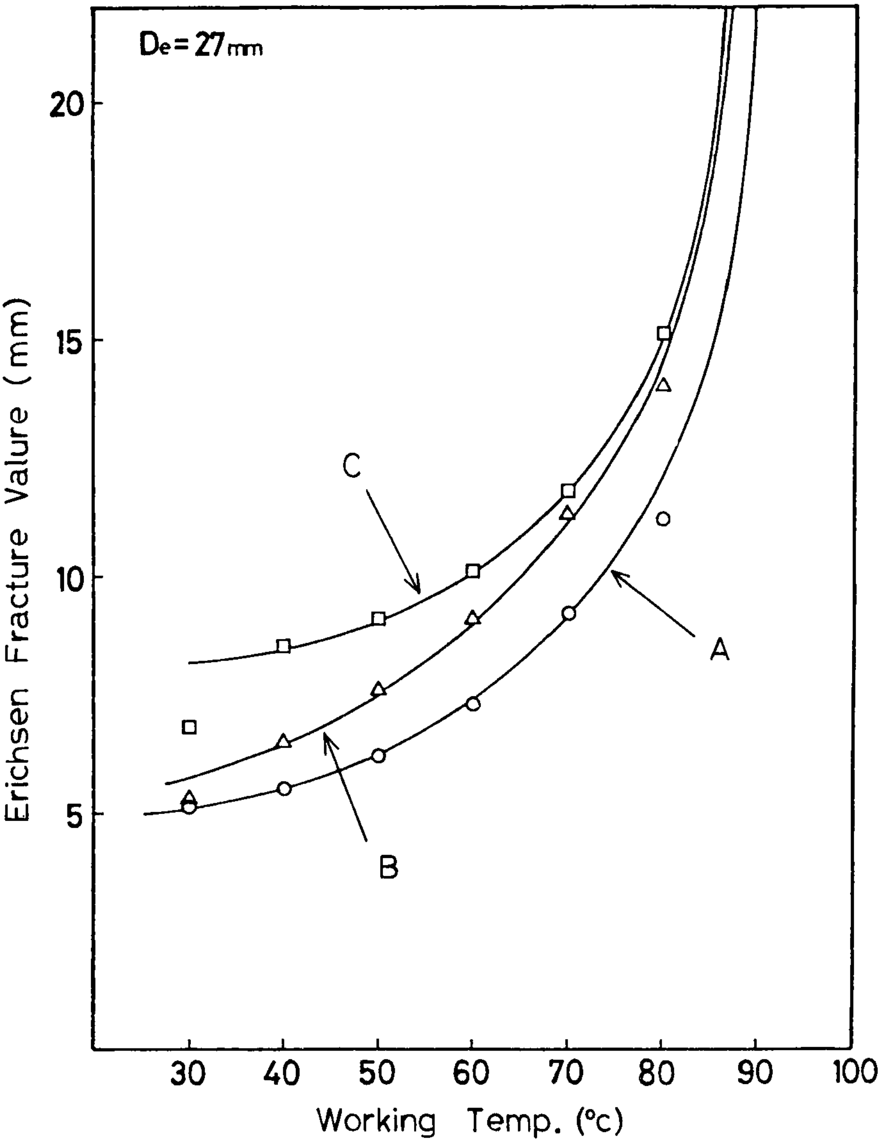

FIGURE 6 Effect of blank thickness on Erichsen fracture values of foamed polystyrene at warm temperatures (inner diameter of the holding die in punch forwarding side: D_e = 27 mm).

