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Prediction of Wall Thickness Distribution in Simple Thermoforming Moulds

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Thermoforming is widely used in manufacturing industries to produce large and labour-intensive products. Compared to other manufacturing techniques, thermoforming is an extremely efficient process that is suitable for high-efficiency mass production. In this paper, experimental thermoforming operations were carried out using a lab-scale, sheet-fed thermoformer. Carbon fibre-reinforced PP and unreinforced PS thermoplastic sheets were used in experimental thermoforming operations. The processing parameters were determined for each thermoformed material. Furthermore, a simulation of the thermoforming process was performed using LS-Dyna™ software. The thickness distributions obtained from the experiments were compared with the simulation results. The results show that the parameter that most affects the wall thickness distribution is the geometry of the clamping ring. To produce thermoformed products that have a more uniform thickness distribution, the clamping tool geometry must be selected according to the geometry of the product being thermoformed.
Keywords: thermoforming, wall thickness prediction, geometric element analysis (GEA), polystyrene, polypropylene

0 INTRODUCTION

In thermoforming, a polymeric sheet is heated to the proper temperature, which is termed 'the forming temperature'. This temperature depends upon the type of thermoplastic material. The polymer sheet is rubbery and elastic-plastic deformable at the forming temperature [1]. The sheet is then stretched into a female mould or over a male mould with positive or negative air pressure. The sheet is in contact with the cold mould surface for some time, which allows the polymer sheet to cool down to a temperature at which the sheet is sufficiently rigid to release from the mould. Formed sheets include the semi-finished product and the undesired trimming areas.

Furthermore, thermoforming is an efficient, cost-effective manufacturing process that produces flexible, strong and durable parts. Large, highly detailed and light-weight parts can be formed economically using thermoforming. Some useful properties, such as the low tooling costs, the ease of creating aesthetically desirable finishes, and the fast adaptation to the market, make thermoforming one of the fastest growing segments in the plastics industry. Thermoforming is an integration of many techniques. Vacuum forming, pressure forming and twin-sheet forming are techniques used to produce many products with distinct external features [2]. Lieg and Giacomin [3] performed an analysis in which the method of Kershner and Giacomin was applied to triangular troughs. The analysis focused on the speed of the manufacturing process. This study of the trough issue yielded no analytical solutions for the forming time; instead, Lieg and Giacomin combined a series expansion with a numerical solution to provide practitioners with a method to estimate the thermoforming time, the trough edge sharpness and the frozen-in stress. Ayhan and Zhang [4] investigated the effects of the process parameters, including the forming temperature, the forming air pressure and the heating time, on the wall thickness distribution of plug-assist thermoformed food containers using a multi-layered material. The resulting wall thickness data obtained for the various thermoforming parameters showed that the wall thickness was significantly affected by the forming temperature, pressure and heating time; the wall location, the container side and the interactions between the wall and the container side significantly affected the wall thickness. Rosenzweig et al. [5] studied an isothermal, one-dimensional model predicting the wall-thickness profiles of thermoformed products. The theoretical analyses of pressing into conical and truncated moulds were presented and discussed. They developed a theoretical geometric model based on eight simplifying assumptions that were independent of the material properties and the forming conditions. This model predicted the wall thickness distribution in thermoforming, which correlated with the experimental results. Azdast et al. [6] investigated the combination of free-forming and plug-assisted forming methods. During free forming, no moulds are used, and no undesired mould marks are obtained; however, the thickness distribution of the product is not desirable. In plug-assisted thermoforming, the thickness is almost uniform, but mould marks appear. A combination of the two processes is recommended in order to maximise the advantages of both processes

