Journal of Materials Processing Technology 229 (2016) 36–53

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Physical modelling, numerical simulation and experimental investigation of microfluidic devices with amorphous thermoplastic polymers using a hot embossing process

Gang Cheng [a,b], Mohamed Sahli [a], Jean-Claude Gelin [a], Thierry Barriere [a,*]

[a] FEMTO-ST Institute, Applied Mechanics Department, 24 Rue de l'Epitaphe, 25000 Besançon, France
[b] Mechanical Engineering Design Department, INSA Lyon, 85 Rue Henri Becquerel, 01100 Bellignat, France

ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form 25 August 2015
Accepted 26 August 2015
Available online 2 September 2015

Keywords:
Hot embossing
Polymer
Amorphous
Viscoelastic
Simulation
Microfluidic

ABSTRACT

This paper studies the hot embossing process applied to amorphous thermoplastic polymers, including the characterization and identification of the polymers' viscoelastic behaviour, numerical simulation of the filling stage in the micro hot embossing process and experimental elaboration of microfluidic devices prepared by a hot embossing process. Static compression creep tests have been carried out to investigate the selected polymers' viscoelastic properties. The Generalized Maxwell model has been proposed to describe the relaxation modulus of polymers PS, PMMA and PC, and good agreement has been observed. The numerical simulation of the hot embossing process in 3D has been achieved by taking into account the viscoelastic behaviour of the polymers. A new complete micro compression moulding tool, including a heating system, a cooling system and a vacuum system, has been developed in our research group. Microfluidic devices with cavity dimensions equal to approximately 200 μm, 100 μm and 50 μm in PS, PMMA and PC plate (thickness equal to 2 mm) have been elaborated by the hot embossing process. The effects of the processing parameters, such as the compressive gap imposed, the compression temperature, the embossed material and the die cavity dimensions, on the replication accuracy of the hot embossing process have been investigated. The comparison between the numerical simulation and the experiments shows proper agreement for the prediction of the polymer substrate deformation in the replication of a microfluidic device using the hot embossing process. The developed hot embossing experimental system exhibits a low cost and short production cycle for the elaboration of microfluidic devices based on amorphous thermoplastic polymers, which provides the possibility of mass production for the elaboration of microfluidic devices.

1. Introduction

The hot embossing process is considered to be a very promising replication process in various fields, such as the micro-mechanical, micro-optical (Ottevaere et al., 2015), chemical, medical and biological fields (Mekaru et al., 2002). The hot embossing process is widely used in the manufacturing of macro and micro structures, especially for structures with high aspect ratios. With the fast development of lithography and etching technologies, the size of the patterns on the mould die insert can reach the nano range, enabling the replication of the nano structures (Yang et al., 2010). Although many contributions have been made in the experimental investigation of the hot embossing process, the numerical simulation of the process has not been well studied (Worgull and Heckele, 2004). This is a cost-effective way to optimize the hot embossing process design. The filling stage is the most important step during the hot embossing process, as it determines the replication accuracy of the final components. Polymer deformation during the filling stage can be predicted by the simulation, which can help us reduce the defects of the replicated components.

Amorphous thermoplastic polymers, considered important engineering materials, are widely used in a variety of applications (Srivastava et al., 2010). Amorphous polymers are more suitable than semi-crystalline polymers for use in the hot embossing process because they soften smoothly above T_g, which leads to a larger moulding temperature range (Worgull et al., 2011). The thermo-mechanical behaviours of the amorphous polymers have to be investigated to predict the deformation during the hot embossing process. Considerable efforts have been devoted to developing constitutive models of the large deformation elastic-viscoplastic

---

* Corresponding author. Fax:+33 3 81 66 67 00.
E-mail address: thierry.barriere@univ-fcomte.fr (T. Barriere).

http://dx.doi.org/10.1016/j.jmatprotec.2015.08.027
0924-0136/

behaviours of these materials, such as the influence of the intrinsic strain softening of the strain location in PC by Govert et al. (2000); the theory of the large deformation of amorphous polymers by Anand and Gurtin (2003) and its applications in micro-indentation processes by Anand and Ames (2006); the modelling of the mechanical behaviour of amorphous polymers based on the quasi point defect theory by Rinaldi et al. (2011); the constitutive model for the finite deformation of amorphous polymers developed by Fleischhauer et al. (2012) and the comparison of the existing model predictions with the modelling of the mechanical behaviour under variable loadings effectuated by Holopainen (2013). However, the strong temperature dependence and rate dependence are not well understood, especially in the hot embossing temperature range, which is slightly above T_g. The characterization of the polymers' physical properties is the key factor in realizing the numerical simulation of the hot embossing process.

