Journal of Materials Processing Technology 236 (2016) 183–188

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Micro-ultrasonic welding using thermoplastic-elastomeric composite film

Wei Xuan Chan[a,b], Sum Huan Ng[b], King Ho Holden Li[a], Woo-Tae Park[c], Yong-Jin Yoon[a,*]

[a] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, S 639798, Singapore*
[b] *Singapore Institute of Manufacturing Technology, 71 Nanyang Dr, Singapore 638075, Singapore*
[c] *Department of Mechanical and Automotive Engineering, Seoul National University of Science and Technology, Gongreung-2 dong, Nowon-gu, Seoul 139-743, South Korea*

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 20 May 2016
Accepted 21 May 2016
Available online 24 May 2016

Keywords:
Ultrasonic welding
PMMA
PDMS
Microfluidics
Composite

ABSTRACT

A composite film of PMMA microspheres in PDMS is used as the fusion layer to avoid trapped air and to restrict the flow of the melted polymer during welding. The matrix material selection and distribution of PMMA microspheres is determined by the 1-D theoretical model. The theoretical work reveals that the difference in dynamic modulus between the matrix material and PMMA is the most significant contribution to the viability of this composite ultrasonic welding film. The experiment is conducted with PDMS as the matrix material to determine effect of the concentration of PMMA microspheres as micro energy directors on the welding strength and quality of the proposed methodology with the chosen composite. While there are no visible signs of trapped air in all specimens, the resultant welding strength in this methodology is limited by the particle size range of the PMMA microspheres. For ultrasonic energy input of 1 kJ on a 32 mm × 32 mm sample, the optimum concentration of PMMA microspheres is found to be 0.24.

1. Introduction

Recently, there has been tremendous interest in microfludics for applications in biomedical due to their ability to provide fast response and low cost production with only trace amounts of chemical bio-receptors. The microfluidic devices are usually fabricated using glass or silicon with chemical and plasma etching, and photolithography. Becker and Locascio (2002) reviewed other materials including polymethyl methacrylate (PMMA) and polydimethylsiloxane (PDMS) which are commonly preferred in industries as cheaper alternatives to glass. Kalkandjiev et al. (2011) highlighted the low fabrication cost and the ease to mass produce as the major reasons of using PDMS and PMMA, and Luo et al. (2010) demonstrated that the PMMA also have the potential to create complex, stable geometries using simple fabrication methods (without fabricating energy directors), while being able to accommodate errors in terms of reversible change upon softening and melting.

In the production of microfluidic devices, Luo et al. (2010) highlighted the critical role of the welding process in sealing open microstructures and allowing integration into a closed fluidic paths. There are numerous welding techniques including capillary adhesive welding, chamber adhesive welding, adhesive film welding, laser welding, solvent diffusion welding, conventional thermal welding and plasma assisted (thermal) welding. There are also techniques such as UV degradation supported thermal welding, developed by Truckenmuller et al. (2006), which applies to a few types of polymers only. The main welding research on these techniques focused on finding the ideal process that has short process time and retains the channel geometrical structure while still produces high strength welds. However, there are not much breakthroughs in the efficiency of mass production of microfluidic devices due to welding process time and weld quality of existing techniques. The stability of design geometry and strength of welding are important criterion the manufacturing of microfluidic devices. Hence, Zhang et al. (2010b) provided guidelines that the welding has to be tight sealing at joint interface and void of contaminants. They (Zhang et al., 2010a) also added that the process has to create minimal deformation of the existing microstructures.

Ultrasonic welding is a technique in which the specimens are connected by the melting of plastic with ultrasonic acoustic energy source. Benatar and Gutowski (1989) claimed the high efficiency of this method due to its stability and ability to produce strong joints with automated compact equipment, and Ng et al. (2009) use ultrasonic welding to join connectors which enables rapid process time (in the order of seconds) and economical mass production

---

* Corresponding author.
E-mail address: yongjiny@ntu.edu.sg (Y.-J. Yoon).

http://dx.doi.org/10.1016/j.jmatprotec.2016.05.025
0924-0136/

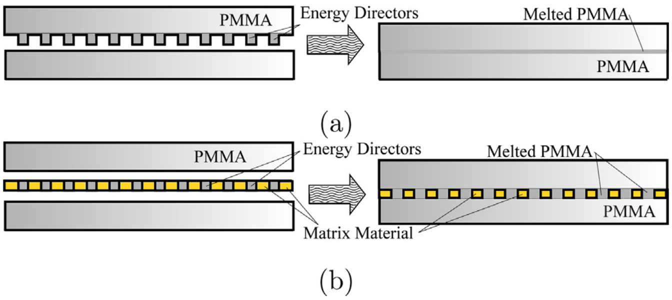

Fig. 1. Illustration of polymer using (a) conventional and (b) composite film ultrasonic welding. In conventional ultrasonic welding, the energy directors melt and flow across the surface of the samples, resulting in a thinner fusion layer. In ultrasonic welding using composite film, the energy directors melts but maintains its height due flow restriction by the matrix material.

of the microfluidic devices. Rani et al. (2007) studied the parameters in ultrasonic welding and gave an better understanding to the process. The ultrasonic welding process, with current simplicity of operation developed by Grewell (1999), utilizes an ultrasonic energy source (usually with a frequency of 20–50 kHz) and low amplitude (15–60 μm) mechanical vibration to induce localized frictional heating through viscoelastic dissipation by intermolecular friction. The generated heat melts contacting surfaces of the polymer and joins the two surfaces.