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and minimise the disadvantages. Harron et al. [7] identified the critical variables in the thermoforming process. They investigated the effects of some process parameters, such as wall thickness distribution, compressive strength, plug force and pot weight, on the final part properties. They described five factors affecting the wall thickness distribution of a thermoformed product: the sheet temperature, plug depth, plug timing, air timing and plug shape. They also found that the compressive strength of a product is directly related to the wall thickness distribution and is controlled by the same factors. Marchal et al. [8] studied the thermoforming of three different geometries (a yoghurt pot, a cellular phone housing and a safety helmet) and examined different process parameters, such as the initial temperature distribution across the sheet, the viscosity, the forming pressure and the mould surface quality. To analyse the influence of these parameters on the final thickness distribution and the final temperature distribution, the studied parameters were modified using the commercially available software Polyflow. The simulation results showed that the numerical simulation reveals all of the analytical power in the investigation of the influence of the different parameters on the quality of the final product. The numerical simulation results can be combined with the knowledge of the designers, which can reduce the time required to design a new product. Nam and Lee [9] thermoformed two distinct acrylonitrile-butadiene-styrene (ABS) polymers. The thermoforming behaviour of these polymers was compared with a numerical simulation. Hot tensile tests were performed to obtain some material parameters for the simulation. The thickness distribution obtained from the experiments was compared with the simulation results. Although Nam et al. performed a three-dimensional analysis of the thermoforming process using different ABS grades, they found that this difference does not mean that one grade is better than another. To classify these materials according to the thermoforming process parameters, a more realistic simulation is necessary for further understanding. Dong et al. [10] used the PAM-FORM™ software package to simulate the thermoforming process of a polymeric sheet. They adopted a hyper-elastic constitutive law based on the Mooney-Rivlin model in order to carry out the bubble inflation simulation and to identify the material parameters. They focused on the thickness distribution analysis and the strain states of the bubble inflation. They found that the deformation profile correlated well with the experimental results. In addition to these literature studies, there are alternative methods to predict the wall thickness distribution in simple thermoforming moulds. One method is an approach that has been widely used in blow moulding and in thermoforming for more than forty years; it has been used in Germany, Poland, Russia and Japan. Geometric element analysis (GEA) [11] to [15] method follows a protocol for the stretching of an infinitely extensible membrane over a surface with a known geometry, and the polymer properties are not needed. Throne [11] and [12] studied the application of GEA to the conical thermoforming moulds. He created several equations that are used for the prediction of wall thickness distribution for deep and shallow thermoforming moulds. Kutz [13] and Crawford [14] both created calculations that can yield a useful first approximation of the dimensions of a thermoformed part. In addition, Osswald [15] studied the prediction of thickness distribution profiles in hemispherical and open cylindrical thermoforming moulds. These literature studies help scientific researchers and thermoformers to produce thermoformed packages with more uniform thickness distribution and dimensional stability.

In this work, the wall thickness distributions in three thermoformed products were predicted using GEA and experimental methods. Carbon fibre-reinforced, and unreinforced thermoplastic sheets were used in experimental thermoforming operations. Processing parameters were determined for each thermoformed material, and polymer sheets were formed using a lab-type thermoformer. Additionally, simulation of the thermoforming process was performed using LS-Dyna™ software. The thickness distributions obtained from the experiments were compared to the simulation results.

1 MATERIALS AND METHODS

Unreinforced polystyrene and carbon fibre-reinforced polypropylene sheets with different thicknesses were used in the experimental study. The thicknesses of the polystyrene sheets were 2.0 and 2.5 mm. The polystyrene used in the experiment was SABIC PS 825 E, which is a high-impact polystyrene for thermoforming. Polypropylene was extruded using a laboratory type extruder with a 55 mm screw diameter. The extruded polypropylene sheets were produced at a constant line speed of approximately 1 m/min. With the use of this laboratory extruder, thermoplastic sheets can be produced with 1 to 3 mm thicknesses and 30 mm widths. Polypropylene sheets were extruded as 5 and 15% carbon fibre-reinforced in weight in order to determine the effect of reinforcement on the final wall thickness distribution. The effect of the fibre reinforcement on the thermoforming process parameters was investigated. Prepared PP sheets were extruded to be 2 mm (±0.01 mm) thick. Reinforced PP sheets were extruded using Borealis BE50-7032 Polypropylene granules.

