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ORIGINAL ARTICLE

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Optimising the thermoforming process of polymeric foams: an approach by using the Taguchi method and the utility concept

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Abstract The use of the conventional Taguchi method for determining the optimum setting of controllable factors through off-line experiments focuses on products with a single quality characteristic or response. However, most products have several qualitative characteristics or responses of interest. The Taguchi method in itself optimises a single response or performance characteristic, yielding a set of process parameters. This particular setting, however, may not give the desired results for other characteristics of the product. There is a need to obtain a single optimum setting of process parameters that can be used to produce products with optimum or near optimum quality characteristics as a whole. Multi-characteristic response optimisation may be the solution to the above problem. In this report, a case study on thermoforming polypropylene foams, utilising a simplified multi-criterion methodology based on Taguchi's approach and utility concept, is discussed. Key processing factors affecting product quality are identified. It has been shown that the proposed Taguchi approach with the utility concept can provide an appropriate solution to yield a satisfactory product quality for a multi-response process optimisation problem.

1 Introduction

The design optimisation problem [1, 2, 3, 4, 5, 6, 7, 8, 9] is a cost-effective method for improving product/process quality that is determined by an optimum set of values for controllable variables, from the point of view of its robustness versus various uncontrollable variables. The design of high-quality products/processes at low cost leads to increasing market share and increasing, continuous customer loyalty. Robust design based on the Taguchi method, which combines experimental design techniques with quality loss consideration, is an engineering approach to quality improvement that seeks to obtain a lowest cost solution to the product design specification based on the customer's requirement. The application of the Taguchi methods to plastic and composite processing has been attempted by a number of researchers. These include applications in the areas of injection moulding [10, 11] and compression moulding [12] as well as in extrusion of polymeric materials [13, 14].

One of the limitations of the Taguchi technique is that for determining the optimum setting of controllable factors through off-line experiments, Taguchi's work focuses on products with a single qualitative characteristic or response. However, most products have several qualitative characteristics or responses of interest [15]. The Taguchi method in itself optimises a single response or performance characteristic, yielding a set of process parameters. This particular setting, however, may not provide the desired results for other characteristics of the product. In such cases, there is a need to obtain a single optimum setting of process parameters, which can be used to produce products with optimum or near optimum quality characteristics as a whole. Multi-characteristic response optimisation may be a solution of the above problem [16].

In this report, a case study on the thermoforming of polypropylene foams, utilising the simplified multi-criterion methodology based on Taguchi's approach and utility concept, is discussed.

1.1 Thermoforming and its characteristics

Thermoforming [17, 18] of thermoplastic materials and foams has become an important process in industry due

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to its low cost and good formability. It outperforms other competitive processes such as injection moulding and compression moulding because it uses simpler moulds and a much lower forming pressure. Thermoforming is the process of choice where short production runs cannot justify the expense of the more expensive injection tooling, or where short lead times from design to production are critical. It is most widely used in the packaging industries. Other applications include production of large parts such as refrigerator door liners, bathtubs, signs and automotive interior trims. Thermoforming of foamed structures provides several advantages in thermoplastic products. Advantages include lightweight, excellent strength/weight ratio, superior insulation abilities, and energy absorbing performance (including shock, vibration, and sound).

Although the thermoforming process has been developed for over two decades, there are still some unsolved problems that confound the overall success of this technology. Non-uniform thickness distribution caused by inappropriate mould design and processing conditions is one of them. Conventionally, moulders optimise the thickness of thermoformed parts using a time-consuming trial-and-error process.

2 Process parameters of the thermoforming process

In the thermoforming process [17], a thick sheet is clamped in a frame and is heated to a temperature well above its glass transition temperature so that it becomes rubbery and soft. The sheet is then placed over a mould and stretched to obtain the contours of the mould, either by plug assist or a differential pressure (Fig. 1a). During forming, the foamed sheet thins, which makes it necessary to optimise the process before moulding a part. The following process parameters may affect the quality of the thermoformed parts [17]:

1. Temperature related parameter—heating temperature and heating time of the heating pipes
2. Material related parameter—foam or non-foamed, sheet thickness
3. Pressure related parameter—vacuum pressure
4. Assisting plug-related parameter—plug material, moving speed, and moving distance

The following five process parameters were identified as potentially important in affecting the qualitative characteristics of thermoformed products under consideration [18].

