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Research paper

A novel methodology to characterize the constitutive behaviour of polyethylene terephthalate for the stretch blow moulding process

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ABSTRACT

The stretch blow moulding (SBM) process is the main method for the mass production of PET containers. And understanding the constitutive behaviour of PET during this process is critical for designing the optimum product and process. However due to its nonlinear viscoelastic behaviour, the behaviour of PET is highly sensitive to its thermomechanical history making the task of modelling its constitutive behaviour complex. This means that the constitutive model will be useful only if it is known to be valid under the actual conditions of interest to the SBM process. The aim of this work was to develop a new material characterization method providing new data for the deformation behaviour of PET relevant to the SBM process. In order to achieve this goal, a reliable and robust characterization method was developed based on an instrumented stretch rod and a digital image correlation system to determine the stress-strain relationship of material in deforming preforms during free stretch-blow tests. The effect of preform temperature and air mass flow rate on the deformation behaviour of PET was also investigated.

1. Introduction

Nowadays, due to the continuously increasing market value of the beverage bottle industry, there is an aim to optimize all the elements within the ISBM process to reduce the cost. For instance, to design the geometry of preforms and to reduce the material weight; to recycle the air to reduce the energy cost for high pressure; and to design the infrared oven to save the energy cost for reheating.

In order to achieve these optimizations, numerical simulations are essential to be used to obtain a better insight into the process operation in order to identify the critical process conditions which give a product with optimum quality (Tan et al., 2008). For a simulation to be accurate the material model used and process parameters used in the simulation have to be accurate and validated. One of the important tasks in numerical simulations of the stretching blow moulding process is to model the constitutive behaviour of PET, which is complicated because the responses are typical nonlinear viscoelastic and therefore highly sensitive to thermomechanical history. This means that the constitutive model will be useful only if it is known to be valid under the actual conditions of the SBM process of interest (Gerlach et al., 1998).

In the blow moulding process, the material typically experiences a high speed, large strain biaxial deformation. Numerous researchers world-wide have developed their own test platforms and enabled significant advances to be made in understanding the evolution of microstructure in PET materials under processing conditions (Marco et al., 2002; Vigny et al., 1999; Chandran and Jabarin, 1993a, 1993b; Faisant de Champchesnel et al., 1993; Marco and Chevalier, 2008; Menary et al., 2012a), and to generate stress strain data that is suitable for developing and validating constitutive material laws (Buckley and Jones, 1996; Buckley and Lew, 2011; Menary et al., 2012b; Martin et al., 2005).

However, it is recognised that biaxial testing does have serious limitations. Firstly, the test speed of the biaxial stretching testing machine is relatively low compared to the average deformation speed of material in the SBM process, which was found to be 50/s (Nagarajappa, 2012). Secondly, almost all designs of biaxial stretching testing machine require test specimens to be in the form of thin square sheets, plaques or crucifix. In the case of injection stretch blow moulding, where no sheet is produced, industrial samples cannot be tested directly and equivalent sheet specimens have to be specially prepared. This causes problems in characterization to ensure that the test specimen has similar thermomechanical history and properties to the preform.

Another technology, Digital Imaging Correlation (DIC), has begun to provide researchers in polymer processing with an additional, more direct and immediate means of tracking the response of materials during processing. One of the first to apply this technology to blow moulding was Billon et al. who have conducted several studies using a free blow device in conjunction with a