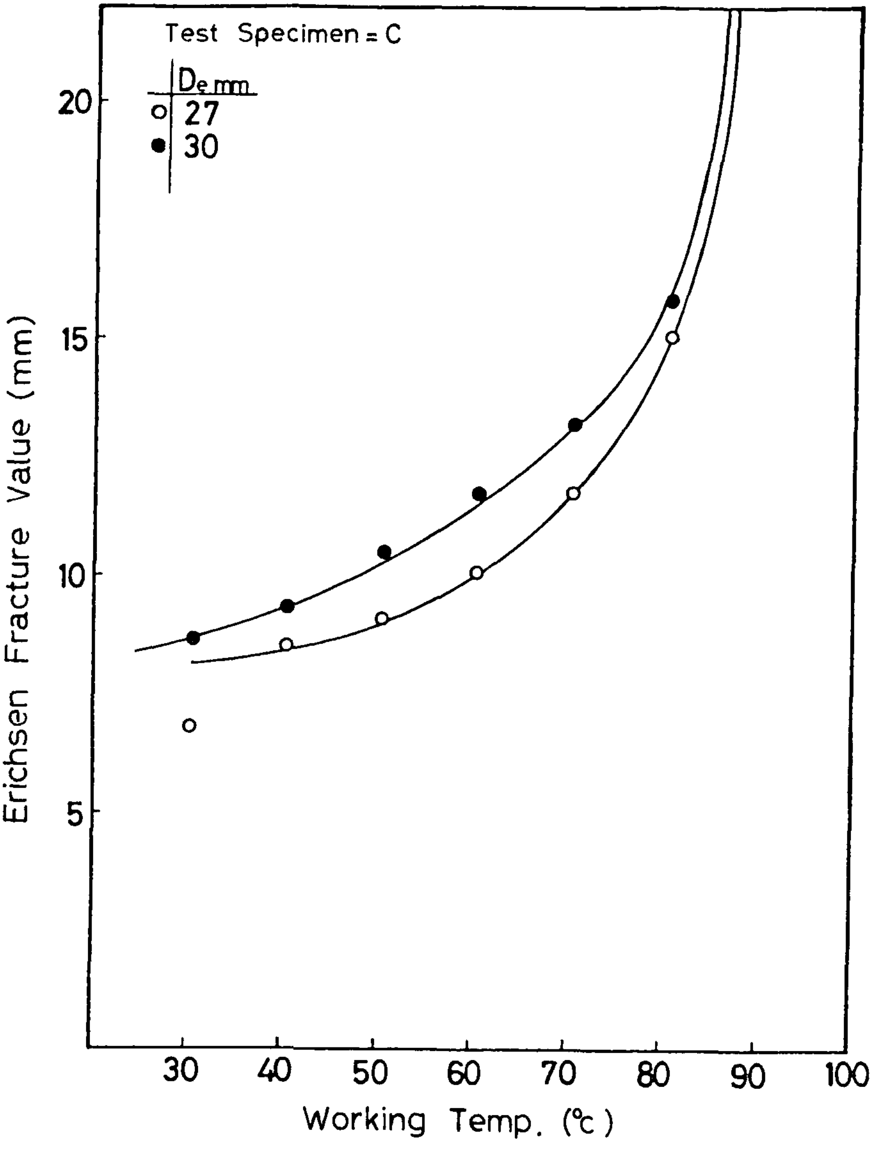

FIGURE 7 Influence of inner diameter of the holding die in punch forwarding side on Erichsen fracture values of foamed polystyrene at warm temperatures (test specimen : *C*).