Sheets were thermoformed using a lab-scale sheet fed thermoformer that was controlled manually. Loading the sheet into the forming table, adjusting the forming temperature, opening and closing of the upper unit, setting the velocity of this unit and starting of the vacuum was entirely controlled by the researcher. Therefore, a specific cycle time was not mentioned for that process. The thermoforming unit (Yeniyurt Machinery) was not manufactured for mass production and can be used only for laboratory experiments. This unit uses only heat and a vacuum to form the sheet and can form sheets from 1 to 3 mm in thickness. The forming technique used in this experimental study is termed ‘negative forming’ or ‘vacuum forming’. In the vacuum-forming technique, female moulds are used. The mould is placed below the sheet; the sheet sags into the mould, and the part is formed down into the tool. In this study, three types of female moulds (cylindrical, conical and cubical) were used in the manufacturing of products. The sheets were cut into squares of 300×300 mm² before thermoforming. The thermoforming process parameters were determined for each material according to the manufacturer catalogue information. However, the thermoforming parameters for the extruded reinforced PP sheets were predicted through trial and error. The sheet forming temperatures for the reinforced PP sheets were modified according to the heating time. The forming temperature was controlled using twelve ceramic heaters. The heating system consists of two zones. The ceramic heaters have a 500×500 mm² heating area capacity. The first heating zone is in the centre of the complete heating system and has a 300×300 mm² heating capacity. The first heating zone was used to heat the sheets before the sheets were thermoformed. All of the dimensions were chosen for a h (height): d (diameter) ratio of 0.5. The forming temperatures were selected as 180 °C for PS, 185 °C for the 5% carbon fibre-reinforced PP and 190 °C for the 15% carbon fibre-reinforced PP sheets. Wall thickness values were measured from Point-1 (at the centre of the base of the product) to Point-2 (at the end of the radius on the rim) (Figs. 1 to 3). The wall thickness measurements were performed on at least five different products for each PS and PP sheet along a vertical cut passing through the centre. Each measurement was repeated at least three times. Measurements of the wall thicknesses were performed using a digital micrometer (0.01 mm precision). The obtained wall thickness profiles from the experiments were compared with the results calculated using GEA for the three mould geometries. The thermoforming simulation was performed using LS-Dyna explicit software. The results for all materials were compared.

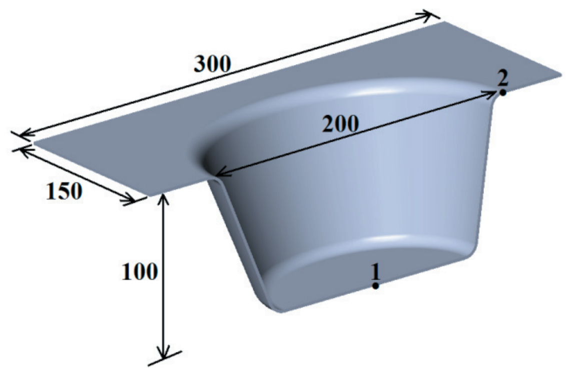


Fig. 1. *Dimensions of half conical thermoformed product in mm*

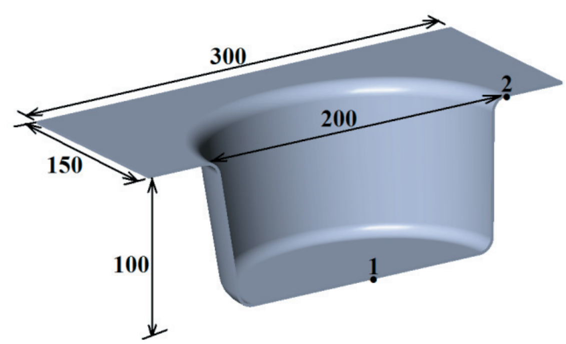


Fig. 2. *Dimensions of half cylindrical thermoformed product in mm*

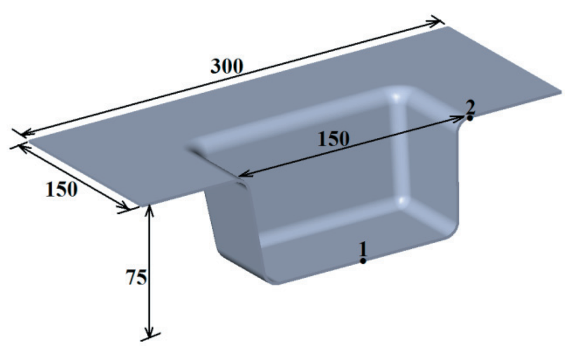


Fig. 3. *Dimensions of half cubical thermoformed product in mm*

2 RESULTS AND DISCUSSIONS

Fig. 4 shows the thickness distribution calculated by both GEA and the experimental method for polystyrene. The thickness was measured using a digital micrometer through a path that passes through the centre of the mould base. From the data in Fig. 4, the thickness distribution results generated by

