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Formability and Mechanical Properties of Polyvinyl Chloride (PVC) in the Thermoforming Process

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ABSTRACT

This study investigated the effects of polyvinyl chloride (PVC) sheet thickness and heating temperature on formability, tensile properties, and thickness shrinkage in the thermoforming process. PVC sheets with thicknesses of 0.15, 0.20, and 0.25 mm were processed at 140, 160, and 170 °C. The experiment consisted of nine treatment combinations, with three repetitions for each combination, giving a total of 27 specimens. Data were obtained by observing the formability of the thermoformed products, measuring tensile properties using a universal testing machine, and measuring thickness changes using a digital microscope and a thickness gauge. The results show that both thickness and temperature affect the thermoformability and mechanical performance of PVC sheets. The highest tensile strength after thermoforming was obtained at a thickness of 0.25 mm and a temperature of 140 °C, with a stress value of 42.7 MPa or a maximum load of 4.30 kgf. Increasing the forming temperature reduced tensile strength, particularly for thinner materials. The greatest shrinkage was 53.3%, observed at a thickness of 0.15 mm and a temperature of 170 °C. Overall, thinner PVC sheets formed more easily at higher temperatures, but they also experienced greater shrinkage and lower tensile strength

1 Introduction

Polyvinyl chloride (PVC) is produced by the polymerization of vinyl chloride monomer with the assistance of a catalyst. PVC is widely used in building materials, piping systems, electrical cable installations, electrical components, household products, product packaging, and other design products [1], [2]. PVC is a thermoplastic material with good durability and resistance to water, alkalis, acids, oils, and organic substances [1]. PVC is generally available in rigid and flexible forms. Rigid PVC is commonly applied to construction materials, toys, pipes, household appliances, and automotive components, whereas flexible PVC is commonly used for hoses and electrical insulation.

The mechanical properties of PVC are influenced by the glass transition temperature, the capacity of the material to form crystals, and the crystal melting behavior. Mechanical characterization generally includes yield strength, tensile strength, and elongation at break, which are obtained using tensile testing equipment [3]. A suitable forming technology is therefore required to manufacture plastic products with controlled shape and performance.

Thermoforming is a method for shaping plastic sheets by heating the sheet to a forming temperature, stretching it, and then forming it over a prepared mold using vacuum pressure. The formed sheet is subsequently cooled until a new design is obtained. The thermoforming process generally involves three main stages: heating, vacuum forming, and cooling [4]. The heater softens the sheet before forming, while vacuum pressure forces the sheet to follow the mold geometry [5], [6].

The heating temperature required to form plastic sheets strongly depends on the type and thickness of the plastic material. In vacuum forming, thermoplastic sheets are heated until they become sufficiently flexible but are not melted. The sheet is then shaped according to the mold by suction pressure in the vacuum chamber. Because thermoplastics soften when heated and harden again when cooled, they can be reshaped into different forms through repeated heating and cooling cycles [7]. Vacuum forming machine design and thermoforming equipment development have also been reported for different plastic sheet materials and forming dimensions [8], [9].

This study aims to determine the effects of PVC sheet thickness and forming temperature on formability, tensile properties, and shrinkage after thermoforming. The investigated PVC thicknesses were 0.15, 0.20, and 0.25 mm, and the forming temperatures were 140, 160, and 170 °C.

2 Method

This research used a local sensitivity analysis method based on one factor at a time (OFAT), also commonly referred to as a trial-and-error approach. In this method, one factor is tested while the other factors are kept constant, and the effect of that factor on the response is then observed. The material used in this study was PVC sheet with a thickness of less than 1 mm.

Three PVC sheet thicknesses were used, namely 0.15, 0.20, and 0.25 mm. The forming temperatures were set at 140, 160, and 170 °C. Therefore, nine treatment combinations were obtained. Each treatment combination was repeated three times, resulting in 27 experimental specimens.

