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Simulation of the plug-assisted thermoforming of polypropylene using a large strain thermally coupled constitutive model

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ABSTRACT

Thermoforming is widely employed in industry for the manufacture of lightweight, thin-walled products from pre-extruded plastic sheet and its largest application is in packaging. Over many years attempts have been made to simulate the process and thereby exploit modern computational tools for process optimisation. However, progress in this area has been greatly hampered by insufficient knowledge of the response of polymer materials under thermoforming conditions and an inability to measure this and other processing phenomena accurately. In recent years some address has been made to these problems through advances in measurement technologies, and in particular, the development of high speed, high strain, biaxial testing machines that are designed to replicate the conditions in thermoforming processes. In this work the development of an advanced finite element-based thermoforming process simulation is presented. At its heart is a sophisticated large strain thermally coupled (LSTC) material model for polypropylene, which has been developed after several years of research and is founded directly on biaxial test results at elevated temperatures. This material model has been demonstrated to provide an excellent fit to the biaxial data and to offer a very stable computational platform for the process simulation. The performance of the working simulation was validated through comparison with matching experimental test results, and this enabled investigation of the sensitivity of the process output (in the form of part wall thickness distribution) to changes in a range of other processing parameters. This work confirmed that the process is most sensitive to the parameters controlling plug/sheet contact friction. Heat transfer parameters were also shown to be significant and the requirement for the model to be fully thermo-mechanically coupled has been clearly established.

1. Introduction

The manufacture of packaging is a large and very important industrial sector. Within packaging a large proportion of the market is concerned with the production of thin-walled polymer containers that are manufactured using industrial thermoforming processes. As the name implies, thermoforming involves the shaping of a heated polymer material through the application of pressure in an appropriate thermal environment. Most commonly the feedstock is a heated pre-extruded polymer sheet and air pressure is the principal means of forming. However, as the required depth of draw in the product increases it becomes necessary to employ a two stage thermoforming process, where the heated sheet is initially pre-stretched through contact with a moving mechanical plug, before forming is completed through the application of air pressure. This process is known as plug-assisted thermoforming and it is very widely used in the manufacture of food packaging products such as pots, tubs and trays. In the past such products were almost exclusively manufactured from amorphous polymers such as polystyrene (PS) and polyvinylchloride (PVC), as these can be shaped with relative ease above their glass transition temperatures and also exhibit forgivingly wide forming temperature windows. However, in recent times the same market has become dominated by polypropylene (PP) which has gradually replaced its amorphous rivals due to its superior mechanical properties and lower material costs. As a semi-crystalline material, PP is more difficult to thermoform as it must be processed within a narrow temperature range just below its crystalline melting point. This, along with its greater tendency to sag when heated, has significantly increased the challenge facing the thermoformed packaging industry. At the same time the packaging market has become increasingly demanding, particularly with respect to product aesthetics, performance and costs, and the industry has responded through improvements in design and manufacturing technologies. This has included many advances in the speed and efficiency of production machines, but despite the widespread use of simulation

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elsewhere, the thermoforming industry still largely remains wedded to traditional trial and error methods for product and process development.

Over many years researchers have made significant advances in the simulation of most of the major polymer processing techniques, for instance injection moulding, and this has increased the level of sophistication of materials processing technology used throughout the industry. However, the equivalent body of work in thermoforming is comparatively small, and to date its industry has failed to capitalise on many of the benefits of process simulation seen in other areas. Nevertheless, advances in process simulation have been steadily reported, although the majority of this work has been focussed upon simple vacuum forming processes such as the preliminary models described by Bourgin et al. (1995), where a heated sheet was formed by air pressure alone, the material was treated as a membrane and there was no interaction with a moving plug. Later vacuum forming studies published by Wang et al. (1999) of an acrylonitrile butadiene styrene (ABS) square cup have reported good correspondence between experiment and simulation. In most cases simulations have employed finite element techniques for modelling the process components and in early work the assumption of isothermal conditions was commonplace. As a result, these simulations generally employed membrane elements to represent the sheet during thermoforming and tooling surfaces were modelled as rigid surfaces as in the study of Karamanou et al. (2006). The performance of the membrane assumption compared to solid continuum elements was presented in the study by Nam et al. (2000). It was proposed that under conditions of free inflation that the membrane assumption corresponded well with the three-dimensional solids when the sheet width to thickness ratio is larger than 100. Experimental work by Collins et al. (2002) has presented clear evidence of significant changes in sheet temperature during thermoforming and has highlighted the need to include heat transfer in thermoforming process simulations. The development of non-isothermal simulations have been reported by Laroche and Erchiqui (1999) who used a thermally activated material model in the finite element analysis of a vacuum formed container and Christopherson et al. (2001) in a thermally conducting computational fluid dynamic simulation of blister packaging. Use of more sophisticated element types such as shell (Debbaut and Homerin, 1998) or continuum (solid) elements (O'Connor et al., 2007) have been reported in thermoforming simulations to model the sheet material. The treatment of contact slip within thermoforming simulations has also advanced substantially over the years. In early models it was common that no slip or absolute sticking conditions were assumed, as is the case in the perfect plug slip assumption of Nam et al. (2000) and the perfect mould stick assumption of Warby et al. (2003). Later models have included contact slip with the use of Coulomb friction functions and this has been aided by efforts to experimentally measure friction either by using a moving sled technique (Collins et al., 2001) or a rotational viscometer (Beilharz et al., 2007). Researchers such as McCool et al. (2006) have also recognised the need to make frictional behaviour temperature dependent and have used non-isothermal friction models to improve their simulations. Beilharz et al. (2007) proposed several experimentally based mathematical relations for frictional behaviour governed by temperature, pressure and strain rate dependence. However, accurate measurement of friction during thermoforming is recognised as an ensuing challenge for researchers and it remains as a serious impediment to the improvement of the predictive accuracy of current simulations.