1. Heating temperature (while keeping heating time constant)
2. Vacuum pressure
3. Plug material
4. Plug speed
5. Plug displacement

To select the range of parameters for evaluation, a few test trials were first completed to determine the range of parameter values with which the parts could be successfully moulded. Some arbitrary values were then chosen among these formable ranges of parameters for the subsequent statistical analysis. The moving speed of the assisting plug was set to either 27, 24 or 21 centimetres per second. The vacuum pressure was maintained at 0.03, 0.06 or 0.09 Mpa. The temperature of the heating pipes was kept at 150, 160 or 170°C. The heating time for all foams was set to be 20 s. Three different materials were selected to make the plugs, including wood, polyoxymethylene (POM) and phenol formaldehyde (PF). Finally the plug displacement was set to be 9.8, 9.4 and 9.0 cm, which were 98%, 94% and 90% of the maximum displacement (10 cm). Table 1 lists the factors and factor levels selected in the main experiment.

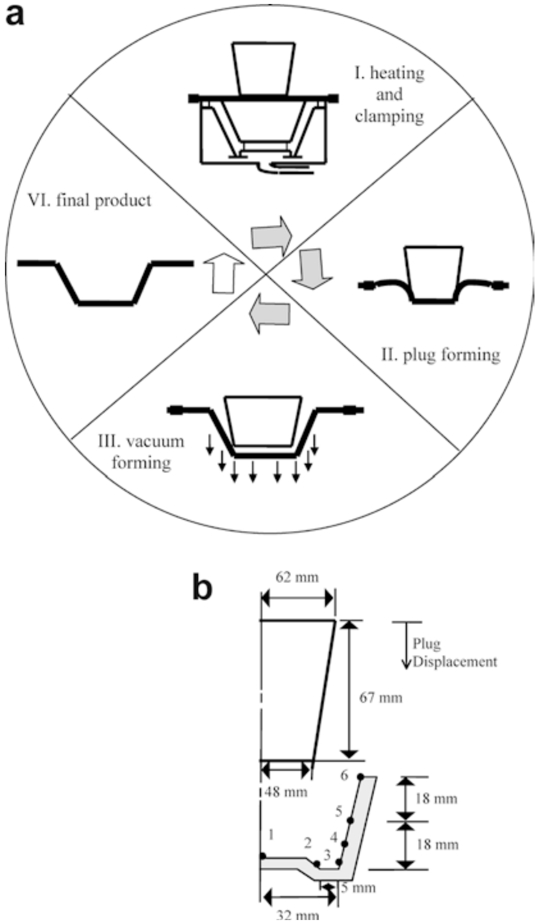

Fig. 1 a Schematic of the thermoforming process, **b** Axisymmetric geometry of the mould and the assist plug

3 Qualitative characteristics of thermoformed parts

The outcome of any process is judged by the quality of the final product. The quality of thermoformed foam parts is characterised by the part thickness distribution [18]. The thickness at six different locations (marked positions 1–6) in Fig. 1b was selected to evaluate the quality of thermoformed foams. It is necessary to

Table 1 Factors and factor levels selected in the main experiment

Factors	Level 1	Level 2	Level 3
A: Plug velocity (cm/sec)	27	24	21
B: Vacuum pressure (Mpa)	0.03	0.06	0.09
C: Heating pipe temperature (Â°C)*	150	160	170
D: Plug material	Wood	POM	Phenol formaldehyde
E: Plug displacement (% relative to the maximum displacement of 10 cm)	9.8 cm (98%)	9.4 cm (94%)	9 cm (90%)

* The heating time was 20 s

optimise the performance characteristics of the product as a whole. A simplified multi-criterion methodology based on Taguchi's approach and utility concept (given below) is used to achieve the objective of this study.

