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Research article

Effects of manufacturing defects on thermoformed product quality

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Abstract

In this study, 5% and 15% in weight carbon fiber reinforced polypropylene (PP) sheets were formed under appropriate vacuum and temperature conditions by using truncated cone-shaped thermoforming mold. In addition to this, 5% in weight glass fiber reinforced High Density Polyethylene (HDPE) sheets were formed using truncated cone-shaped, cylindrical, and cubic shaped thermoforming molds by thermoforming. Composite sheets used in this work were produced with a laboratory-type plastic extruder which has a screw diameter of 50 mm. In production of HDPE composite sheets, as a reinforcing material, chopped glass fibers (E-glass) which were provided from glass fiber manufacturer SISECAM A.S. Company were used. Using the same procedure PP (Borealis BE50-7032) thermoplastic granules were used as a matrix material in production of carbon fiber composite sheets. In carbon fiber reinforced sheets, chopped fibers were added during manufacturing. After thermoforming, composite semi-products were examined by visual inspection. Visual defects that affect product quality were obtained. Also carbon fiber distribution was investigated on different sections which were taken from the thermoformed semi-products by Scanning Electron Microscopy (SEM). Through this experimental study, it is aimed to investigate the effect of defects during plastic extrusion on thermoformed product quality.

Keywords: *Polypropylene (PP), High Density Polyethylene (HDPE), glass fiber, carbon fiber, thermoforming.*

1. Introduction

Bio-modeling describes the ability to replicate the morphology of a biological structure. Numerical (computer) and physical models are important tools for engineers, scientists, and experts in any field to help understand physical phenomena, to analyze physical objects and systems, as well as to perform design. Physical models range from simple bone models mounted on a testing jig to more complex bio-models rendered in solid form that can be produced by engineering technologies such as rapid prototyping technologies, which replicate the morphology of the bone structure [1,2].

In the late 1940s, thermoforming was adopted as basic process to the packaging industry. This adaptation is so powerful that thermoformed package was considered to be the

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most important advance in 1950s. In the 1970s, demand on packaging of foods easily created the market for ovenable portion servings and disposable drink cups. Production of these packages provided to develop pressure forming of PS (Polystyrene) foam, CPET (Crystalline Polyethylene Terephthalate), and PP (Polypropylene). Production of bath tubes and refrigerator door liners using heavy gauge thermoforming happened during these years. In time, engineers' thermoformed reinforced and flame-retardant plastic sheets and these products were used in many industrial areas. In course of time packaging covers, welded steel material on the food cans, glass in the jars, drinking cups, and thermoset composites in the airplane industry were replaced with the products which were manufactured by using thermoforming [1,2].

Today, packaging products create a large and high-volume industry. This industry is low-cost packaging products industry which provides to cover and exhibit the product and extend the product life [3-6]. There are lots of studies about thermoforming in the literature. As examples of these studies, Kim *et al.* [7] performed a comparative study about variation of process parameters in "Film Insert Molding". Kim *et al.* [7] performed uniaxial tensile tests in different strain rates and temperatures to characterize the deformation behavior of multi-layered ABS film material. True stress-strain curves were obtained for ABS film material. By using these curves, some coefficients in the G'Sell Viscoelastic governing equation were obtained. True stress-strain curves that were obtained by uniaxial tensile tests in different strain rates and temperatures were compared to the results obtained by G'Sell governing equation. Comparison results indicated that the results agreed well with each other. According to Kim *et al.* G'Sell Governing equation can be employed by defining deformation characteristics of multi-layered ABS film material. Song *et al.* [8] thermoformed the HDPE film material and studied the effect of polymer sheet temperature distribution on final thickness distribution of thermoformed product by using hemispherical and rectangular shaped thermoforming molds. For both thermoforming molds, thermal stress and warpage analysis were performed by simulation as well as experimental procedure. The results which are obtained by both methods were compared to each other. The results show that wall thickness distribution and sheet temperature distribution results for both rectangular and hemispherical thermoformed products have the same variation trend. Results also reveal that the final thickness distribution of thermoformed products can be determined as non-destructive by using a thermal camera.