Truckenmuller et al. (2006) fabricated the first ultrasonically welded microfluidic device by concentrating energy with convex energy directors. The time for energy director to melt is in the order of seconds. Therefore, it is difficult to precisely control the flow of the melted polymer. Although, overflow and underflow of molten polymer is acceptable for welding of most macro devices, Zhang et al. (2010b) have highlighted that it may clog (overflow) or leave small gaps (underflow) in the micro structures and cause a microfluidic device to be unusable. Sun et al. (2012) used micro energy directors to allow more space for the flow of molten PMMA. However, this does not eliminate problems of overflow and underflow entirely and it also causes air trapped when the energy directors are tightly arranged.

This present study explores the feasibility of using a composite film made of distributed thermoplastic particles in an elastomeric matrix to restrict the flow of melted energy directors and eliminate problems of trapped air, thus reducing its impact on the shapes of flow channels of microfluidic devices. The design process includes the matrix material selection, energy director distribution and optimizing the ultrasonic welding process parameters. Experiments are also conducted on the welding strength of PMMA samples welded using the present methodology.

2. Method

The fusion layer of the ultrasonic process in this work is a thin composite film consisting of micro-energy directors and a elastomeric matrix. The elastomeric matrix would constrict the flow of PMMA energy directors when they are in viscous state as well as replace the air which might be otherwise trapped during the process. Fig. 1 shows the ultrasonic welding using air (conventional) and elastomeric polymer as matrix. Other than the presence of trapped air and uncontrolled molten polymer flow, the two main notable differences of the welded products are the change in separation distance (shown in Fig. 1) and welding strength. The change in separation distance of conventional ultrasonic welding is,

$$h_s = h_{ed} - \frac{Vol_{ed}}{A} \tag{1}$$

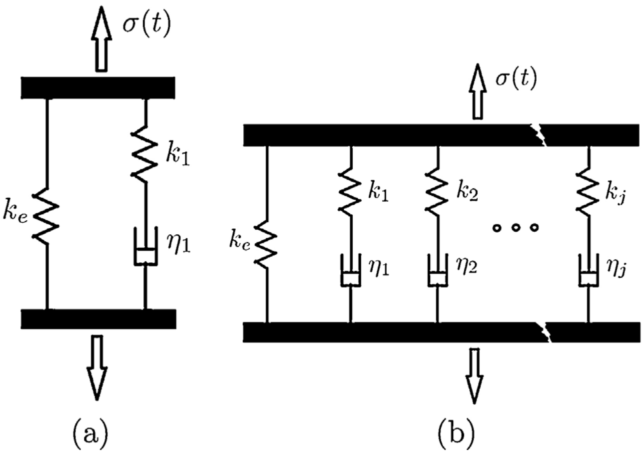

Fig. 2. (a) Maxwell standard linear solid and (b) Wiechert model (Wineman and Rajagopal, 2000). The viscoelastic materials of the thermoplastic-elastomeric composite is modeled as a system of springs and Newton dashpots. In a small range of temperature and vibration frequency, we approximate the Wiechert model to the Maxwell standard linear solid with equivalent spring and damping constants.

where h_{ed} is the initial height of the energy directors, Vol_{ed} is the total volume of the energy directors and A is the area of material welding (excluding channels, etc.). The change in separation distance using composite film is negligible due to incompressibility of the matrix material.

In this section, a methodology of composite material selection and design with a theoretical model for initial feasibility analysis followed by an experimental verification of such design is presented. The 1-dimensional theoretical model assesses the suitability of different matrix material as well as distribution of energy directors on the composite welding film. For this work, PDMS is chosen as the matrix material based on studies from the theoretical model after comparing some common elastomeric materials. The composite is fabricated by spin coating PMMA-microspheres-mixed-PDMS-base. Following so, the experiment presents the effect of different composite ratio on the welding strength of the proposed method. The experimental result also elucidates limitation of the fabrication method.

2.1. *Ultrasonic welding model*

Benatar and Gutowski (1989) categorized the mechanism of ultrasonic welding into mechanics and vibrations, viscoelastic heating of thermoplastic, heat transfer process, flow and wetting, and intermolecular diffusion. In this model, the mechanics and viscoelastic heating of thermoplastic is considered for the purpose of material choosing and energy director distribution. The Maxwell form of the standard linear solid (SLS) (Fig. 2(a)) is adopted to estimate the strain response with material parameters.

The strain response for input stress, $\sigma(t) = \sigma_0 \cos(\omega t) + \sigma_c$, in SLS is,

$$\epsilon(t) = \sigma_0 R \cos(\omega t - \delta) + \frac{\sigma_c}{k_e + k_1} \tag{2}$$

$$R^2 = U^2 + V^2 \tag{3}$$

$$U = \frac{(k_e + k_1)^2(\tau\omega)^2 + k_e^2 + k_1 k_e}{(k_e + k_1)[(k_e + k_1)^2(\tau\omega)^2 + k_e^2]} \tag{4}$$

$$V = \frac{k_1(k_e + k_1)(\tau\omega)}{(k_e + k_1)[(k_e + k_1)^2(\tau\omega)^2 + k_e^2]} \tag{5}$$

$$\delta = \tan^{-1}\frac{V}{U} \tag{6}$$

where $\tau_i = \eta_i / k_i$.