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Study of thermal–mechanical properties of polyurethane foam and the three-dimensional shape of molded bra cups

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ABSTRACT

Molded bras nowadays are dominating the overall bra market place, while the bra cups are mostly made of polyurethane foam sheets. The smooth and seamless inner surface of a molded bra cup gives three-dimensional nice fit to the wearer and provides unlimited designs for different softness and thickness. However, it has been a difficult question to determine the optimum molding conditions for various types of foam and there was no reliable method to measure the cup shape conformity. In this study, the properties of five polyurethane foams were investigated by thermal–mechanical analysis (TMA) and their 3D shapes formed in various molding conditions were measured by a Steinbichler Comet scanner and a new parameterization-based remesh algorithm method. The results revealed that the optimal temperature and dwell time for molding bra cups were greatly affected by the thermal–mechanical properties of polyurethane foams. The softening temperature and deformation properties of the foams tested by TMA can facilitate the determination of optimal molding temperature for the desirable cup shape and thickness. This study provides an effective and quantitative approach to eliminate the time-consuming "trial-and-error" in the molding tests traditionally being used in the industry.

1. Introduction

The elastometric microcellular polyurethane (PU) foam is available in a wide range of hardness, thickness, density, thermal, physical and mechanical properties. It is widely used in medical and apparel products as cushioning materials and wound dressing (Campbell et al., 2008; Park et al., 2007; Sakurai et al., 2007). For intimate apparel, PU foam is commonly used to mold 3D seamless bra cups to fit women's breast shapes (Yu et al., 1998). The smooth inner surface of molded cup prevents irritation to the nipples and the outer surface provides a full and round breast shape as desired. Nevertheless, the hasty growth of market has brought significant challenges to the bra industry due to the severe shortages of appropriate molding technologies. How to control the molding process and product quality accurately and effectively becomes a critical question.

When producing bra cups, a contour molding machine with a pair of aluminum male and female molds in specific 3D shape is used. The heated male molds stretch and compress the originally flat foam sheets toward the female molds at a temperature over the foam's material softening point. The high temperature was maintained for about 1 min to allow the heat to transmit through the foam sheets which are held in a space between the male and female molds, so that the foam sheets are heat-set to the desired cup shape. Traditionally, the molded cups are assessed by visual examination against the "plastic shot" which is a transparent cup template used for checking the shape conformity of the outer cup surface (Yip and Ng, 2008). The quality of molded bra cups often varies with different foam materials, molding temperatures and time (Yu et al., 1998).

The processes of developing new master aluminum molds, molding experiments and quality inspection have been involving lots of "trial-and-error" for at least 3 cycles (Myer and Montgomery, 1995). The quality of molded cups such as hand feel, appearance, shape conformity was assessed subjectively based on experience (Yu, 1996). There has been little literature found to provide accurate and reliable guidelines for bra cup molding.

This study therefore aims at studying the relationships between the thermal–mechanical properties of PU foam materials and the optimal molding conditions for the required quality and shape of bra cups. It also presents an objective and quantitative way of assessing the 3D shape of PU foam cups by using 3D scanning and a new parameterization-based remesh algorithm method. This provides useful knowledge for the determination of optimal molding conditions for bra cups.

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Table 1
Specifications and physical properties of the 5 PU foam materials.

Style	Density (kg/m^3)	Cell count (cells per 25 mm)	Extension stress at 8% strain (kPa)	Compression stress at 40% strain (10^6 kPa)	Hardness (°ShD)	Cell Type
Test standard	ISO845-1988	AS2282.5-1999	ISO1798-1983	ISO3386/1-1986	ASTM D2240-05	
A	35.56	47.2	5.7	5.27	52.50	Closed
B	28.23	46.2	2.8	2.16	21.96	Open
C	39.37	49.5	5.8	4.72	53.96	Open
D	45.07	44.3	4.8	4.27	43.98	Open
E	30.71	43.5	5.1	1.15	23.02	Open

2. Experimental

2.1. Physical properties of polyurethane foams

Five PU foam sheets with thickness of 10 mm which are commonly used for bra cup molding were sourced from a large bra cup molding company in the present study. Their physical properties including density, cell count, extension, compression, hardness, and cell type were examined and summarized in Table 1.

