Thermoforming of HDPE

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Abstract. The thermoforming process involves a previously extruded sheet of material being reheated to a softened state below the melting temperature and then forced into a mould either by a plug, air pressure or a combination of both. Thermoplastics such as polystyrene (PS) and polypropylene (PP) are commonly processed via thermoforming for products in the packaging industry. However, high density polyethylene (HDPE) is generally not processed via thermoforming and yet HDPE is extensively processed throughout the packaging industry. The aim of this study was to investigate the potential of thermoforming HDPE. The objectives were to firstly investigate the mechanical response under comparable loading conditions and secondly, to investigate the final mechanical properties post-forming. Obtaining in-process stress-strain behavior during thermoforming is extremely challenging if not impossible. To overcome this limitation the processing conditions were replicated offline using the QUB biaxial stretcher. Typical processing conditions that the material will experience during the process are high strain levels, high strain rates between $0.1\text{-}10s^{-1}$ and high temperatures in the solid phase (1). Dynamic Mechanical Analysis (DMA) was used to investigate the processing range of the HDPE grade used in this study, a peak in the tan delta curve was observed just below the peak melting temperature and hence, a forming temperature was selected in this range. HPDE was biaxially stretched at 128°C at a strain rate of $4s^{-1}$, under equal biaxial deformation (EB). The results showed a level of biaxial orientation was induced which was accompanied by an increase in the modulus from 606 MPa in the non-stretched sample to 1212MPa in the stretched sample.

INTRODUCTION

The thermoforming process involves a preformed sheet of material being reheated to a softened state, deformed into a mold via a plug or air pressure, cooled and ejected as shown in Fig.1. The process is ideal for the large scale mass production of thin gauge packaging items such as trays, pots and tubs. The reason for this is that during processing a level of biaxial orientation is induced, which improves the mechanical properties of the formed part and hence, enabling the thickness of the final part to be reduced without compromising the final mechanical properties. The softening temperature is a critical aspect of the process as the sample must be readily formable but still maintain its structural integrity, as overheating can potentially lead to sagging which results in significant variations in the thickness profile of the part. Amorphous polymers such as High Impact Polystyrene (HIPS) can be thermoformed relatively easily, due to wide softening temperature range and the relatively simple microstructure. Whereas, semi-crystalline polymers such as polypropylene (PP) are significantly harder to process due to the highly temperature-dependent crystalline structure. However, due to the enhanced mechanical and chemical properties offered by semi-crystalline it is very desirable to process them via thermoforming.

High density polyethylene (HDPE) like PP is a semi-crystalline polymer which is widely processed within the packing industry with 5.5 million tones processing in 2013 (1) however, while PP is widely processed via thermoforming HDPE is not. HDPE is typically processed from the molten state via processes such as extrusion blow molding, injection and rotational molding. While melt processing HDPE is now standard practice, a few studies have highlighted that the mechanical properties can be further enhanced by processing below the melting temperature (2)(3). For example, Li et al (2) were able to increase the yield strength of extruded HDPE from 28MPa when extruded from the molten state to 181MPa when extruded below the melting temperature, this becomes particularly interesting when considering thermoforming HDPE which must be below the melting temperature. However, while this clearly

highlights the potential there is currently a lack of literature published on the response of HDPE under comparable processing conditions i.e. high temperature, high-rate (0.1-10s^{-1}) equal biaxial deformation (4). The understanding of the materials response it vital when it comes to setting up the process. The QUB biaxial stretcher has previously been used to apply representative thermoforming processing conditions for HIPS, PP and aPET (5,6), where a key outcome from this work was an understanding of the temperature and strain-rate dependence of the materials.

The aim of this study was to investigate the potential of thermoforming HDPE, by applying representative processing conditions offline. The objectives were to firstly investigate the mechanical response under comparable loading conditions and secondly, to investigate the final mechanical properties post-forming.
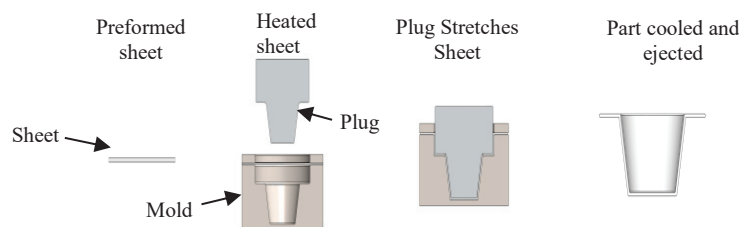

FIGURE 1. Thermoforming process.

EXPERIMENTAL

Material

HDPE samples with dimensions 76x76x2mm were injection molded using an Arburg 320S Allrounder 500-350 machine. The injection temperature was 235°C and the injection pressure was 85MPa, samples were held in the mold for 15seconds before ejection and were allowed to cool to room temperature. The HDPE resin used in this study had a Mn of 28623 Daltons, Mw of 151174 Daltons and Mz of 850210 Daltons. A Perkin Elmer DSC6 was used to analyze 10mg samples of HDPE, cut from the injection-molded sheet. The sample was sealed in an aluminum pan and heated at a controlled rate along with an empty reference aluminum pan. The reference sample was subtracted from the final results to account for the heating of the pan. Both samples were heated to 180°C, to ensure the sample was completely melted. The endothermic melting peak obtained via DSC is shown in Fig.2a along with the baseline used to determine the degree of crystallinity. The crystallinity was determined by dividing the area under the endotherm by the enthalpy of fusion for PE, which was taken as 293J/g (7). This was repeated three times and an average was taken for the degree of crystallinity and peak crystalline melting temperature, which were 64% and 132°C respectively, for a heating rate of 10°C per minute.