The vacuum forming machine operates based on the principle of air pressure difference. Air moves from a higher-pressure region to a lower-pressure region, and therefore the external air is drawn into the vacuum chamber. The air inside the chamber is removed by a rapidly rotating rotor or fan, creating a vacuum that pulls the plastic sheet toward the mold surface. This operating principle is consistent with previous developments of vacuum forming equipment for plastic-sheet forming [8], [9]. The machine frame was made of 3 mm angle iron and 1 mm hollow steel, with a 1 mm plate, a PID REX C100 temperature controller, and a 6 mm diameter, 300 mm long heating element.

Tensile testing was conducted to determine the stress-strain response of the PVC specimens. Tensile testing is commonly used to evaluate material strength and test accuracy in mechanical characterization [10]. The tensile properties were evaluated using a Tensilon RTF 2350 universal testing machine with a maximum capacity of 50 kN. The testing speed used for the film specimens was 200 mm/min, equivalent to 3.3 mm/s. The tensile test followed ASTM D882 for thin plastic sheeting.

Thickness changes after thermoforming were measured at curved, top, and side regions. The curved regions were measured using an INSIZE ISM-PM200SA digital microscope, whereas the relatively flat top and side regions were measured using a digital thickness gauge. The thickness gauge had a measurement range of 0-12.7 mm and a resolution of 0.01 mm.

3 Result and discussion

3.1 Initial tensile properties of PVC sheets

The initial tensile properties of the PVC sheets before thermoforming are shown in Table 1. The results indicate that increasing sheet thickness increased the maximum load and tensile stress. This behavior shows that the thicker PVC sheet provided greater resistance to tensile loading before thermal forming.

Table 1. Tensile properties of PVC sheets before thermoforming

Specimen size (mm)	Thickness (mm)	Stress (MPa)	Load (kgf)	Tensile strength (kgf/mm²)
110 × 35	0.15	58.6	5.9	0.357
110 × 35	0.20	78.4	7.9	0.359
110 × 35	0.25	98.8	10.0	0.363

The cross-sectional area and tensile strength were calculated using Equations (1) and (2).

$$A_0 = t \times l \quad (1)$$

$$\sigma = Fmax / A_0 \quad (2)$$

3.2 Thermoformed product quality

The thermoformed PVC products are shown in Figure 1. After heating and vacuum forming, the PVC sheets followed the mold geometry, and the formed products were cut into tensile specimens and thickness measurement specimens. Three sections were measured for each formed product, producing 27 specimens from the combination of three temperatures, three thicknesses, and three repetitions. The 0.25 mm sheet formed at 140 °C produced a less complete product shape, whereas the best visual formability was obtained from the 0.15 mm sheet formed at 170 °C. This result is consistent with the reported forming temperature range of PVC materials, namely approximately 160-180 °C [11]