2.2. Thermal–mechanical analysis

The thermal–mechanical properties of polyurethane foams were tested by the Thermomechanical Analyzer (Perkin Elmer TMA 7, USA) which determines the deformation of a sample as a function of temperature according to ISO11359-1:1999. Considering the high-strain deformation of foam at molding, a high tension probe load of 50 mN was used to compress the samples of same thickness (10 mm) that were heated from 25 °C to 250 °C at a heating rate of 10 °C/min (Yu, 1996). The compression strains of foam at x °C (ε_x), in absolute values can be calculated by Eq. (1).

$$\varepsilon_x(\%) = \frac{|t_x - t_o|}{t_o} \times 100 \qquad (1)$$

where t_o is the original thickness of foam, t_x is the thickness of foam at x °C while x is set as room temperature 25, the molding temperatures 180, 200 or 220 respectively which are within the common temperature range of 180–220 °C generally used at foam cup molding.

2.3. Foam cup molding process

The PU foams were molded by using a contour molding machine of New Pads molding machine type DM-021HP4-2PR with a pair of size 34B mold heads (including male and female molds) as shown in Fig. 1a and b (Yu et al., 2006).

PU foam sheet was placed on top of the fixed female mold head while the mold heads were heated to a pre-determined temperature under control of thermostats, then the male mold heads were brought down vertically by compression air and released automatically after molding. The setting of molding temperature could be ranged from 180 °C to 220 °C and each adjustment was set at 10 °C interval. The dwell time of the molding process, ranging from 60 to 180 s with 30 s interval for every adjustment, was determined by a time controller. The thickness of the foam cup is affected by the gap distance between the two mold heads, the material properties and molding condition. Specimens were allowed to cool down at room temperature atmosphere for no less than 24 h before the cup shape and cup thickness were measured (Yu et al., 1998).

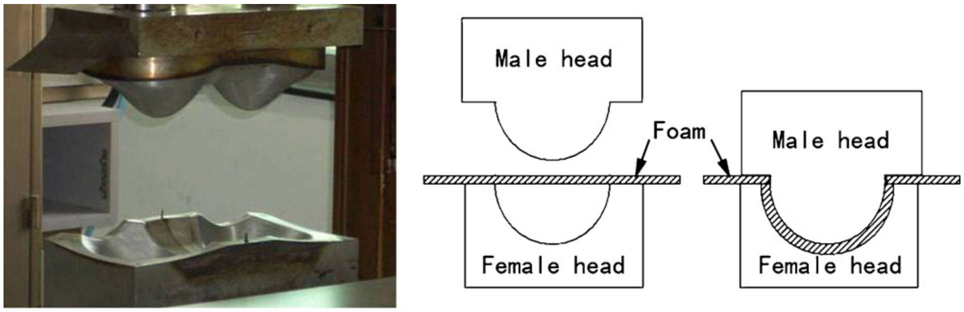
2.4. Measurement of 3D shape conformity

An optical digitization system (Steinbichler Comet scanner, Germany) was used to measure the 3D shape conformity of outer surface of molded bra cups produced in various molding conditions. It applies projected grids and a high-resolution camera to capture 3D images, then accurate data sets can be generated by image analysis (Brosky et al., 2000).

First, the highest bust point of the male mold head was defined. To measure the deviation of corresponding points on different scanned cup surfaces, a parameterization-based remeshing and registration algorithm method was used to characterize the 3D shapes of the convex surface of the scanned bra cups and a software interface was developed. The female mold head was set in a reference mesh, the outer surface of foam cup samples were then remesh based on the reference mesh. A rigid transformation was computed by matching the corresponding vertices around the bra cup peak. As shown in Fig. 2, the scanned surface of aluminum mold head and the fitting surface of a molded cup have been transformed respectively into 2D meshes for easy comparison.

By aligning the bust point, the shape difference between the mold head and the outer surface of molded cup can be measured by a summation of deviations at all corresponding points in the two meshes as shown in Fig. 3.

To quantify the degree of overall shape conformity between the molded cups and the mold head, the percentages of deviations



(a) The contour molding machine with male and female mold head.