DMA

Dynamic Mechanical Analysis (DMA) was conducted using a Triton Tritec 2000 DMA. Specimens of dimensions 25 x 7.75 x 1.85mm were loaded in dual cantilever configuration with a span length of 15mm. Temperature sweeps at constant frequency of 1Hz and displacement of 0.025mm were conducted between 35°C and 135°C at a rate of 1°C/min. The tan delta curve is shown in Fig.2b as a function of temperature.
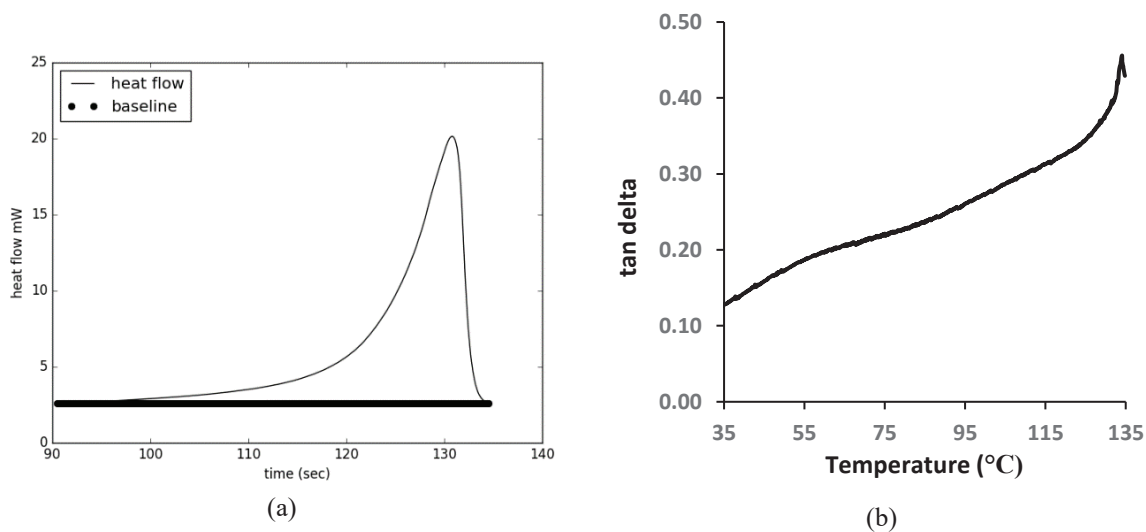
(a)

(b)

FIGURE 2. (a) DSC melting endotherm with baseline used for crystallinity calculations. (b) tan delta curve obtained from DMA

Biaxial Stretching

Biaxial stretching experiments were carried out on the QUB biaxial stretcher, which is capable of stretching square samples at rates up to $32s^{-1}$ and temperatures up to 200°C i.e. representative thermoforming processing conditions. The sample was gripped around its perimeter by pneumatic clamps and heating on both sides via two convection heaters, as shown in Fig.3. During the experiments, the air was heated to the stretching temperature and then the sample was held for the specified soaking time of 4 minutes, the heater was then turned off and the sample was stretched immediately. The temperature of the air close to the sample was controlled via a thermocouple, in a closed loop system. A more in depth description of the QUB stretcher is provided in (5)and (6).
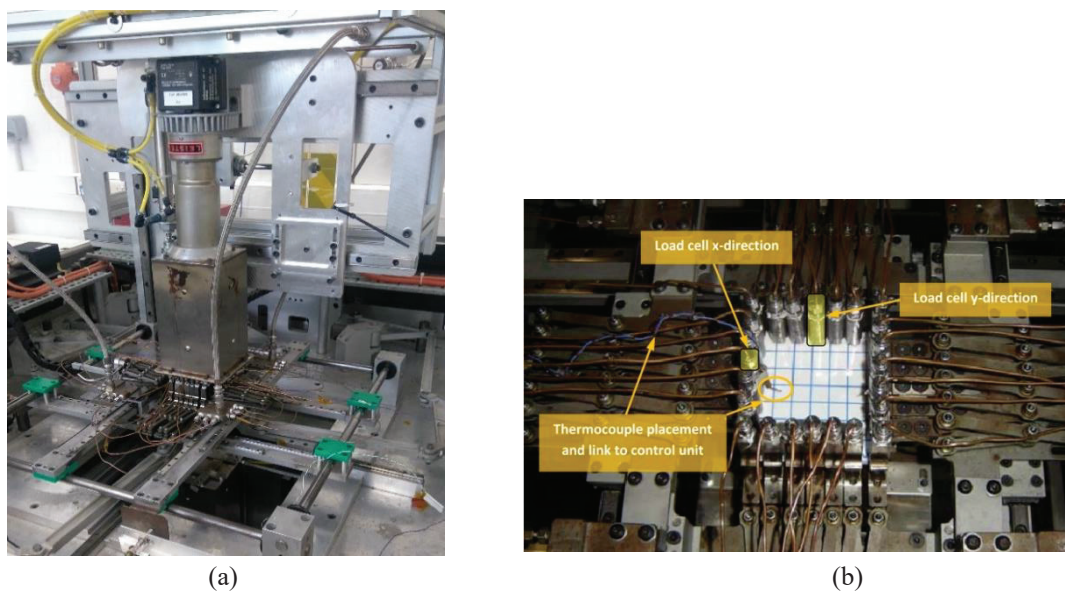

(a)

(b)

FIGURE 3. (a) QUB biaxial stretching machine. (b) QUB biaxial stretching machine sample holder and instrumentation

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