Kamal *et al.* [9] studied the deformation behavior of plastic bottle at the parison stage in extrusion blow molding process. Additionally, they investigated the thickness distribution of blow molded bottle at the time of inflation and cooling. They utilized two different PE (Polyethylene) resins, which are called Resin D and Resin E, from previous literature studies. In experiments, IMPCO (MODEL A13-R12) screw blow molding machine was used. The mold used in that work was manufactured specifically for this study. The mold was designed as transparent blow molding tool. Kamal *et al*. [9] made all these preparations in order to determine the parison's time dependent thickness variation during and after the inflation stage. Kamal *et al.* [9] took different images at different times during and after inflation stage. Obtained wall thickness distributions for Resin D and Resin E were not the same. That phenomenon reveals that Resin D and Resin E have different rheological and deformation characteristics. Ayhan and Zhang [10] studied the factors that affect the wall thickness distribution of 20 ml volume package by using "Benco Aseptic" type vacuum forming unit. Ayhan and Zhang [10] investigated the effect of process variables such as forming temperature, forming air pressure, and heating time etc. on final thickness distribution of a thermoformed package. It is reported that the variation of all the process parameters studied in this work affect the final thickness distribution. However, forming temperature is reported as the process parameter that influences the wall thickness distribution significantly. Lieg and Giacomin [11] investigated wall thickness prediction on thermoforming molds which have triangular and channel like geometry. They created analytical equations for the triangular trough-like products in thermoforming manufacturing process. Lim *et al.* [12] studied the deformation characteristics of woven fabric reinforced thermoplastic matrix composite sheets in thermoforming. They investigated the process variables by using an improved material model which defines the deformation behavior of composite sheet. Additionally, Lim *et al.* [12] performed a deep drawing of PP and reinforced PP sheets. Results show that woven fabric reinforced PP sheet can be deformed more easily than unreinforced PP by deep drawing. They investigated deep drawing process of PP and reinforced PP for each step during deformation visually. Rosensweig *et al.* [13] created wall thickness prediction equations for deep and shallow thermoforming molds. Wall thickness profiles were obtained for both shallow and deep thermoforming mold geometries. Furthermore, obtained wall thickness profiles were compared to each other. Thickness distribution results were found to comply with each other.

In this study, chopped fiber reinforced composite sheets were thermoformed. In addition, the effects of manufacturing defects on final product quality were investigated experimentally.

2. Material and Method

Laboratory-type plastic extruder was used in manufacturing of glass and carbon fiber reinforced sheets in different thicknesses. The plastic extruder used in experiments is located in Trakya University Composite Research laboratory. In this study, 5% and 15 wt% carbon fiber reinforced PP sheets were formed under appropriate vacuum and temperature conditions by using truncated cone-shaped thermoforming mold. In addition to this, 5 wt% glass fibers reinforced High Density Polyethylene (HDPE) sheets were formed using truncated cone-shaped, cylindrical and cubic shaped thermoforming molds by thermoforming. Composite sheets used in this work were produced with a laboratory type plastic extruder which has a screw diameter of 50 mm. In production of HDPE composite sheets, chopped glass fibers (E-Glass) which were provided from SISECAM A.S. were used. Using the same procedure PP (Borealis BE50-7032) thermoplastic granules were used as the matrix material in production of carbon fiber reinforced composite sheets. In carbon fiber reinforced sheets chopped fibers were added during manufacturing.

Sheets were thermoformed using a lab scale sheet fed thermo former that was controlled manually. Loading the sheet into the forming table, adjusting the forming temperature, opening and closing of upper unit, setting the velocity of this unit and starting of the vacuum was completely controlled by the researcher. Therefore, a specific cycle time was not mentioned for that process. Thermoforming unit (Yeniyurt Machinery) was not manufactured for mass production. It can be used only for laboratory experiments. This unit uses only heat and vacuum to form sheet and is able to form sheets in the range of 1 to 3 mm in thickness (Fig. 1). The forming technique used in this experimental study is called negative forming or vacuum forming. In vacuum forming technique, female molds are used. The mold is placed below the sheet, the sheet sags into the mold, and the part is formed down into the tool.

Fig. 1 Thermoforming unit used in experiments

In this study, three types of female molds (cylindrical, conical, and cubical) were used in manufacturing of products. The sheets were cut into squares with 300×300 mm² surface areas before thermoforming. The thermoforming process parameters were determined for each material according to the manufacturer catalogue information. However, the thermoforming parameters for extruded reinforced PP sheets were predicted through trial and error method. 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 center 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 an h (height): d (diameter) ratio of 0.5. In thermoforming of 5 and 15 wt% carbon fiber reinforced PP, only conical mold was used. In addition, 5 wt% glass fiber reinforced HDPE were thermoformed by using conical, cylindrical and cubical molds. During thermoforming, sheet forming temperature was measured by an infrared thermometer (RAM DT-8855). The process parameters for the thermoformed sheets were given in Table 1.