(b) Schematic diagram of contour molding method

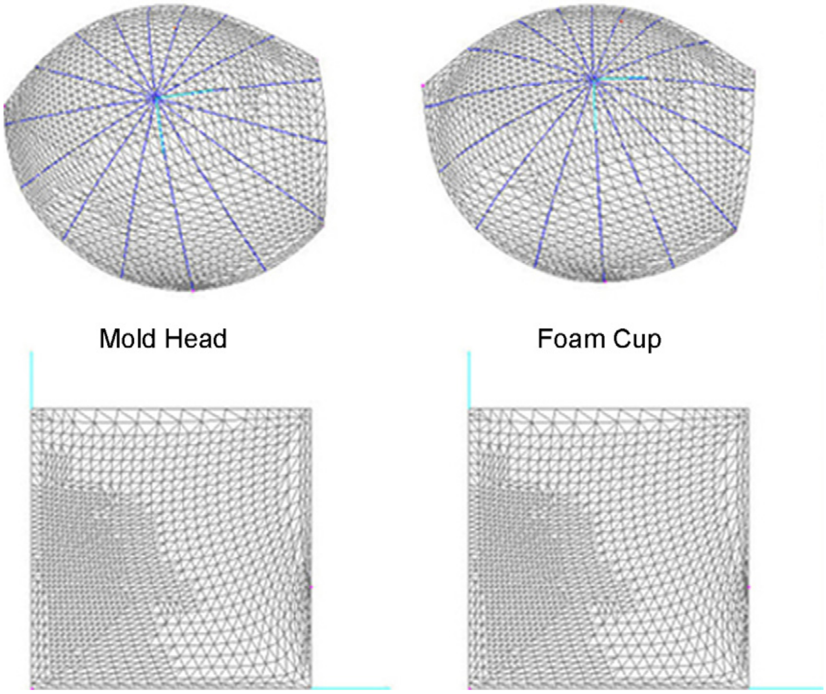


Fig. 2. A software interface of calculating deviation.

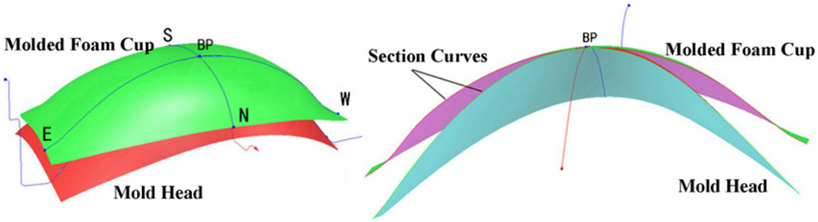


Fig. 3. Shape deviation between mold head and molded cup.

between corresponding points are calculated as

$$T_1 = \frac{\sum \mathrm{Num}(|X_i - M_i| \le 1\,\mathrm{mm})}{\sum \mathrm{Num}(|X_i - M_i| \le 10\,\mathrm{mm})} \times 100\% \qquad (2)$$

$$T_2 = \frac{\sum \mathrm{Num}(|X_i - M_i| \le 1\,\mathrm{mm})}{\sum \mathrm{Num}(X_i - M_i)} \times 100\% \qquad (3)$$

where T_1 is the calculated percentage of points which have deviation less than 1 mm in comparing with the number of points which have deviation less than 10 mm; while T_2 is the calculated percentage of points which have deviation less than 1 mm at 3 cm radius around the cup tip since the shape conformity at the cup tip region is critical and traditionally assessed in the industry. M_i is the arbitrary coordinate on the mold head and X_i is the corresponding coordinate on the molded cup. The function Num(i) is a number count of sampling points.

2.5. *Measurement of bra cup thickness*

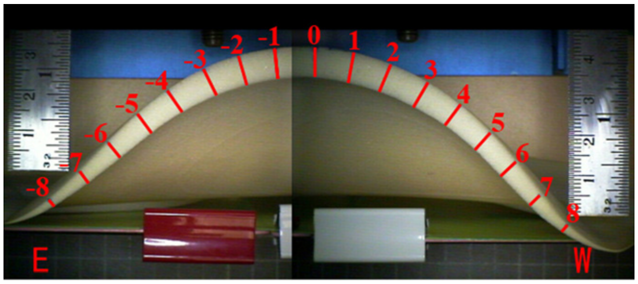
In the industrial practice, the thickness of molded bra cups were measured by cutting cross-sectional horizontal and vertical lines passing through the cup peak. This has to destroy the cup sample and involved handling errors. Yu et al. (1997) used non-contact moire topography and curve fitting to measure the thickness of molded foam cup along West–East (W–E) and North–South (N–S) directions. However, moire method gave limited resolution for

In this study, a non-contact optical microscopy measuring instrument (LEICA QWin, Germany) was adopted to scan the foam cups as shown in Fig. 4. The cup peak was identified by computer software. Measurement points on the outer surface with equal distance of 10 mm between each point were used for thickness measurement along the horizontal and vertical cross-sectional lines passing through the cup peak. As the outer curve is longer than the inner curve, perpendicular lines intersecting each measurement point on the corresponding tangent touching the outer cup surface were drawn to measure the thickness at specific marked locations.