4 The utility concept

A customer evaluates a product based on a number of diverse qualitative characteristics. To be able to make a rational choice, the evaluations of various characteristics should be combined to give a composite index. Such a composite index represents the utility of a product. The overall utility of a product measures the usefulness of that product in the eyes of an evaluator. However, the utility of a product with respect to a particular characteristic measures the usefulness of that particular characteristic only.

Kumar et al. [15] proposed the Taguchi method and utility concept to optimise the V–process castings of Al-7% Si alloy. They assumed that the overall utility of a product is the sum of utilities of each of the quality characteristics in their model. This technique and concept was applied in this report to optimise the thermoforming of plastic foams. During forming, the sheet thins, which makes it necessary to optimise the process before moulding a part. The Taguchi method can only predict the optimum processing set for the thickness at one of the measured points. Nevertheless the same optimum processing conditions may not lead to the optimum thicknesses for the other measured sites. Therefore, the utility concept was adopted to obtain the optimum setting for the whole thermoformed part.

In addition, the thickness at each measured point (of points 1–6) was influenced by how much the sheet was stretched, how high the sheet temperature was (since the mechanical property of the sheet decreased with increased temperature), how fast the sheet stretched (due to the visco-elastic effect of the polymer materials), how much the sheet formation was assisted by the plug and how quickly the plug eliminated the heat and cooled the plastic sheets. The thickness at one point on the formed parts was not influenced by the thicknesses of the other points. Therefore it was assumed that the different attributes (the thickness at different points of thermoformed parts) were independent and that there was no interaction between them.

Thus if X_i is the measure of effectiveness of an attribute (thickness) i and there are n attributes evaluating the outcome space, then the joint function can be expressed as

$$U(X_1,X_2,...,X_n) = f(U_1(X_1),U_2(X_2),...,U_n(X_n)) \qquad (1)$$

Where $U_i(X_i)$ is the utility of the ith attribute [15].

For simplicity, when attributes X_i's are independent and there is no interaction between them, the overall utility function can be a linear sum of individual utilities. The overall utility function becomes

$$U(X_1,X_2,\ldots,X_n) = \sum_{i=1}^{n} U_i(X_i) \qquad (2)$$

Depending on the customer's requirements, the attributes may be given priorities or weights. Therefore, the general or weighted form of Eq. 2 can be written as

$$U(X_1,X_2,\ldots,X_n) = \sum_{i=1}^{n} W_i u_i(X_i); \text{ where } \sum_{i=1}^{n} W_i = 1 \qquad (3)$$

where W_i is the weight assigned to attribute i. The utility function is of the "higher the better" type. If the composite measure (the overall utility) is maximised, the qualitative characteristics considered for the evaluation of utility are automatically optimised (maximised or minimised, whichever the case may be). To determine the utility value for a number of quality characteristics, a preference order is considered. These orders are weighted to obtain a composite number (overall utility) [15].

5 Optimisation algorithm and experimental method

5.1 The multi-response optimisation procedure

In this report, a step-by-step procedure using the Taguchi method and utility concept [19] was proposed. The steps are:

1. Determining the problem
2. Determining the performance characteristics and the measuring system
3. Determining the variables affecting the performance characteristics
4. Determining the number and values of the levels
5. Selecting appropriate orthogonal arrays and assigning the variables to the suitable columns

6. Determining the loss functions and performance statistics
7. Conducting experiments, recording results
8. Assigning weights, W_i, $i=1,2...n$, to various quality characteristics based on experience and the end use of the product such that the sum of the weights is equal to 1
9. Analysing data and finding the optimum setting of the process parameters for optimum utility
10. Predicting the individual characteristic values in consideration of the optimum significant parameters determined in step 9
11. Conducting a confirmation experimentation at the optimum setting and comparing the predicted optimum values of the qualitative characteristics with the actual ones
12. Evaluating and implementing