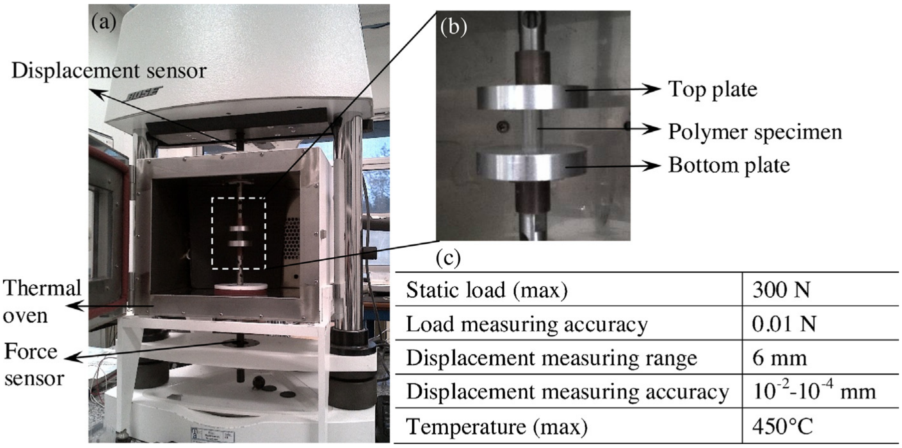
Microfluidic devices emerged in the beginning of the 1980s with the development of Micro Electro Mechanical Systems (MEMS) in relation to microelectronics, particularly in the fields of pressure sensors and printer heads. In the past few years, applications of microfluidic devices have been extensively explored at the interface of biology, chemistry and engineering (Whitesides, 2006), such as protein and DNA analysis (Liu and Fan, 2011), point-of-care diagnostics (Yelisen et al., 2013) and detection of biomolecules (Hu et al., 2013). Microfluidic devices offer unique advantages over conventional macro scale devices, such as decreased consumption of reagents, reduced analysis time and more portable instrumentation (Jena et al., 2011). Many developments have been made in the manufacture of miniaturized devices ranging from simple microfluidic chips up to multifunctional integrated systems, such as lab-on-a-chip devices (Cheng et al., 2015). However, the majority of these manufacturing processes involved lithography or the etching of glass and silicon, which require complex manufacturing steps and long production cycles with high fabrication costs. Mass production using a rapid prototyping method is quite desirable for the wide application of microfluidic devices. Injection moulding and hot embossing are the most commonly used replication processes for mass production in a variety of industries. Hot embossing is an ideal method for rapid the prototyping of micro and nano structures into polymers (Hutter et al., 2013), especially for producing delicate microstructures with high aspect ratios (Becker and Heim, 2000). Hot embossing provides several advantages over injection moulding, such as a lower cost for the embossing tool, flexibility in the choice of embossing material and a high replication accuracy for small features. The temperature variation in the hot embossing process is smaller than that in injection moulding, which leads to reduced shrinkage during cooling. In addition, the much shorter flow distance and lower flow velocity from the substrate into the die cavities during hot embossing results in a lower residual stress in the mould component (Worgull, 2009). The first generation of microfluidic devices were based of silicon or glass, mainly in micro component manufacture in the microelectronics industry (Koerner et al., 2005). Polymeric materials received attention in the development of microfluidic devices after the 2000s, due to their lower cost, diverse availability of materials and the variety of processes available for device manufacturing.

Even though the elaboration of microfluidic devices has been well developed in various areas, the numerical simulation tools need to be improved, especially a fast simulation method to predict or verify experimental investigations. Taylor et al. proposed a computationally simple method for simulating the micro embossing of thermoplastic layers (Taylor et al., 2009). The viscoelastic material model has been used in simulations, and these linear models have proven to be of great value because of their fast computation. The Kelvin–Voigt viscoelastic model has been encountered in hot embossing process simulation, and the accuracy of the simulation procedure has been confirmed by experimental embossing (Taylor et al., 2010).

The paper describes the study of the hot embossing process performed on amorphous thermoplastic polymers, including the characterization of the polymer's thermo-mechanical properties, the identification of the polymer's viscoelastic and viscoplastic behaviours, the numerical simulation of the filling stage of the hot embossing process and experimental investigations on the microfluidic device elaboration by hot embossing process. A linear viscoelastic model, the Generalized Maxwell model, has been applied in the numerical simulation because of its efficiency in numerical computation and its well-fitting with the experimental characterization. The work is motivated by the goal of improving the understanding of the polymers' strongly temperature and rate dependent properties and their effects on the replication accuracy of the microstructures by the hot embossing process. The findings provide guideline on polymer selection in the manufacture of microstructures in the hot embossing process and show the possibility of complex geometry replications by the hot embossing process.

2. Characterization of polymer behaviour in the hot embossing process

In contrast to the other engineering materials such as metal or ceramic, polymers offer a variety of advantages, such as low density, ease of manufacture and low cost (Mohammad, 2007). Polymers are considered to be suitable materials for the manufacture of



(c)

Static load (max)	300 N
Load measuring accuracy	0.01 N
Displacement measuring range	6 mm
Displacement measuring accuracy	10^{-2}-10^{-4} mm
Temperature (max)	450°C

Fig. 1. (a) Uniaxial compression testing equipment used in our experiments, (b) the assembly of the polymer specimen and plates, (c) main characteristics of the equipment.