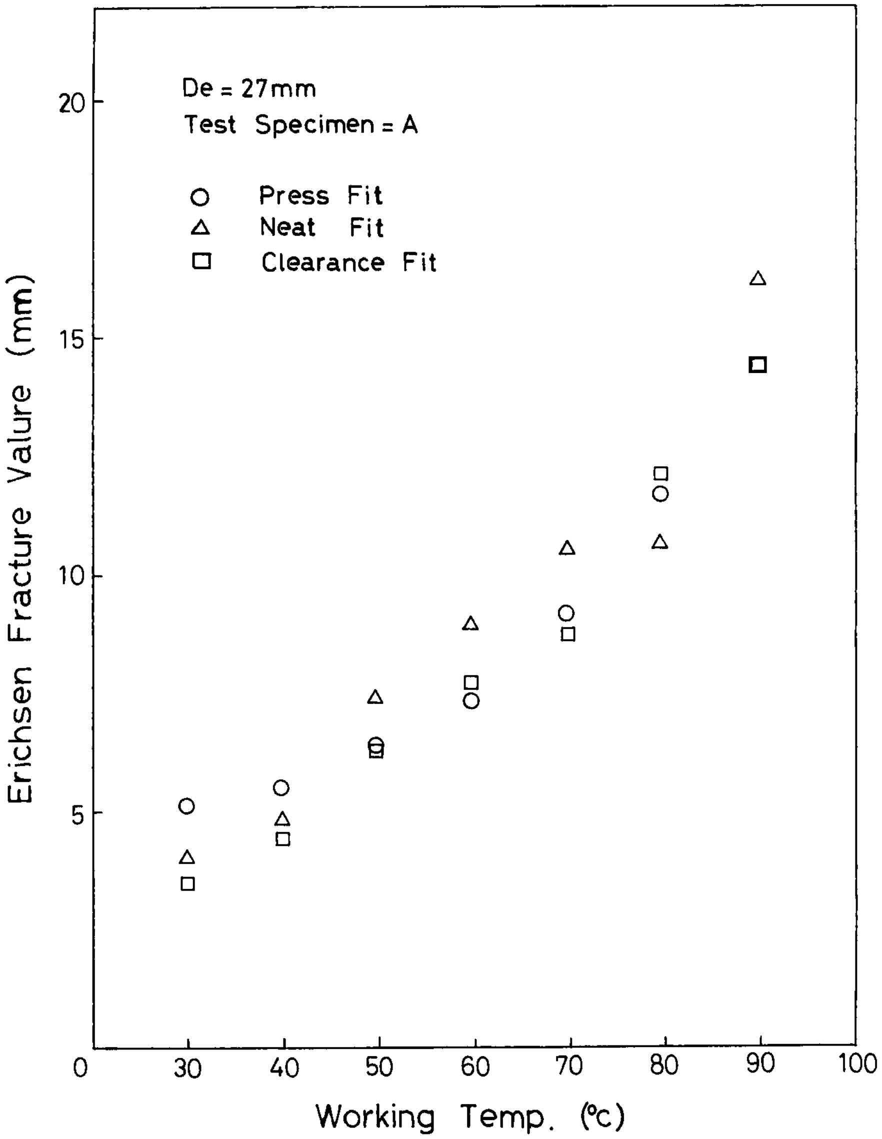

FIGURE 8 Effect of initial clamping conditions of sheet blank on Erichsen fracture values of foamed polystyrene at warm temperatures (test specimen: A, inner diameter of the holding die in punch forwarding side: $D_e = 27$ mm).

4. RETENTIVITY IN SHEET FORMING

Erichsen strain recovery was measured as strain retentivity for complicated sheet forming. The test specimen, to which fixed Erichsen value h_e was processed initially at various temperatures, was free-annealed for about three hours at the temperature higher than initial working temperature in order to evaluate the behavior of retentivity from the amount of the Erichsen recovery of the test specimen. The residual Erichsen value h_r was measured after the annealing, and the ratio of Erichsen strain recovery ε_r in percentage was calculated from the following equation.

$$\varepsilon_r = \frac{h_e - h_r}{h_e} \times 100\,(\%)$$

The Erichsen strain recovery behavior by annealing for the specimens initially processed in $h_e = 9$ mm was investigated. The experimental results are shown in Figure 9 and Figure 10, taking blank thickness and inner diameter of the holding die in punch, as parameters, respectively. Irrespective of initial processing conditions in this experiment, as expected, the Erichsen strain recovery increases greatly in a similar path with annealing temperature rise and then is nearly perfect at the annealing temperature of about 100°C, which corresponds to glass transition temperature of polystyrene. This result can be anticipated from typical amorphous molecular configuration of polystyrene and further highly foamed structure.