5.2 Experimental matrix design

To identify the relative significance of these five factors, each one with three levels demands a large array of experiments with as many as 3^5 runs. A statistics-based design of experiments, the Taguchi method [20], was used to reduce the experimental runs. The main experiment was comprised of 18 test trials, designed based on the L18 orthogonal array (Table 2). Five specimens were tested for each test trial. Shorter arrays would be too simplified and would not produce enough data to properly analyse the process and longer arrays would complicate the process. The optimum processing condition was obtained by combining all the levels that have the optimum thickness distribution of thermoformed foam parts.

Table 2 L'18 (3^5) Orthogonal array used in the main experiment

Run	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	2	1	1	2	2
5	2	2	2	3	3
6	2	3	3	1	1
7	3	1	2	1	3
8	3	2	3	2	1
9	3	3	1	3	2
10	1	1	3	3	2
11	1	2	1	1	3
12	1	3	2	2	1
13	2	1	2	3	1
14	2	2	3	1	2
15	2	3	1	2	3
16	3	1	3	2	3
17	3	2	1	3	1
18	3	3	2	1	2

5.3 Method

The sheet used for the experiments was polypropylene foam with an initial thickness of 3.0 mm. Thermoforming experiments were conducted on a lab-type thermoforming machine that was specially designed and built for this study. After the thermoforming experiment, the thickness of the polypropylene foam parts was selected at six different locations (marked positions 1 to 6) in Fig. 1b for evaluation. The selection of these points was to ensure sufficient coverage of the mould. Parts were cut across their cross section and were observed and measured under an optical microscope.

During the thermoforming process, the foamed sheet thins due to stretching. A decrease in part thickness leads to a decrease in the mechanical properties of the part. It is necessary to optimise the process before moulding a part. The maximisation of the part thickness is the goal of the optimisation. In the analysis, a signal-to-noise (S/N) ratio is the statistical quantity representing the power of a response signal divided by the power of the variation in the signal due to noise. The S/N ratio is derived from the loss function and assumes different forms depending on the optimisation objectives. The maximisation of the S/N ratio leads to the minimisation of properties sensitive to noise. Since maximisation of part thickness is the goal of optimisation, the equation describing the "larger-the-better" characteristic [20] can be used for the analysis (which is consistent with the concept of consumer's maximum utility):

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\log_{10}\left[\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)\right] \qquad (4)$$

where y_i is the measured thickness, and n corresponds to the number of samples in each test trial. The optimum factor levels with the largest S/N ratios could then be obtained, which would minimise sensitivity over the range of noises. Table 3 lists the S/N response at various locations of the thermoformed polypropylene.

6 Analysis of data

6.1 Taguchi analysis with different weights

The S/N ratios for the thickness distribution were calculated with respect to different positions (position 1 to position 6) in Fig. 1b in the polypropylene foam parts; the results are shown in Figs. 2, 3, 4, 5, 6 and 7, respectively. Based on these figures, the optimum factor levels that could statistically result in the largest thickness at different positions were predicted to be different. For example, the optimum factor levels (to obtain the maximum part thickness) for position 1 and position 3 were A3/B3/C1/D1/E1 and A1/B1/C1/D2/E1, respectively. (The optimum settings for these two points were obtained by reading the signal-to-noise response graphs in Figs. 2 and 4. For position 1, for instance, A3/B3/C1/

Table 3 Tabulation of S/N response at different positions of the thermoformed polypropylene foams