Table 1
Process parameters for 5 and 15 wt% carbon fiber (CF) reinforced PP and 5 wt% glass fiber (GF) reinforced HDPE

	PP (5 wt% CF)	**PP (15 wt% CF)**	**HDPE (5 wt% GF)**
Heater temperature (^{0}C)(Zone-1)	350	350	350
Heater temperature (^{0}C)(Zone-2)	75	75	75
Heating time (min)	3.5	3.75	3.5
Sheet thickness (mm)	2	2	1.5
Vacuum (mmHg)	-400	-420	-680
Vacuum time (s)	30	30	30
Cooling time (min)	3	3	3
Thermoforming temperature (^{0}C)	185-190	190-195	170-175

After thermoforming, composite semi-products were examined by visual inspection. Visual defects that affect the product quality were obtained. Also carbon fiber distribution was investigated on different sections taken from the thermoformed semi-products by SEM (Figs. 3-6). Through this experimental study, it is aimed to investigate the effect of defects during plastic extrusion on thermoformed product quality. Thermoformed PP conical product was cut and divided into two symmetric parts. On the occurred cut sections four points were chosen and fiber alignments in these points were analyzed by SEM. Two points were selected on the sidewalls of the conical product. The third one was selected on the radius, which was at the base of the product. The last one was selected at the center of the base of the PP conical product (Fig. 2).

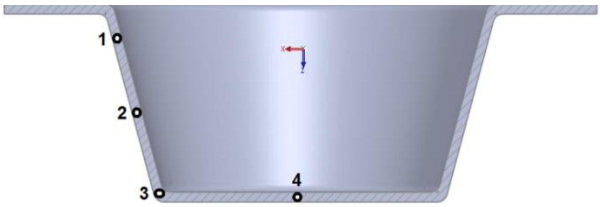

Fig. 2 Four locations where the SEM images were taken

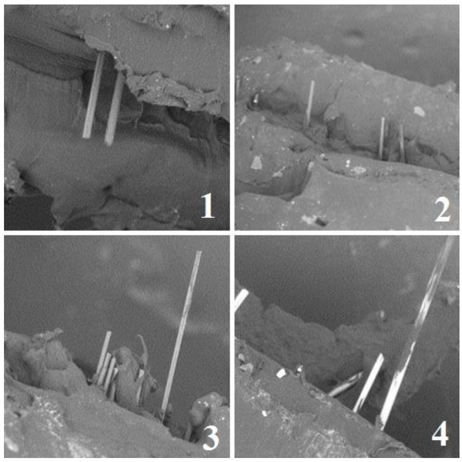

Fig. 3 SEM (500x) images of the 5 wt% carbon fiber reinforced PP conical product

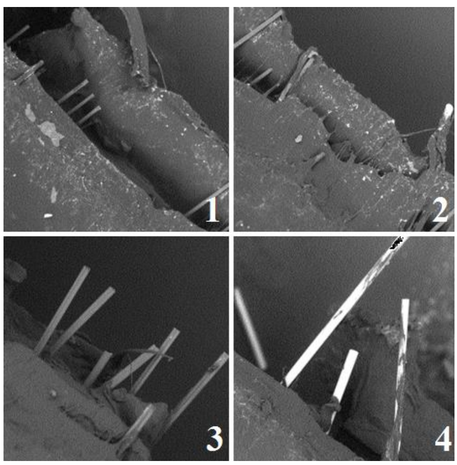

Fig. 4 SEM (500x) images of the 15 wt% carbon fiber reinforced PP conical product

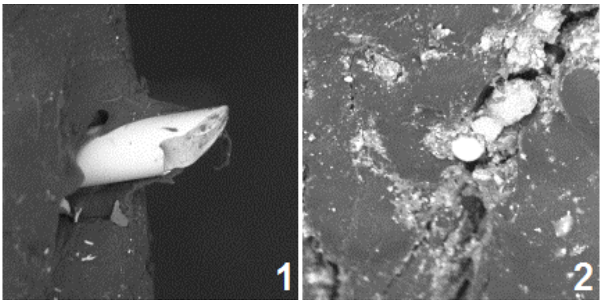

Fig. 5 Interaction between matrix and reinforcing element for 15 wt% carbon fiber reinforced PP conical product, (1) perpendicular (2940x) and (2) parallel (3750x) to the fiber direction