5. REMARKS

This paper is a preliminary report of post-forming of foamed polystyrene sheet and further work should be performed with a theoretical approach.

Theoretical analysis on this thermoforming by the penetration of a solid punch should always consider the following two different domains[5] neighboured in the same circular blank.

(Part 1): central domain contacted with solid punch.
(Part 2): circumferential domain fixed with circular boundary.

The ratio of the above two domains is varied with the penetration depth of solid punch. Though for simplicity it is assumed that for rapid practical thermoforming (Part 1) is to be in perfect solidification through the total thickness of the section as soon as the bottom surface contacts with the punch head and (Part 2) is to be in rubber elasticity due to the fact that membrane theory is applicable at elevated temperature in practical high-speed thermo-

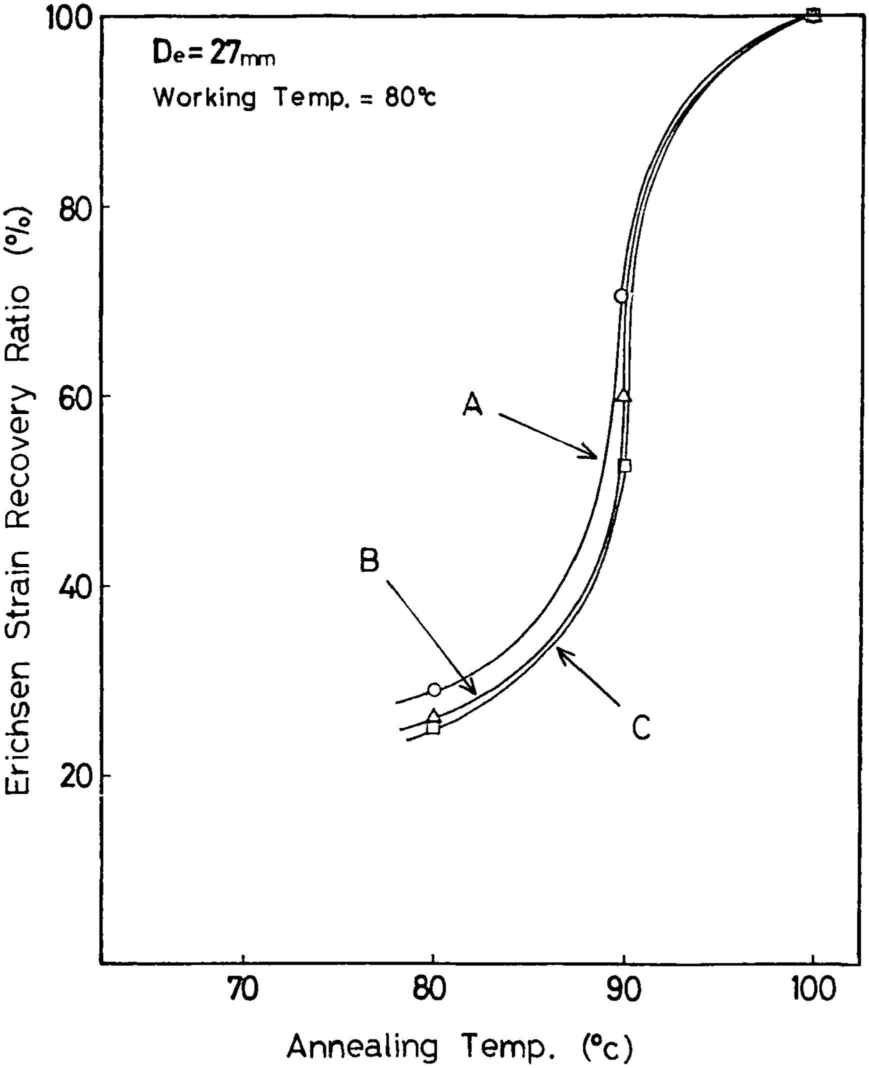

FIGURE 9 Erichsen strain recovery ratio of foamed polystyrene *vs.* annealing temperatures, taking blank thickness as parameter, for the Erichsen specimens initially processed in the depth of 9 mm at 80°C.

forming, this theoretical analysis would be more difficult than that of free thermoforming[15,16] by pneumatic pressure.