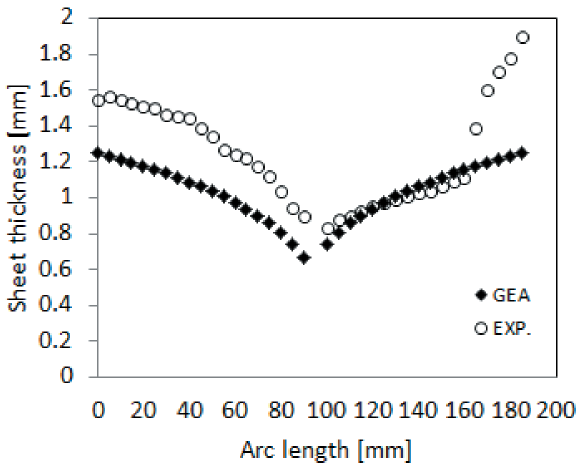


Fig. 4. The wall thickness distribution in the cylindrical thermoforming mould; polystyrene sheet 2.5 mm in thickness

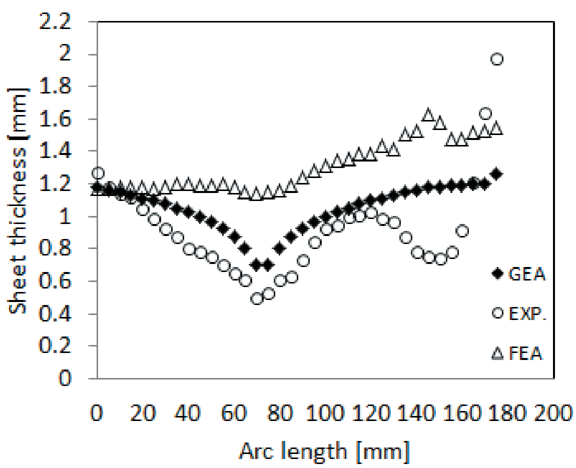


Fig. 5. *The wall thickness distribution in the conical thermoforming mould; polystyrene sheet 2 mm in thickness*

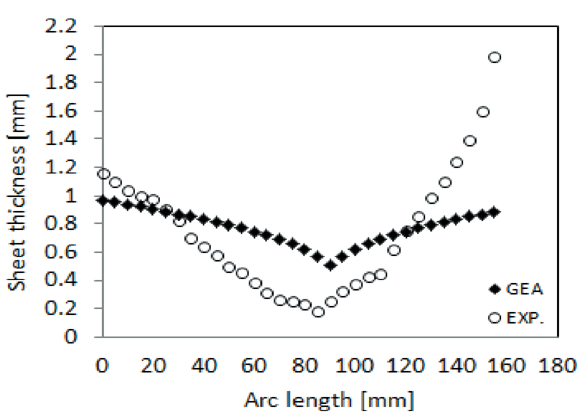


Fig. 6. The wall thickness distribution obtained along a vertical cut through a diagonal line of cubical thermoforming mould; polystyrene sheet 2 mm in thickness

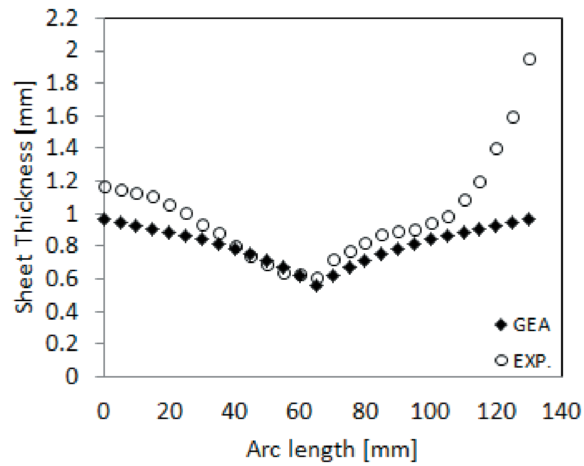


Fig. 7. The wall thickness distribution obtained along a vertical cut through a symmetry axis of cubical thermoforming mould; polystyrene sheet 2 mm in thickness