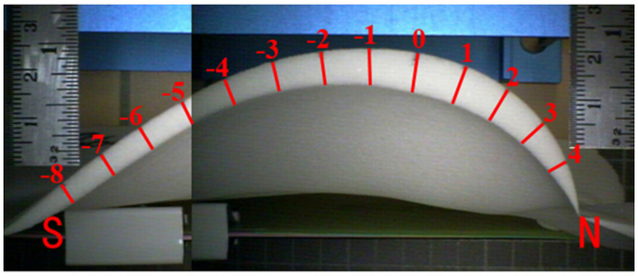
3. Results and discussion

3.1. *Thermal–mechanical properties of polyurethane foams*

The TMA scans of the 5 PU foams under constant load of 50 mN are presented in Fig. 5. The extrapolated onset temperatures of the compression curves indicate the softening points of the 5 foams respectively. It is obvious from the TMA scans that foams B, C, D and E are very stable and do not show significant deformation until 120–160 °C. On the other hand, foam A started deforming at a much lower temperature (around 60 °C) and the foam further deformed at temperature of 165 °C. Physical cross-linking between hard segments was substantially damaged around 220 °C in foam A. For the other 4 foams, such failure of physical cross-linking did not start



(a) **Horizontal cross-section line (W-E)**



(b) **Vertical cross-section line (N-S)**

Fig. 4. Thickness measurement of molded cup sample along W–E and N–S directions. (a) Horizontal cross-section line (W–E) and (b) vertical cross-section line (N–S).

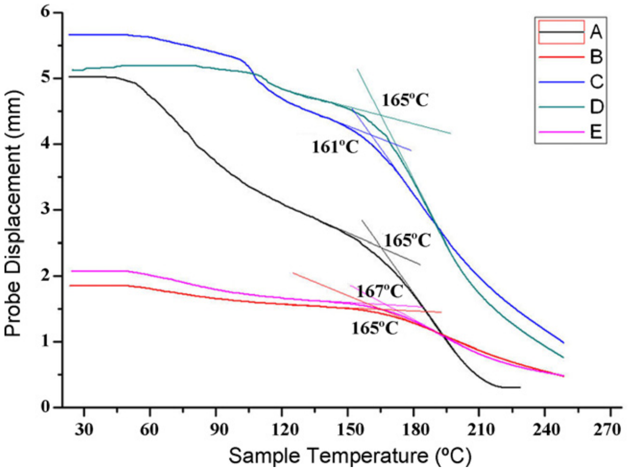


Fig. 5. TMA scans of different polyurethane foams.

The compression strains of foam materials in a 50 mN load under different temperatures are reported in Table 2. The value at 25 °C (ε_{25}) of foams B and E are much higher than those of foams C and D due to their lower density and hardness as presented in Table 1. Foams with lower densities (foams B and E) generally have lower compression resistance (i.e. indentation hardness) than high density foams (foams C and D). However at the softening temperature range of 180–220 °C, the compressive strains (ε_{180}, ε_{200} and ε_{220}) of foams C and D increased substantially. The results indicate that high density foams showed major deformation behaviour at high temperatures, whilst the effects of high temperatures on low density foams were relatively less significant. The values of compressive strains only increased gently with the increase of heating temperature in foams B and E.

Although foam A has a relatively high density of 35.56 kg/m^3 with a low compressive strain of 50.40% at 25 °C (ε_{25}), it started deforming obviously at around 60 °C. The compressive strain increased extraordinarily to 96.92% at 220 °C (ε_{220}). This may be explained by the fact that foam A has a closed-cell structure which has different plastic compositions from that of the open-cell structures in other four foam samples (Klempner and Sendijarevic, 2004). PU is made up of the PEG (polyethylene glycol) and the TDI (Toluene diisocyanate). The melting point of the PEG soft segment is about 50 °C (Su and Liu, 2007). Foam A has a higher content of soft segment as compared with the other four foams in this study. When the temperature exceeds the melting temperature of PEG, the plentiful soft segments start to fuse and the elastic properties of the foam began to decline. Foams B, C, D and E have higher contents of hard segment and thus withstand deformation at high temperatures more effectively.