The gift of various samples of foamed polystyrene sheet from Sekisui Plastics Corp., Ltd (Japan) is gratefully acknowledged.

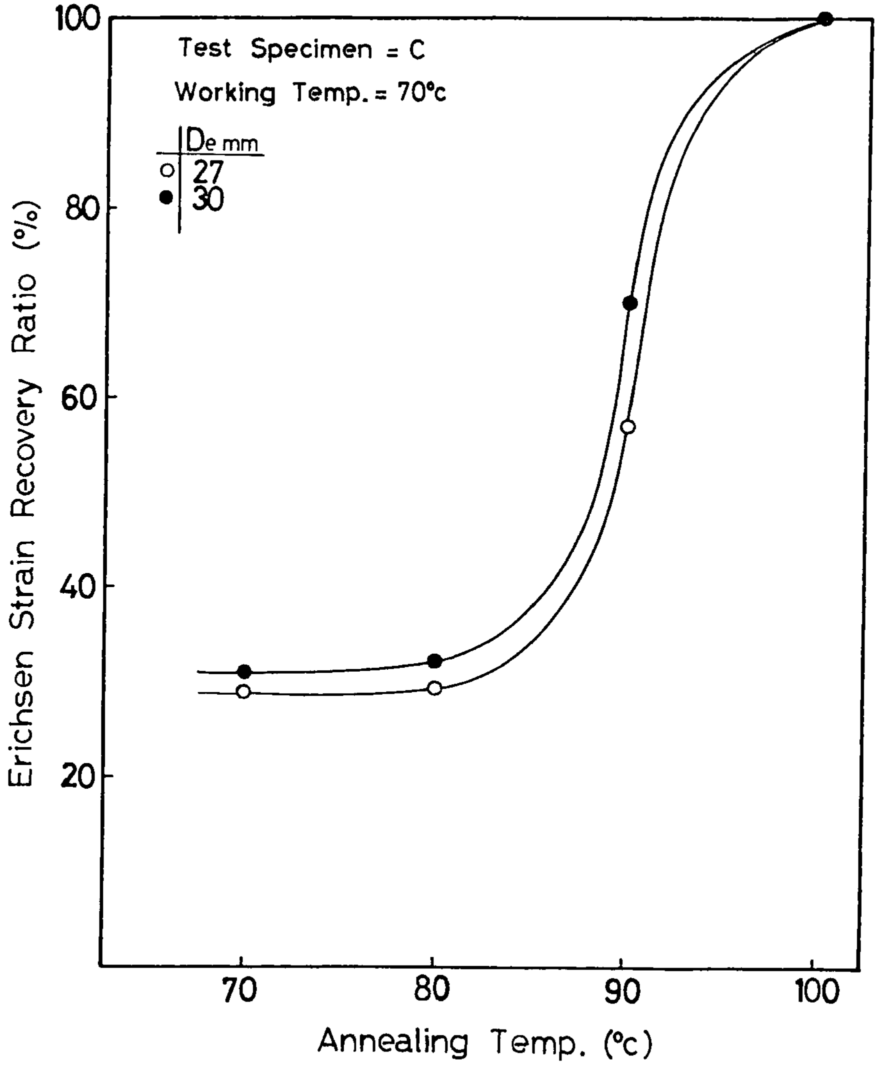

FIGURE 10 Erichsen strain recovery ratio of foamed polystyrene *vs.* annealing temperatures, taking inner diameter of the holding die in punch forwarding side as parameter, for the Erichsen specimens initially processed in the depth of 9 mm at 70°C.

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