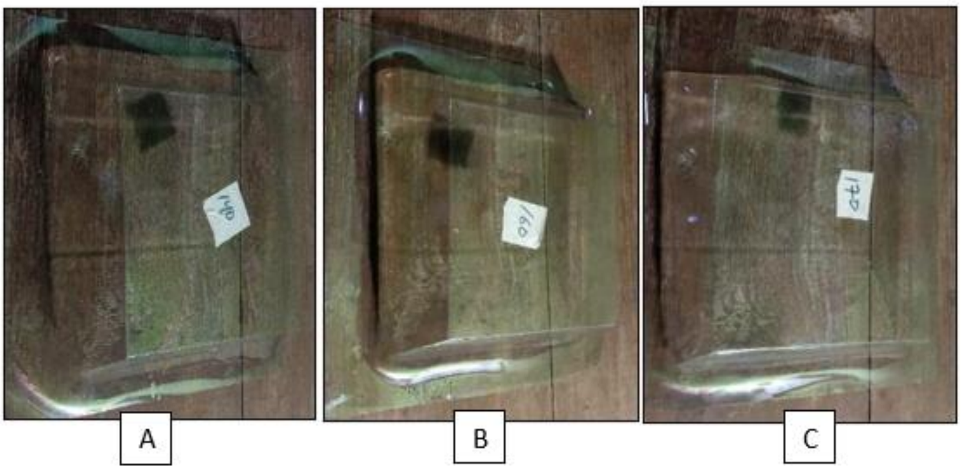

Figure 1. PVC products formed at (A) 140 °C, (B) 160 °C, and (C) 170 °C

3.3 Tensile properties after thermoforming

Figures 2-5 show the tensile test results after thermoforming. At 140 °C, the highest tensile value was obtained from the 0.25 mm sheet, with a stress of 42.7 MPa and a load of 4.30 kgf. At 160 °C, the highest value was also obtained from the 0.25 mm sheet, with a stress of 39.34 MPa and a load of 4.01 kgf. At 170 °C, the highest value decreased to 25.06 MPa and 2.55 kgf for the 0.25 mm sheet.

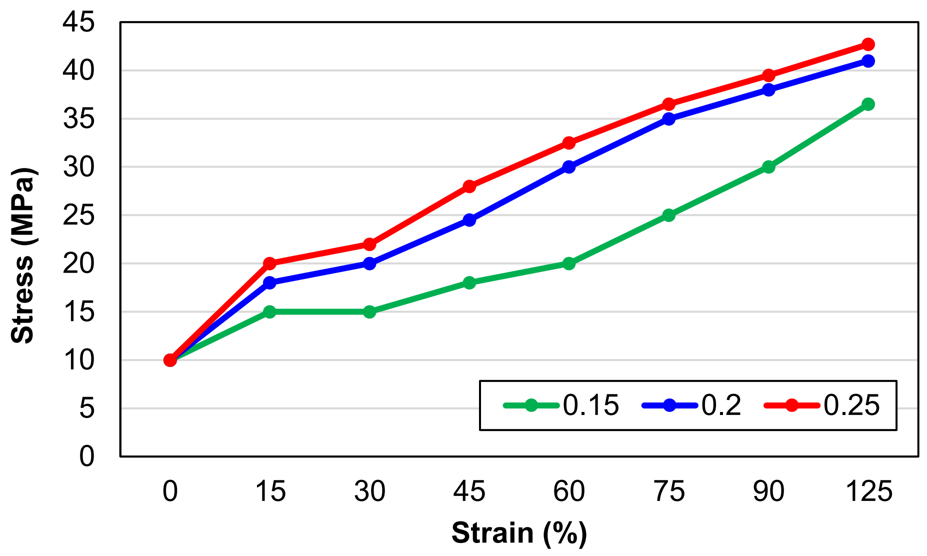

Figure 2. Tensile test graph at 140°C.

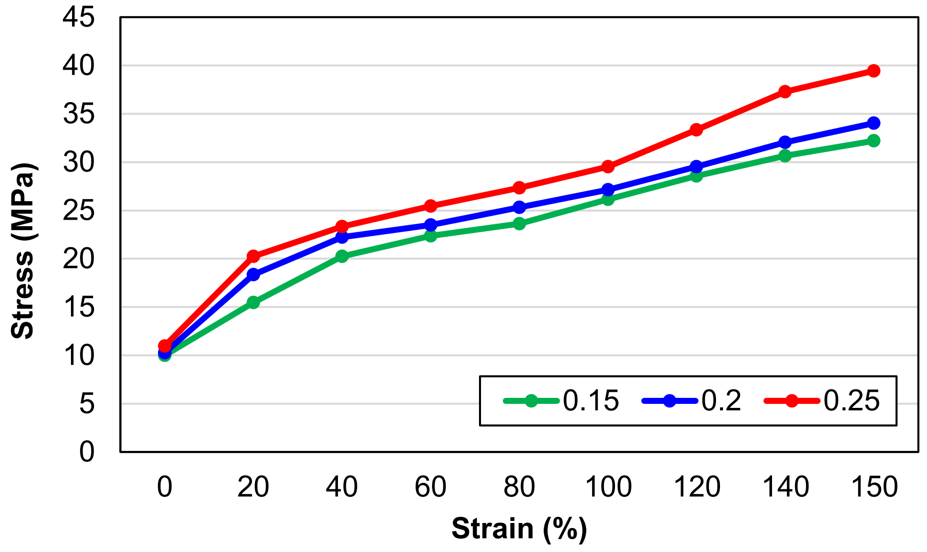

Figure 3. Tensile test graph at 160°C.