As the soft PU foams under investigation have cross-linked thermosetting properties, the processing temperature of foam cup molding could range between the lower region of the softening point of hard segment and the upper region of pyrolysis temperature (Jiang et al., 2006). This phenomenon indicates that the softening temperature obtained from TMA scans can be taken as the lower bound of bra cup molding temperature, for example, 165 °C for foam A.

3.2. *Foam molding performance and 3D shape conformity of foam cups*

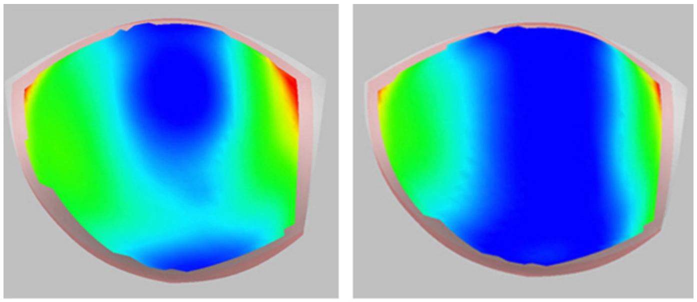
The molding results revealed that molding temperature and dwell time greatly affect the foam cup performance. It is evident that high molding temperatures and long time applied generally resulted in better shape conformity in all of the 5 foams studied. Nevertheless, excess molding temperature not only resulted in high incidence of yellowing, bubbling and hand feel problems, but also failed to conform to the desirable shape of the mold head. Fig. 6 shows the spectrums of the mean deviations between the mold head and the cup samples of foam D obtained at various molding conditions.

When the molding temperature was 180 °C and the dwell time was 60 s, large deviations were observed between the two surfaces as in Fig. 6(a). The minimum deviations were found at 190 °C and 120 s as in Fig. 6(b). When molding temperature reaches 210 °C and/or the dwell time prolonged to 180 s, the level of shape conformity declines readily as shown in Fig. 6(c) and (d). It is noteworthy that relatively large deviations existed at two sides of the cup rim in all molding conditions. The results can be explained by the mechanical loadings applied to the foam sheet during the molding process as the cup rim had the largest geometric deformation of compression and extension (Yu et al., 1998).

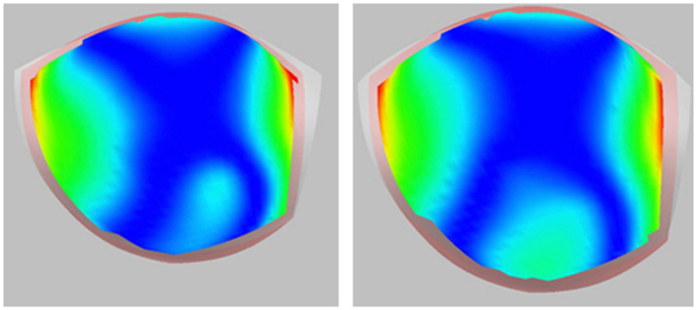
Using Eqs. (2) and (3), the shape conformity is defined as the percentage of point deviations between the mold head and the foam

Table 2
Thermo-mechanical properties of foam at 50 mN load.

Sample	t_o (mm)	t_{25} (mm)	ε_{25} (%)	t_{180} (mm)	ε_{180} (%)	t_{200} (mm)	ε_{200} (%)	t_{220} (mm)	ε_{220}
A	10.12	5.02	50.40	1.72	83.00	0.8	92.09	0.31	96.92
B	9.97	1.85	81.44	1.29	87.06	1.01	89.87	0.75	92.50
C	9.98	5.66	43.30	3.24	67.54	2.36	76.36	1.68	83.22
D	10.00	5.12	48.81	3.44	65.61	2.18	78.20	1.41	85.87



(a) Foam D at 180ºC and 90 seconds (b) Foam D at 190ºC and 120 seconds



(c) Foam D at 190ºC and 180 seconds (d) Foam D at 210ºC and 90 seconds

Fig. 6. Spectrums of mean deviations between mold head and cup samples (Foam D) at various molding conditions (small deviations in blue and large deviations in red). (a) Foam D at 180 °C and 90 s, (b) foam D at 190 °C and 120 s, (c) foam D at 190 °C and 180 s and (d) foam D at 210 °C and 90 s.