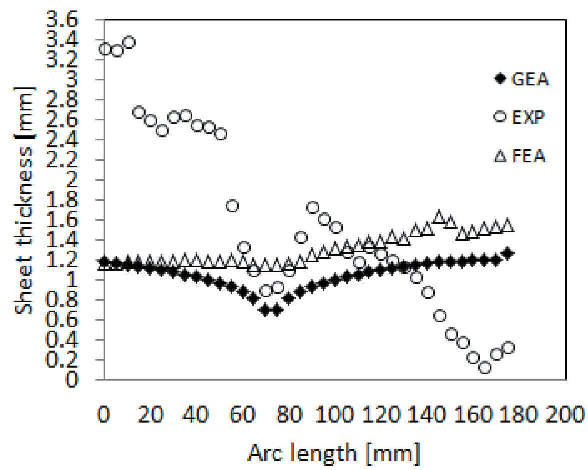


Fig. 8. The wall thickness distribution in the conical thermoforming mould; (5% carbon fibre-reinforced sheet 2 mm in thickness

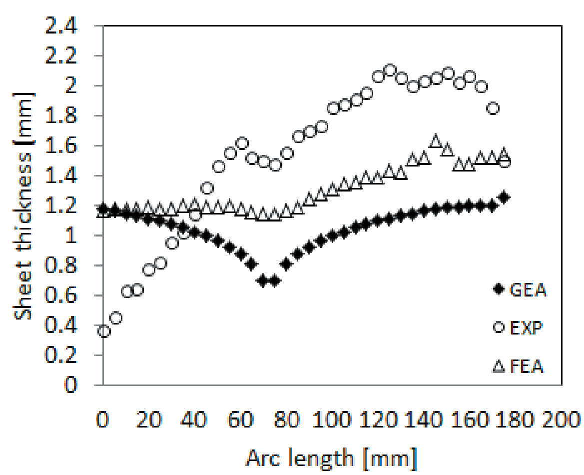
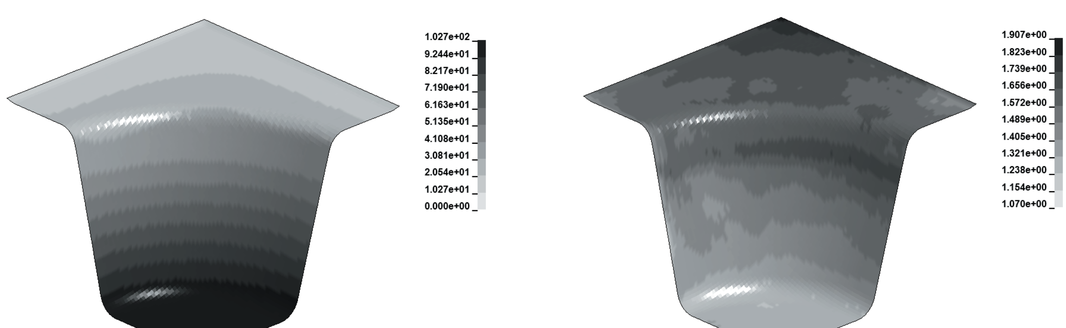


Fig. 9. The wall thickness distribution in the conical thermoforming mould; 15% carbon fibre-reinforced sheet 2 mm in thickness