Run	Position 1 S/N (dB)	Position 2 S/N (dB)	Position 3 S/N (dB)	Position 4 S/N (dB)	Position 5 S/N (dB)	Position 6 S/N (dB)
1	4.792004	1.248632	5.024651	6.378832	−3.32225	−0.5457
2	5.520228	−3.36668	−0.79743	−8.63185	−4.21855	1.173927
3	5.13829	−0.04988	−8.13583	−10.012	−7.78874	−4.15987
4	3.36089	−0.93995	−2.01281	−4.56232	−0.94158	2.824009
5	4.949824	1.043009	−7.51327	−12.9462	−8.97137	−3.04343
6	5.562629	−0.21102	−2.76282	0.49173	−8.21974	−4.28037
7	4.801776	−0.82336	−2.05325	−2.65251	−3.78604	1.567069
8	3.959454	−1.17929	−1.42059	0.511866	−4.22335	−3.39726
9	7.102496	1.989846	−2.30588	−6.08177	−5.64131	−3.03305
10	4.02187	0.955156	−1.14679	−3.99145	−1.55931	5.543743
11	5.987845	1.267526	−5.24834	−8.67311	−4.52219	2.470694
12	6.795805	2.166123	2.233031	−2.65872	−9.52906	−5.88086
13	4.301366	0.171652	−2.58248	−2.97698	−0.1909	4.05465
14	5.499142	2.345893	−0.15374	−4.31592	−4.98885	1.585883
15	6.706521	3.167775	−1.67554	−9.237	−4.34589	−1.72644
16	3.954154	0.267285	−1.05167	−2.90004	0.86275	4.553839
17	6.510565	1.874722	−7.38395	−9.63434	−4.20062	−0.0527
18	6.092485	0.491495	−4.83717	−9.4832	−5.64207	1.475092

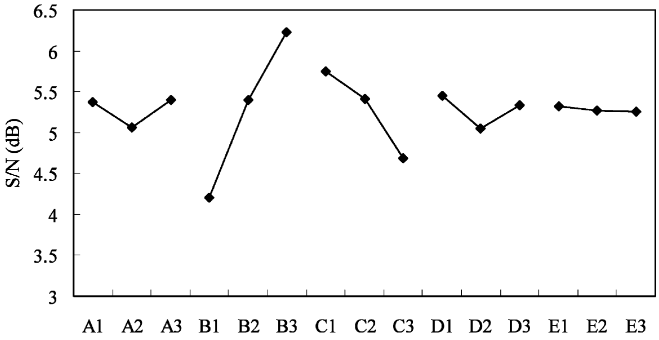

Fig. 2 Variation of the S/N ratio with factor level for various points (position 1)

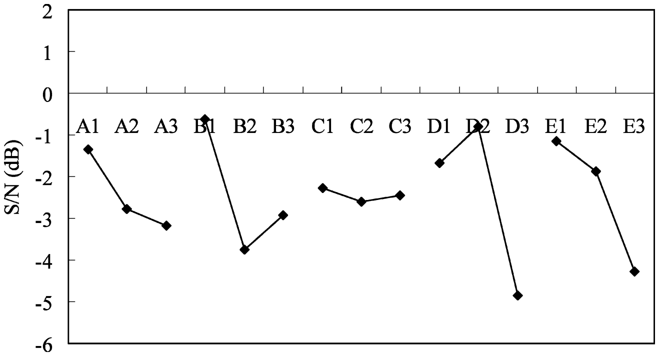

Fig. 4 Variation of the S/N ratio with Factor Level for Various Points (position 3)

D1/E1 were recommended since they were the highest points on the response graph of Fig. 2.) Obviously, these factor level two settings were not identical. Thus, a trade-off must be made between various settings.

The task of determining the best setting for each control factor can become complicated when there are multiple characteristics to be optimised [15, 19], as in the current study. This is because different levels of the same factor could be optimal for different characteristics. The quality loss function could be used to make the necessary trade-offs when different characteristics suggest different optimum levels. To differentiate the relative importance of various characteristics or responses, a