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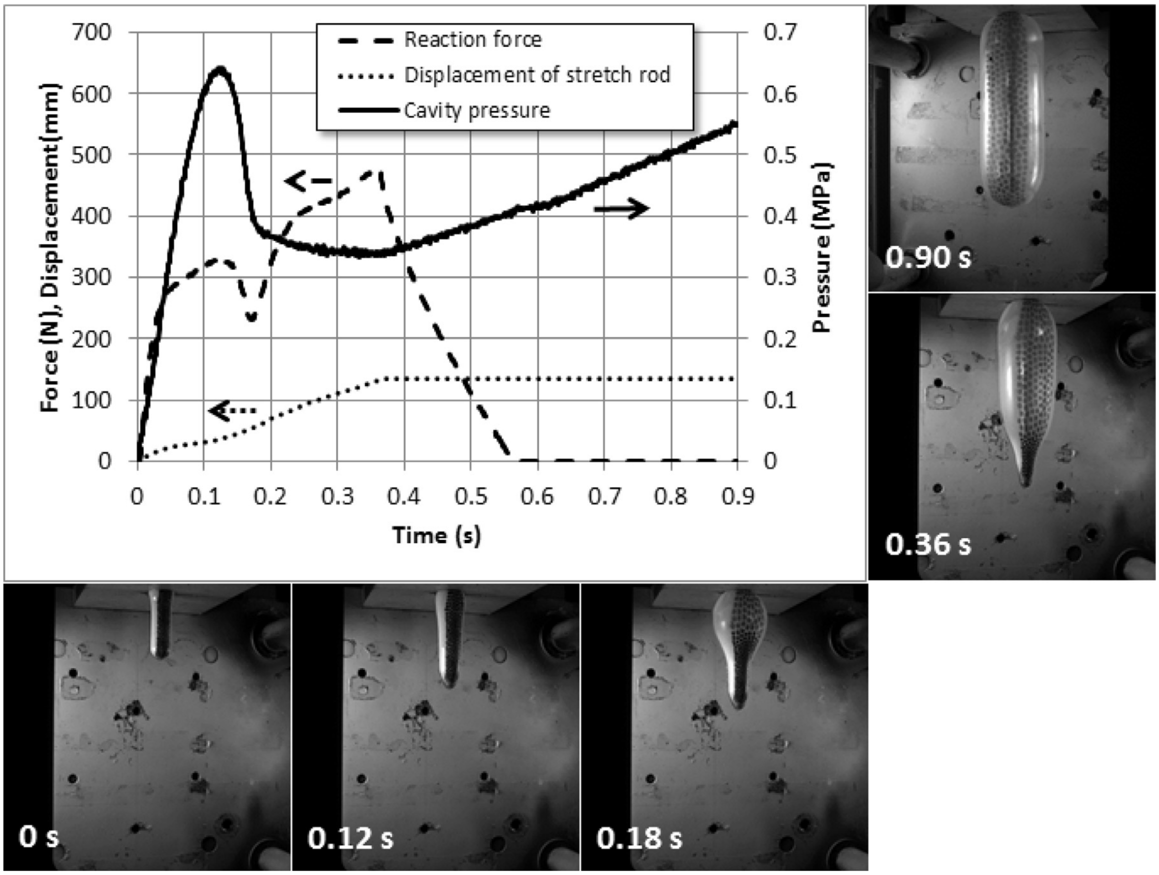

Fig. 1. A typical measurement via the instrumented stretch rod and the corresponding high speed images from one FSB test.

single high speed camera (Billon et al., 2005). They used surface grids to assess the evolution of strain rate in the preform during blowing for different conditions and correlated this with separate microstructure measurements. Menary et al. have also collaborated with Billon in using the device to validate ISBM simulations (Menary et al., 2010) by comparing images of the evolving preform at specific time points with simulation. Billon (Deloye et al., 2008) proposed a methodology for characterising PET resin using their device by comparing the volume of the final blown preform to tensile tests and Dynamic Mechanical Analysis of samples taken from the final preform. Zimmer et al. (2013) used 3D DIC to determine the stress strain behaviour from a free blown preform and use the data to validate a material model. However, these experiments did not include a stretch rod resulting in the likelihood of process instabilities and like the work of Billon they provided limited capacity for heating and flow control.

The goal of this research is to develop a new characterization method to obtain the constitutive behaviour of the material for the ISBM process directly from the preform and under conditions which are typically used in industry.

2. Free stretch-blow (FSB) process with integrated instruments

A free stretch-blow test is similar to a SBM test wherein the preform is heated firstly above the Tg of PET material, after which the hot preform enters the blowing stage where it is stretched by a stretch rod and freely blown with pressurised air without a mould. The evolution of an inflating preform can be observed and studied. The free stretch-blow experiments offer the opportunity to investigate the process in much more detail than can be found when inflating a preform inside a closed mould.

All FSB trials were performed on a single cavity, laboratory-scale stretch blow mould machine supplied by Vitalli & Son and located at Queen's University Belfast (QUB). The preforms were pre-heated using a Grant^{TM} general purpose stirred thermostatic bath from 95 °C to 110 °C by completely immersing the preform and constantly rotating it inside the oil bath to obtain a uniform temperature profile. The pre-blow pressure was fixed at 0.8 MPa for these trials. The air flow providing preform inflation for the SBM process is a combination of both supply pressure and adjustment of the flow restrictor. With the supply pressure fixed at 0.8 MPa, the flow restrictor (ranged 0 – closed to 6 – fully open) was adjusted to two settings: 2 and 6, indicating low mass flow rate (MFR) and high MFR respectively and corresponding air mass flow rate of 9 and 34 g/s. The detailed description of the experimental setup is described by Nixon et al. (2016a).

An instrumented stretch rod (Salomeia et al., 2010) which is able to measure the cavity pressure evolution within the deforming bottle and the reaction force applied on the tip of the stretch rod has been employed. The sensitivity in force and pressure is 0.798 N and 1.313 kPa, respectively. The stretch-rod displacement is measured using a linear variable differential transformer (LVDT). The LVDT sensor used is an ACT6000C supplied by RDP Electronics. The typical outputs of one free stretch-blow test can be found in Fig. 1. From this figure, one can find the preform expanding in 4 stages. From 0 s to 0.12 s, the preform is deformed entirely by stretch rod displacement. The linearly increasing force curve indicates the elastic response of the material. Then the preform experiences a rapid inflation from 0.12 s to 0.18 s, when the air mass flow rate is lower than the volumetric increase rate resulting in the reduction in both cavity pressure and reaction force. The next stage is from 0.18 s to 0.36 s when the preform expands isobarically,