the experimental method (EXP.) and the Geometric Element Analysis (GEA) do not correlate with each other. The point at which the minimum sheet thickness occurs is different for each of the abovementioned methods. In the experimental method, the minimum sheet thickness for the cylindrical mould was measured to be approximately 0.83 mm, but the minimum sheet thickness was calculated to be approximately 0.666 mm using GEA. In Fig. 5, the thickness distribution of the polystyrene product is given for comparison. The thickness values for the product are different for the experimental and numerical methods. In addition, this minimum thickness value and the point where most of the thinning occurs are closer than before for the two curves generated using GEA, finite element analysis (FEA) and the experimental method. There is slight correlation between the two thickness profile curves obtained by the experimental method and GEA in Fig. 5. In contrast, the simulation results did not have the same trend in Fig. 5. To more accurately predict the wall thickness distribution in the cubical mould, both a diagonal line and one representing the symmetry axis of the cubical mould were measured. These results are illustrated in Figs. 6 and 7; the sheet thicknesses in the centre of the product are different. The thinnest point is different between the thickness profile curves generated experimentally and using GEA. It is apparent that GEA does not accurately generate wall thickness distributions that correlate with the results measured in the experiments. To investigate the effect of fibre reinforcement on the thickness distribution, chopped carbon fibres were included during the polypropylene extrusion. Reinforcement inclusion was achieved by adding carbon fibres into the feeding hopper at 5 and 15% in weight. The resultant composite PP sheets including chopped carbon fibres were 2 mm in thickness. These PP sheets were thermoformed using only the conical thermoforming mould. Figs. 8 and 9 represent the thickness distribution curves. There are considerable differences between the tendencies of the thickness distribution curves in both figures. The points that are the thinnest in the 5 and 15% carbon fibre-reinforced thermoformed products are not in the same location. The thickness for the thinnest area is different for the two carbon fibre-reinforced composite products. In Fig. 8, the measured thickness value is 0.9 mm on the radius that is at the base of the product. On the same radius, the minimum thicknesses calculated by GEA and FEA are 0.704 and 1.1412 mm, respectively. There is approximately a 21% difference between the actual thickness value and the thickness value obtained by GEA. FEA reveals a 26% difference compared to actual minimum thickness value. In Fig. 8, the thickness distribution curve that was obtained experimentally has a decreasing trend. In Fig. 9, the measured thickness value is 1.48 mm on the radius that is at the base of the product. At the same point, the lowest thickness values obtained using GEA and FEA are 0.704 and 1.1467 mm, respectively. There is about 52% difference between the actual thickness value and the thickness value obtained by GEA. FEA reveals a 22% difference compared to actual minimum thickness value. In Fig. 9, the variation of thickness curve obtained using the experimental method follows an increasing trend. In addition to this, in Fig. 8, there are thickness values greater than 2 mm at Arc length = 0 and 20 (at the centre of the base of the conical thermoformed product). That phenomenon occurred during the measurements because of an overlapped sheet. As a result of this, the sheet thickness was measured as being greater than it is. Taking into account that the initial thickness of the PP reinforced sheet is 2 mm, measuring the sheet thickness as 3.5 mm may be regarded as normal. Overlapping is a manufacturing problem caused by the semi-crystalline



a) b)

Fig. 10. *a) the wall thickness and b) resultant displacement distribution results obtained using Ls-Dyna software for a 2 mm PS sheet using the conical thermoforming mould*

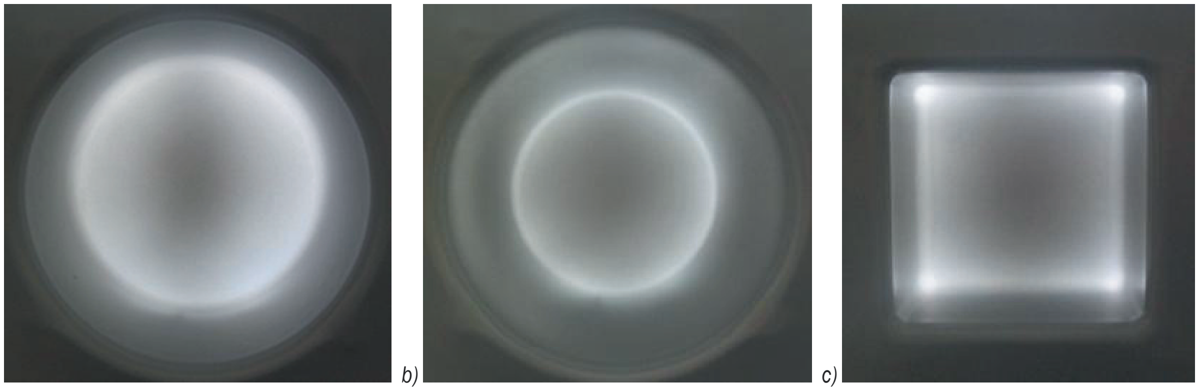

a) b) c)

Fig. 11. *Images of the thermoformed products examined visually; a) cylindrical, b) conical and c) cubical products*

structure of the PP sheet material. It was observed in all 5% carbon fibre-reinforced thermoformed specimens. Fig. 15 shows overlapped and wrinkled sheet surface at the centre of the base of the conical thermoformed product. Overlapping can occur at the base of the product or on the sidewalls. If it occurs at the base of the product as in Fig. 8, thickness variation has a decreasing trend. If overlapping occurs on the sidewalls of the product as in Fig. 9, the thickness curve has an increasing tendency.