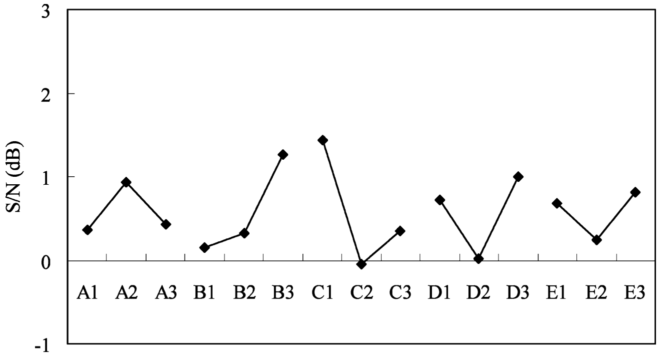

Fig. 3 Variation of the S/N ratio with factor level for various points (position 2)

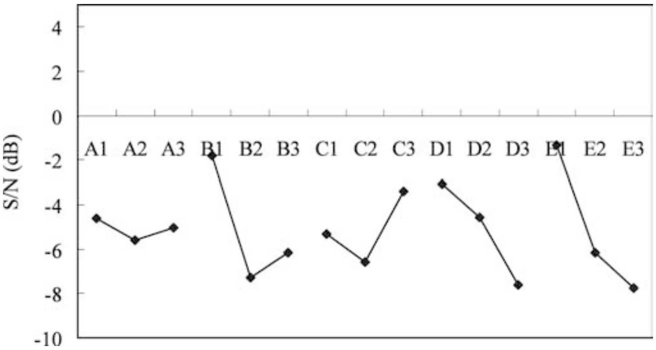

Fig. 5 Variation of the S/N ratio with factor level for various points (position 4)

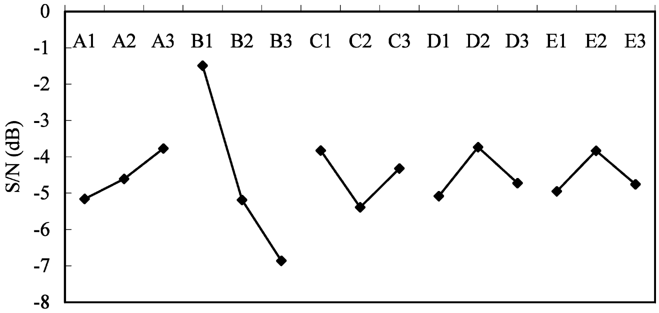

Fig. 6 Variation of the S/N ratio with factor level for various points (position 5)

utility-concept based weight [15] was adopted in this study. Here the S/N ratio η of the measured thickness was considered as the utility that needs to be optimised.

$$\eta(X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} W_i \eta_i(X_i) \tag{5}$$

The higher the utility, the more the weight is given to that characteristic of quality. The optimum setting can be determined by giving different weights to various positions to define relative importance. Different weight percentages were assigned to various positions based on their relative importance for the optimum setting of thermoformed parts. Based on the experience of the engineers from the local thermoforming industries as well as the end use of the product [9], the "weights" at different positions were given by the following; the corner of a thermoformed part (positions 3, 4 and 5) was the most important area to be formed. The thickness at the corner area must be larger than some minimum value, not only to resist the pressure of the contained liquid, but also to prevent possible bucking of the part. The thickness at the bottom (position 6) should also be thick enough to prevent sagging of the part. Position 1 is close to the rim of the cup and its importance is relatively limited. The importance of position 2 falls between position 1 and position 3. Finally, the weights of position 1–6 are set to be 0.05, 0.1, 0.2, 0.3, 0.2, and 0.15, respectively. The S/N ratio η of the measured thickness was then calculated based on the weights of the positions, i.e.

$$\begin{aligned}\eta_{\text{weighted}} &= 0.05 \times \eta_{p1} + 0.1 \times \eta_{p2} + 0.2 \times \eta_{p3} + 0.3 \times \eta_{p4} \\ &\quad + 0.2 \times \eta_{p5} + 0.15 \times \eta_{p6}\end{aligned} \tag{6}$$

where η_{pi} is the thickness at position i. The data of weighted S/N ratio is shown in Fig. 8. The factor levels for the optimum thickness distribution were thus determined to be A1/B1/C3/D1/E1, which correspond to a plug velocity 27 cm/s, vacuum pressure 0.03 Mpa, heating temperature 150°C, a wood plug, and plug displacement of 9.8 cm. The optimum set of processing parameters predicted was closer to the optimum set predicted for that characteristic which was assigned the largest weight (position 4).