Table 3
Optimum molding conditions for the 5 foam materials studied.

Foam	Temperature (°C)	Dwell time (s)	T_1	T_2
A	180	180	38.62%	94.34%
B	200	90	40.10%	89.47%
C	190	120	38.62%	96.97%
D	190	120	41.85%	98.68%
E	200	90	35.54%	80.67%

cups obtained at various molding conditions. The minimum deviation determines the optimum molding conditions for the 5 foam materials as presented in Table 3.

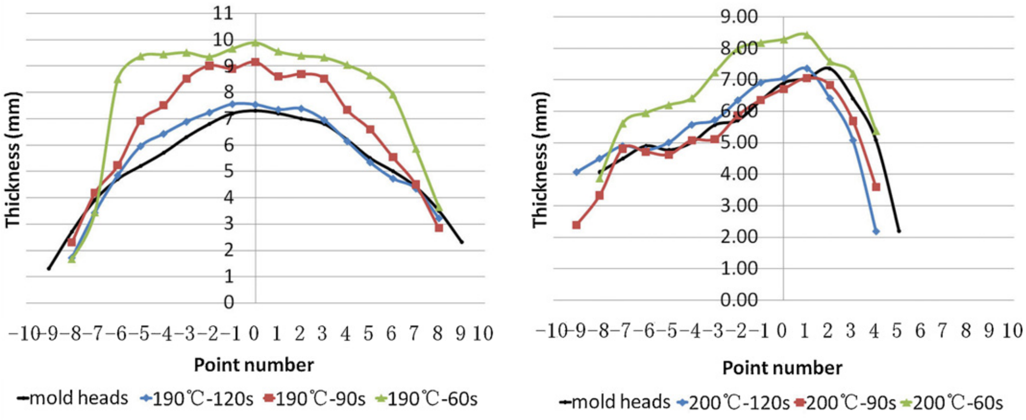
Foam A has a lower optimum molding temperature as compared with the other 4 foam materials. It is evident from the TMA curve that foam A is highly sensitive to thermal changes and starts deforming at 60 °C. To achieve the desirable cup shape, a lower temperature must be used in foam A, whilst a relatively longer dwell time is recommended. For low densities foams (foams B and E), a higher molding temperature is recommended, whilst the dwell time should not be too long to avoid potential problems of foam yellowing and bubbling. On the other hand, the molding temperature of high densities foams (foams C and D) should be lower than those low densities foams.

It is also noteworthy that even though the optimum molding conditions were determined, the shape of foam cup may not necessarily fits the aluminum mold head perfectly. Amongst the 5 foam materials studied, the degree of shape conformity of the foam cups was around 40%. The degree of shape conformity at the cup tip region ranged from 80.67% to 98.68% at deviations less than 1 mm level. Bra manufacturers therefore can quantify the desired degree of shape conformity at cup tip region at 80% target level so as to control the molding process more effectively

3.3. *Thickness of foam cups*

The thickness of foam cups at various locations along the N–S and W–E directions is measured. It is obvious that the foam cup thickness of all of the 5 foams decreases with increased dwell time until the optimum dwell time is reached. When the dwell time is too short, significant thickness variations are observed around the bust point position, whilst small variations are found at cup rims because it has the largest geometric deformation during the molding process. However, prolonged dwell time could also result in excessive thermal shrinkage, in which the foam cup thickness is thinner than the gap between mold heads.

Fig. 7(a) shows the thickness (gap distance) between the male and female mold heads and the cup thickness of foam D at the molding temperature of 190 °C with dwell times of 60, 90 and 120 s respectively. After comparing against the mold head curve, the optimum dwell time of foam D at molding temperature of 190 °C is found to be 120 s, the thickness of the cup sample matches perfectly with the gap distance between the male and female mold heads. Fig. 7(b) reveals that the optimum dwell time of foam B at molding temperature of 200 °C is 90 s. These results also coincide with the optimum molding conditions obtained by measuring the 3D shape conformity of foam cups.



(a) Cup thickness along W-E direction of Foam D molded under 190ºC

(b) Cup thickness along N-S direction of Foam B molded under 200ºC

Fig. 7. Thickness of cup samples measured at various locations. (a) Cup thickness along W–E direction of foam D molded under 190 °C and (b) cup thickness along N–S

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