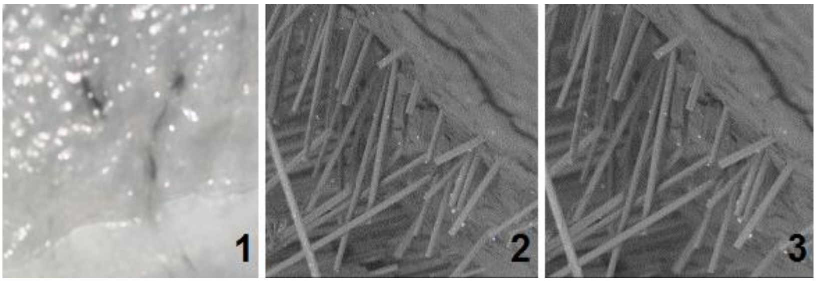

Fig. 6 (1) Undesired fiber orientation for 15 wt% carbon fiber reinforced PP conical product, (2) (745x) and (3) (850x) SEM images taken from carbon fiber agglomeration

4. Results and Discussions

In this study, PP and HDPE thermoplastic granules have been used as a matrix material. But dehumidification process was not able to be applied before extrusion. Occurrence of micro voids in sheets that were produced by extrusion line is inevitable because the extruder used in manufacturing of sheets does not have a degassing unit. At the end of the extrusion line, molten plastic has been passed through the water-cooled metal shafts. But melt temperature has not decreased gradually. Instead of cooling by natural convection, plastic sheet was subjected to rapid cooling by forced convection with the aid of two fans. This phenomenon caused extremely hard, brittle, and warped structure plastic sheets. All reasons are listed as follows;

- Dehumidification process was not able to be applied to PP and HDPE granules.
- Imperfections and defects occurred after thermoforming process are shown in Figs. 7 and 8.
- The used extruder has heating elements which consist of three zones. Heating of the mold and setting of the mold temperature could not be made accurately. Instead of proper heating conditions, mold was heated by electric rod heaters which are placed above and below the extrusion mold. In order to prevent the heat loss, mold and electric rod heaters were surrounded by glass wool.

Fig. 7 Manufacturing defects and imperfections caused by extrusion in reinforced thermoformed products (overlapping, unbalanced deformation caused by heterogeneous fiber distribution, excessive deformation, rough and porous surface defects)

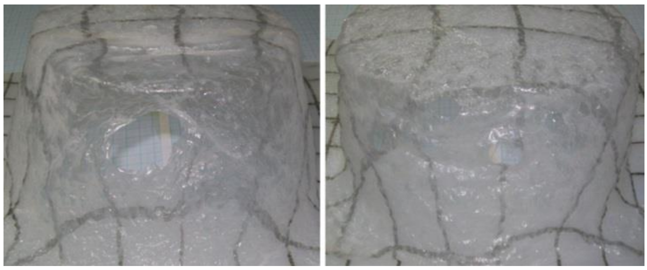

Fig. 8 Damaged products under excessive strain rates at forming temperature

- Molten plastic was cooled with the aid of two fans at the exit of the extrusion mold. But molten plastic must be cooled more slowly in order to prevent residual thermal stresses. This could not be achieved in this study. So high thermal distortion that is caused by different cooling rates is observed in produced plastic sheets.
- The lack of degassing unit caused micro voids which reduce the strength of produced plastic sheets.
- Manufactured composite sheets did not have surface roughness as desired accuracy. The reason for this is that two metal shafts used for calendaring, could not create the sufficient pressure to form sheets with smooth surface.
- PP and HDPE are semi-crystalline polymers. Forming temperature windows are very narrow. This is an indication of how difficult to thermoform these thermoplastic sheets by trial and error method.
- A binding material was not used to provide interfacial bonding between matrix and reinforcing component. No chemical treatment was applied to the surface of the reinforcing components in order to provide better wetting treatment. This is a factor that affects the thermoformability of the plastic material and the thermoforming process parameters.
- Based on the results obtained by visual test method, homogeneous fiber distribution was not provided in early production stages (during extrusion). That phenomenon has caused some fiber agglomerations. As a result of

agglomerations in some locations of the extruded composite sheets, anisotropy has occurred and linearity of deformation behavior has been lost in extrusion and perpendicular to extrusion direction.

- SEM images show that a sufficient interfacial bonding has not occurred between the matrix and reinforcing element. In addition, it was observed that there was not an appropriate wetting on the fiber surfaces by the matrix material.

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