To efficiently analyse the results of the thermoforming simulation process, a quarter of a finite element model (FEM) was created. The FEM consists of 16440 nodes and 13525 shell elements; some of which are rigid (quarter of the inner surface of the conical mould), and other are deformable (quarter of the total polymeric sheet) shell elements. The wall thickness distribution result is illustrated in Fig. 10. The thickness distribution varies along the radius of the mould base. This variation is because the thermoformed product geometry is circular, whereas the clamping ring has a square geometry.

To clearly show the thickness profile of the thermoformed conical, cubical and cylindrical products, a visual representation was created. The thermoformed products were placed in front of a light source, and images were taken (Fig. 11). The light areas are the thinnest and weakest parts of the thermoformed product, whereas the dark areas are the thickest and most durable. The light areas show the parts of the polymer sheet that last touched the mould surface during thermoforming.

Four different points were selected to be examined using scanning electron microscope (SEM) on the composite conical thermoformed product. Fig. 12 shows the locations for these points. A cut section was taken from the centre of the chopped carbon fibre-reinforced PP products. Four points were predetermined on this section. To show the fibre alignments in these points, SEM images were obtained (Figs. 13 and 14). The SEM images show that the carbon fibres are usually perpendicular to the sections in which they exist. The thickness distributions obtained using Geometric Element Analysis and

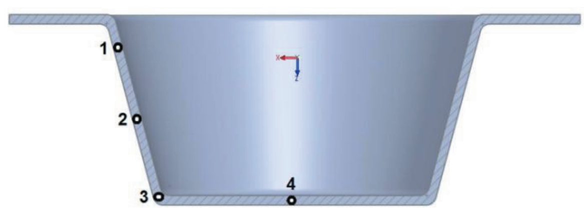


Fig. 12. *Four locations where the SEM images were taken*

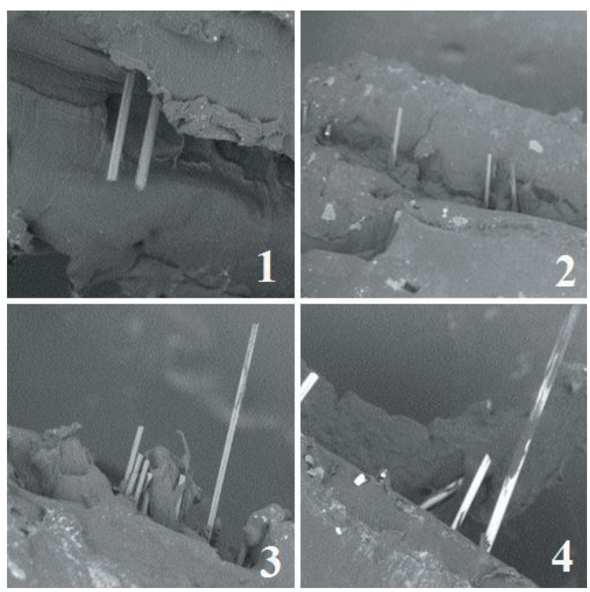


Fig. 13. *SEM images of the 5% carbon fibre-reinforced PP conical product; points 1 to 4 (magnification: 500×)*

Thermoforming Simulation show poor correlations with the measured data. This because carbon fibre-reinforced PP products have some surface defects, which results in roughness. Furthermore, the extruder used in the production of reinforced PP sheets has a single screw. This single screw causes undesired fibre distribution in the PP material. In addition to this distribution, concentrated carbon fibre groups lead to inappropriate thickness distributions (Fig. 15).