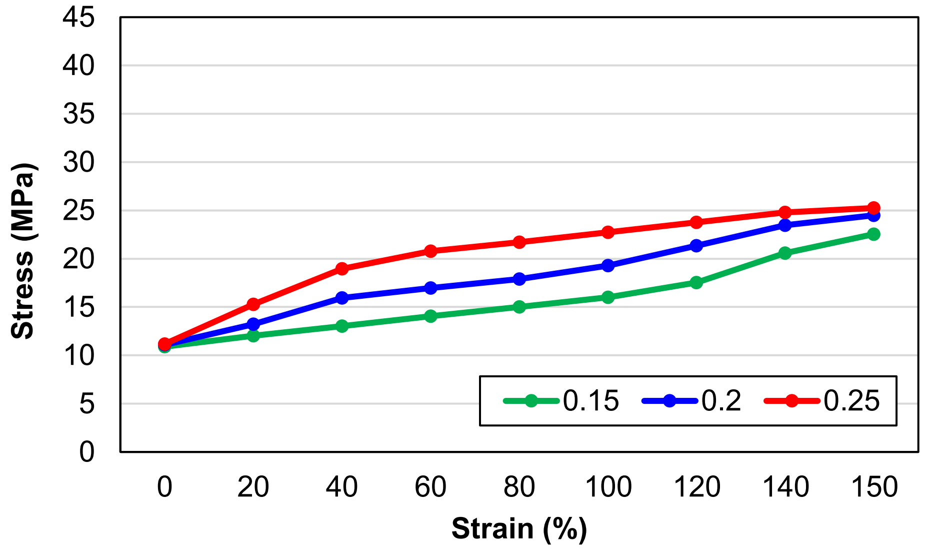

Figure 4. Tensile test graph at 170°C.

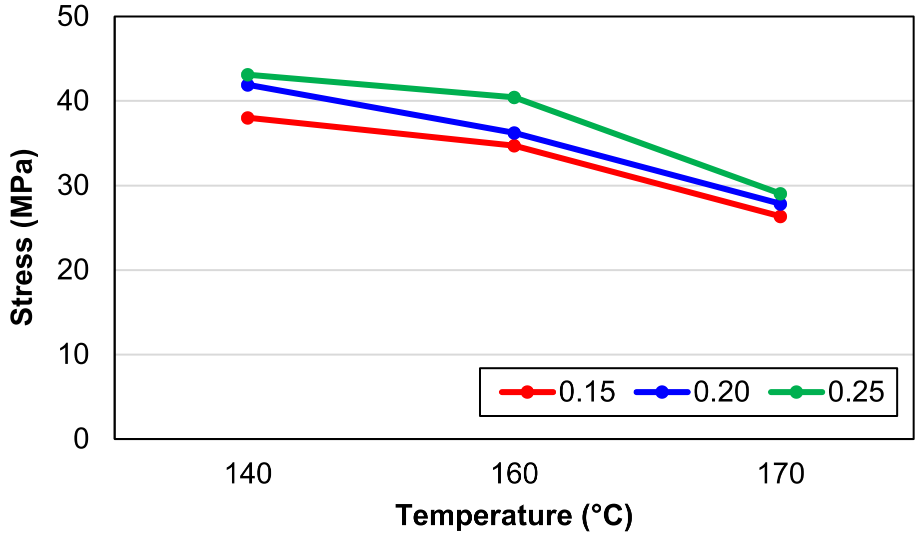

Figure 5. Overall tensile test graph of thermoformed PVC.

The data indicate that greater thickness and lower forming temperature produced higher tensile strength. In contrast, increasing the forming temperature reduced tensile strength. This reduction is attributed to larger thermal softening, increased deformation during forming, and greater thinning of the PVC sheet, especially at lower initial thickness. Similar effects of temperature, heating conditions, vacuum pressure, and sheet thickness on the quality of vacuum-formed plastic products have been reported in previous studies [12], [13], [14], [15].