A range of representative experiments and associated test equipment have been developed to attempt to characterise the behaviour of polymers during thermoforming. These tests must necessarily be representative of the conditions that occur during processing, which include: large deformation generally in tension, high temperatures, significant rates of straining and varying modes of deformation of which plane-strain and biaxial modes are dominant. Uniaxial, biaxial, constant width, sequential stretching, shear and compression techniques have been the most commonly adopted approaches for experimentation. The results of these experimental tests have then been used to develop numerical models which replicate the behaviour of the polymers during testing and processing. Ruiz and Gonzalez (2006) performed conventional uniaxial, biaxial and shear experiments in tension at room temperature to determine material constants for hyperelastic models for the simulation of the forming of fabrics. They reported the need to determine the data based upon a number of differing deformation modes. Lee et al. (2001) used a Meissner-type extensional rotating clamp rheometer and a mechanical spectrometer in experiments at temperatures in the 140–200 °C range to determine the respective uniaxial tensile and shear growth coefficients for their viscoelastic material model of ABS in the investigation of a vacuum snap-back thermoforming process. Martin et al. (2000) developed a hemispherical plug falling-weight impact test apparatus situation in a temperature controlled oven. The plug and attached weight were dropped from a set height onto a heated polymer sheet clamped between two metal plate annuli. Upon dropping the weighted plug, the test rig would record the force from the plug as a function of the displacement and deformation rate. True stress-true strain curves were obtained from the recorded values and from this data set material constants were extracted for both hyperelastic and viscoelastic constitutive models, which were used in the simulation of a plug-assisted thermoforming process of a HIPS container. Laroche and Erchiqui (1999) applied a bubble inflation experimental technique which involved increasing the air pressure on one side of an annuli constrained heated polymer sheet specimen, whilst optically measuring the height to which the pole of the ensuing hemispherical bubble expanded. Data pairs of air pressure on the sheet and the expansion height of the apex of the hemisphere were recorded simultaneously. This data was used in conjunction with an analytical solution for the straining of a pressurised hemisphere to derive constants for hyperelastic strain energy functions. The material model developed was used in simulations of the vacuum forming of heated ABS sheets in two differing mould geometries. Kashyap and Venerus (2010) developed a lubricated squeeze flow technique, where low density polyethylene (LDPE) and PS samples at elevated temperature were squeezed between two lubricated parallel plates causing equibiaxial extension. These researchers investigated the relaxation moduli of the polymer melts comparing them to the Edwards and Vilgis (1988) tube model predictions amongst other constitutive models.

The most significant advance in the technology required for the simulation of thermoforming has come through the development of dedicated biaxial testing machines. For the first time these have been able to subject materials to testing conditions precisely matching those experienced during thermoforming and have enabled the deformation response of different polymer materials to be accurately mapped. Across the world a number of such machines are now being used by research groups to create sophisticated and realistic models for different polymers used in thermoforming and blow moulding applications. These include the dedicated biaxial testing machines at Oxford University (Buckley et al., 1996), the University of Erlangen–Nuremberg (Capt et al., 2003) and Queen's University Belfast (Martin et al., 2005). In early simulations Newtonian or hyperelastic models were commonly employed (Nied et al., 1990), but with the combination of the need to introduce plug contact in many processes and the improved measurement and understanding of the materials, models are now predominantly either viscoelastic (O'Connor et al., 2007) or viscoplastic (Wang et al., 1999). A number of very different mathematical formulations have been proposed for different polymers as presented in the studies by O'Connor et al. (2007) on PP, Buckley et al. (1996) on