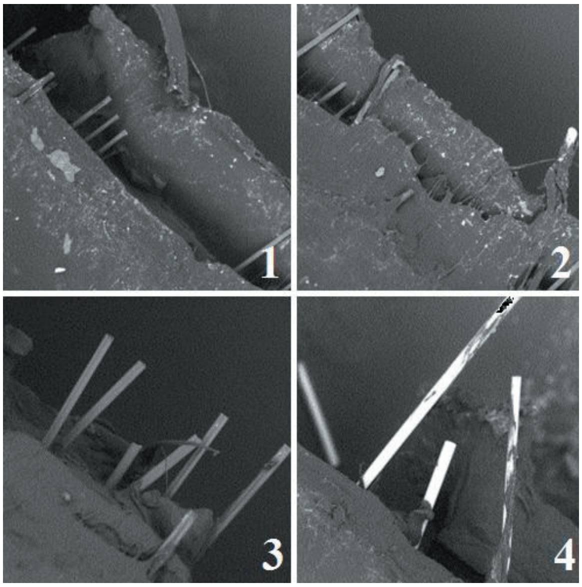


Fig. 14. *SEM images of the 15% carbon fibre-reinforced PP conical product; points 1 to 4 (magnification: 500×)*

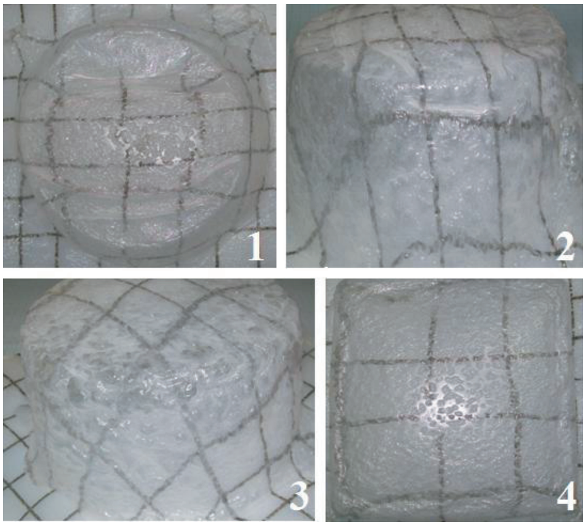


Fig. 15. *1) wrinkled and overlapped sheet surfaces; 2) unbalanced deformation of product because of heterogeneous fibre distribution; 3) undesired product thickness distribution because of the non-uniform initial sheet thickness; 4) rough and porous surface defects*

3 CONCLUSIONS

The experiments performed on the thermoformed products clearly show that one of the leading parameters that affects the wall thickness distribution is the geometry of the clamping ring. To produce thermoformed products that have more uniform thickness distributions, the clamping tool geometry must be selected according to the geometry of the product. It is proposed that a circular clamping tool geometry be selected for cylindrical and conical products and a rectangular one for rectangular products. That can balance the stress in all directions and provide uniform deformation characteristics, resulting in more uniform thickness distribution. Thickness distribution results have changed with the materials used in thermoforming simulation. However, there are minor differences between thickness distribution results (for example, at the same arc length value, for 5% reinforced PP thickness:1.1412 mm for 15% reinforced PP thickness 1.1467 mm). A significant difference not been found between the thickness distribution results of PS and reinforced PP sheets. In order to obtain more appropriate thickness distribution results, thermoforming simulation should be performed according to different material models that can represent polymer deformation behaviour more accurately. Furthermore, thermoforming simulation can be repeated with various polymer material models from LS-Dyna material model library. Additionally, simulations can be achieved in detail by using software packages like Ansys-Polyflow, T-SIM, etc. In this study, the geometry of the clamping tool was predicted to significantly affect the uniformity of the sidewalls and the base of the thermoformed product (Fig. 10). The amount of material in the sidewalls and base of the thermoformed product is governed by the geometry of the clamping tool. Because of the square geometry of the clamping tool, the material in the side walls stretched less along the diagonal axis of the clamping tool. This is considered to be the foremost reason for the non-uniformity of the conical and cylindrical products. As a result, the shape of the clamping ring, the homogeneity of the reinforcing fibre distribution in the matrix material, the anisotropic properties caused by the extrusion direction and the rough and porous surface defects were predicted to be the primary reasons for the non-uniform thickness distribution.

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