6.2 Optimum combination

Since the optimum combination of factor levels was not included in the main experiment, an indirect route was undertaken to predict the response of the thickness to the optimised factor levels. Interactions may have significant impacts on performance characteristics. Taguchi views interaction as unimportant because, to obtain it, the experimenter must control two main effects [20, 21]. Since one or more main effects usually need to be controlled for a product, the interactions cause no additional complications [18, 22]. Therefore, assuming there was no interaction among the selected factors, the predicted S/N ratio for the optimised factor levels, $\eta_{\mathrm{A1B1C3D1E1}}$, is

$$\begin{aligned}\eta_{\mathrm{A1B1C3D1E1}} &= \eta_m + (\eta_{\mathrm{A1}} - \eta_m) + (\eta_{\mathrm{B1}} - \eta_m) \\ &\quad + (\eta_{\mathrm{C3}} - \eta_m) + (\eta_{\mathrm{D1}} - \eta_m) + (\eta_{\mathrm{E1}} - \eta_m) \\ &= \eta_{\mathrm{A1}} + \eta_{\mathrm{B1}} + \eta_{\mathrm{C3}} + \eta_{\mathrm{D1}} + \eta_{\mathrm{E1}} - 4\eta_m\end{aligned} \tag{7}$$

where η_m is the mean S/N ratio for the 18 test trials in the main experiment, and η_{FN} is the S/N ratio for factor

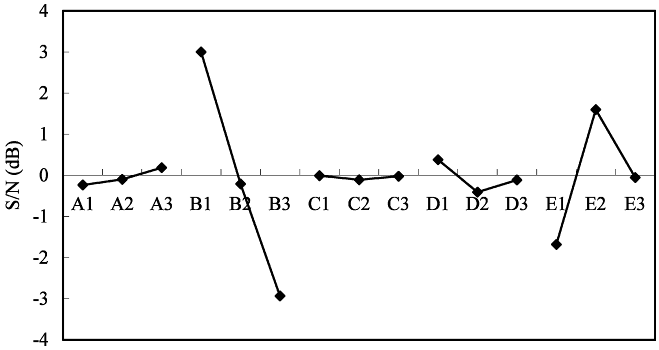

Fig. 7 Variation of the S/N ratio with factor level for various points (position 6)

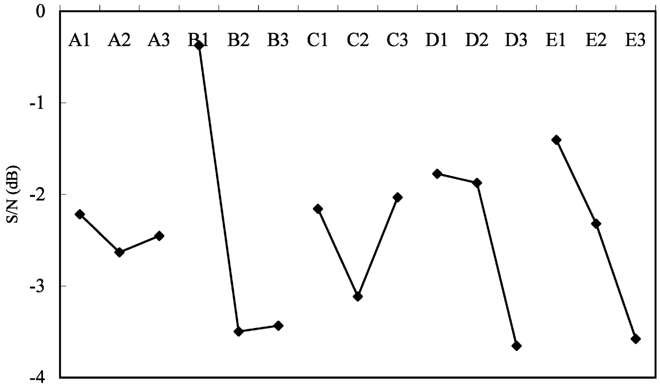

Fig. 8 Variation of the weighted S/N ratio for the thermoformed polypropylene foams

F and level *N*. Based on this equation, the predicted S/N ratio of the thickness for the optimised factor levels, A1/B1/C3/D1/E1, was 1.93 dB. This predicted value was certainly higher than those achieved in the main experiment (Table 3).