3.4 Thickness shrinkage after thermoforming

Thickness shrinkage was evaluated at the curved, top, and side regions of the thermoformed product. The curved region was measured using the digital microscope, while the top and side regions were measured using the thickness gauge.

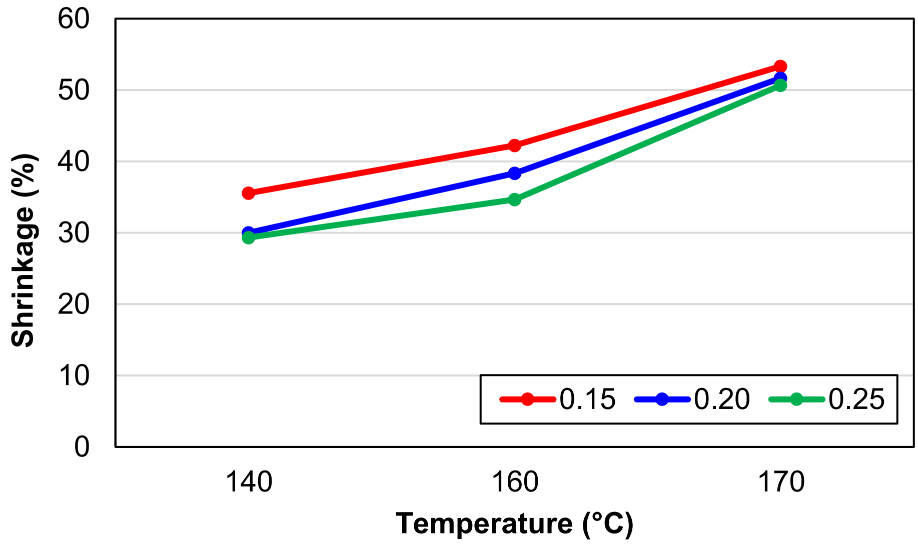

Figure 11. Shrinkage measurement results in the curved region.

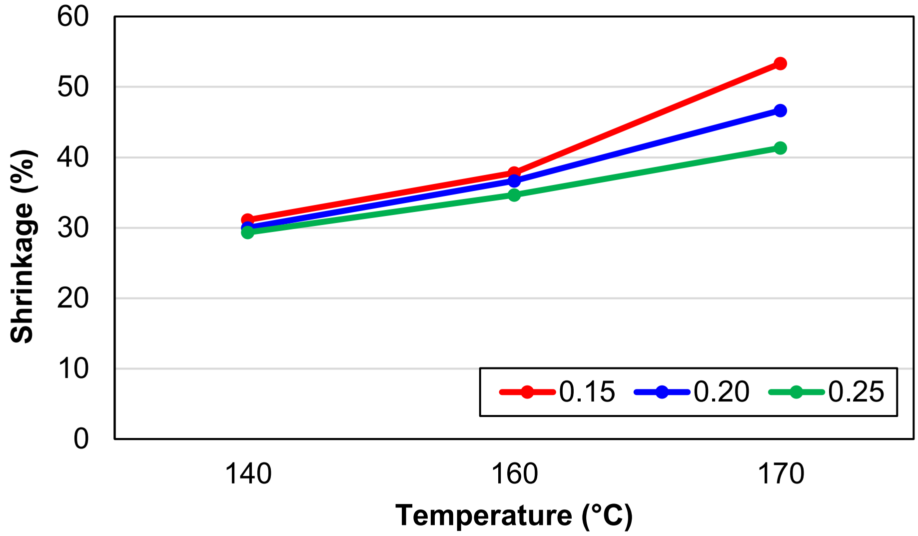

Figure 12. Shrinkage measurement results in the top region.