6.3 Confirmation experiment

A confirmation experiment was conducted according to the optimised factor levels of A1/B1/C3/D1/E1. The thickness distribution thus obtained for thermoformed polypropylene foams at positions 1–6 is 1.94, 1.51, 1.12, 0.9, 1.19 and 1.3 mm, respectively. Additionally, the S/N ratio for this confirmation experiment, 1.21 dB, although being slightly lower than the predicted value of 1.93 dB, was higher than those achieved in the main experiment (Table 3). Consequently, the thickness distribution in thermoformed foam parts was properly reproduced using the optimised factor levels.

6.4 Significant factors

A standard analysis of variance (ANOVA) was also performed. Table 4 lists the calculated results for the multiple signal-to-noise ratio of thermoformed parts. The variance ratio, denoted by *F* in the tables, is the ratio of the mean square due to factor and the error mean square. A larger value of *F* means the effect of that factor is larger compared to the error variance. The larger the value of *F*, the more important that factor is in influencing the process response [20]. The significance of each processing factor on the part thickness of thermoformed parts can therefore be judged by the values of *F* in Table 4.

Based on Table 4, the relative significance of each factor on the part thickness of formed polypropylene foams, was arranged in the decreasing order of vacuum pressure ($F=3.18$), plug displacement ($F=1.18$), plug material ($F=1.11$), heating temperature ($F=0.35$) and plug velocity ($F=0.043$). For the factors selected in this study, the vacuum pressure was found to be the most significant one. The experimental result suggested that a higher vacuum pressure moulds foamed parts with a smaller thickness. Increasing the vacuum pressure squeezes the foamed parts and reduces the part thickness. The second most significant factor was the heating temperature. Forming a part with a high pressure at a high temperature causes the bubbles inside the foamed sheets to diffuse out of the materials. The thickness of thermoformed foams thus decreases. The experimental results suggest that the preferred displacement was 9.8 cm. A larger displacement tended to decrease the thickness at the part's sides and increase the thickness at the corners, due to less stretching of the sheet. In addition, different velocities resulted in different stretching rates of the foam sheets and thus different thickness distributions. Assuming a no-slip condition between the sheet and the assist plug, thickness variation caused by different stretching rates is mainly due to the viscoelasticity of the polypropylene foams. The results revealed that the viscoelasticity of thermoplastic foams at high temperatures should not be neglected. Finally, the preferred plug material was found to be wood. Wood has the highest diffusivity, cools the sheets down faster, and results in a larger part thickness.

This study has shown that in multiple response optimisation problems, it is unreasonable to optimise one characteristic at a time. On many occasions, the optimum conditions obtained for one quality characteristic (or response) are not completely compatible with those for other quality characteristics. Moreover, a factor may have a significant influence on the response when optimising each quality characteristic separately. However, the same factor may have very little influence when optimising all responses simultaneously. A simple and powerful methodology has been presented in this paper to optimise multiple quality characteristics simultaneously with the use of Taguchi's quality loss function and the utility concept.

7 Conclusions

A model based on the Taguchi method and utility concept was used to determine the optimum setting of the process parameters for a multi-characteristic product. The model was used to predict an optimum setting of thermoforming parameters to achieve the optimum qualitative characteristics of polypropylene foams. With a different set of weights based on the utility concept, a different set of optimum parameters was obtained for the qualitative characteristics under consideration. The optimum set of process parameters predicted would be closer to the optimum set that was assigned the largest weight. Key processing parameters affecting the product quality were also identified. The proposed procedure

Table 4 ANOVA table for the multiple signal to noise ratio of thermoformed parts

Factor	Degree of freedom	Sum of squares	Mean square	*F*
A: Plug velocity (cm/sec)	2	0.52424	0.26212	0.04349
B: Vacuum pressure (Mpa)	2	38.3263	19.1632	3.1793
C: Heating temperature (Ñ°C)	2	4.20156	2.10078	0.34853
D: Plug material	2	13.3978	6.69889	1.11139
E: Plug displacement (%)	2	14.2559	7.12793	1.18257
Error	79	13.1066	6.02748	
Total	89	83.81242		

suggests that the Taguchi technique and utility concept approach can provide an appropriate solution to yield a satisfactory product quality for a multi-response process optimisation problem.

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