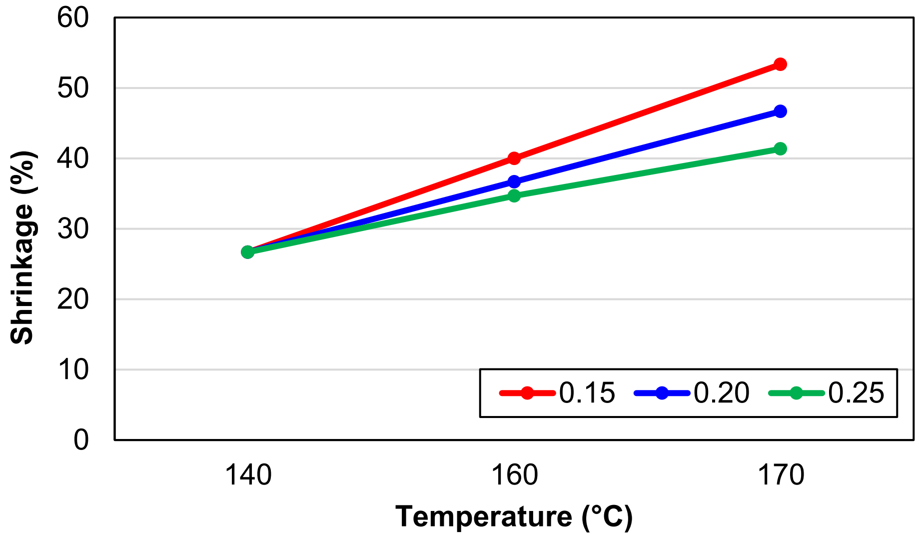

Figure 13. Shrinkage measurement results in the side region.

Table 2. Overall shrinkage of PVC sheets after thermoforming.

Thickness (mm)	Temperature (°C)	Side shrinkage (%)	Top shrinkage (%)	Curved shrinkage (%)
0.15	140	26.0	33.0	33.3
0.15	160	40.0	46.0	40.0
0.15	170	53.0	53.0	53.3
0.20	140	25.0	30.0	30.0
0.20	160	35.0	35.0	35.0
0.20	170	45.0	45.0	50.0
0.25	140	24.0	28.0	28.0
0.25	160	32.0	32.0	32.0
0.25	170	44.0	40.0	48.0

The largest shrinkage at the curved region occurred for the 0.15 mm sheet at 170 °C, with an average shrinkage of 0.08 mm or 53.3%. In the top and side regions, the largest shrinkage was also obtained for the 0.15 mm sheet at 170 °C, with a shrinkage of approximately 0.08 mm or 53.0%. The smallest shrinkage was observed in the side region for the 0.25 mm sheet at 140 °C, with a shrinkage of 0.06 mm or 24.0%.

These findings confirm that shrinkage increased with higher forming temperature and lower initial sheet thickness. Therefore, the best formability condition did not necessarily provide the best mechanical property condition. The 0.15 mm sheet at 170 °C showed good formability, but it also experienced the highest shrinkage. Conversely, the 0.25 mm sheet at 140 °C produced the highest tensile strength but relatively poor forming quality. This tendency agrees with vacuum-forming studies showing that forming quality depends strongly on process temperature, vacuum pressure, heating time, and sheet thickness [15].

4 Conclusion

PVC sheet thickness and forming temperature had clear effects on formability, tensile properties, and shrinkage in the thermoforming process. The formability of PVC improved when thinner sheets and higher forming temperatures were used; however, thicker material and lower forming temperature produced less complete product shapes. The highest tensile strength after thermoforming was obtained from the 0.25 mm sheet at 140 °C, with a stress value of 42.7 MPa and a load of 4.30 kgf. Increasing the temperature at the same sheet thickness reduced tensile strength. The greatest shrinkage occurred in the 0.15 mm sheet at 170 °C, reaching 53.3% in the curved region and approximately 53.0% in the top and side regions. Therefore, the selection of thickness and forming temperature must balance formability and mechanical performance. For future work, the vacuum forming machine should be calibrated more carefully, the heating system should be improved to reduce heat loss between the heater and the sheet clamp, and experiments should be conducted in a controlled-temperature environment.

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Conflicts of Interest

The authors declare no conflict of interest.

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