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A novel ultrasonic precise bonding with non-constant amplitude control for thermalplastic polymer MEMS

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ABSTRACT

Ultrasonic bonding has been emerging paving the way in micro assembly, with the high demand in fusion quality control. Under this background a novel ultrasonic precise bonding method based on non-constant amplitude control is proposed. A two-step bonding process, including frictional heating and viscoelastic heating, divided by the vibration propagation is designed. In step I, initial melting of the contacting surfaces is achieved at the amplitude bigger than the critical value. In step II, the whole interfacial fusion is realized at smaller amplitude to weaken the ultrasonic cavitation effect. The primary parameters in this method, including the amplitudes for the two steps and the conversion point, are studied. Results indicate that whole fusion bonding can be achieved with the flaws restrained. The proportion of cavity reduces to less than 2% when the amplitude for step II is set at a smaller value.

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1. Introduction

Polymer-based micro devices have seen tremendous interest in recent years due to the low material cost and the associated mass production techniques. Especially the thermoplastic polymer is preferred, owing to its good mechanical properties and easy processing, to be the substrate for micro devices, such as microfluidic systems, micro-valves, micro mixers, on-chip micro motors, etc [1,2].

Fast bonding is an essential technique in the micro assembly which demands good seal and low deformation. Several bonding techniques have been applied in MEMS such as adhesive bonding [3], laser bonding [4], microwave bonding [5], thermal bonding [6] and ultrasonic bonding [2]. Owing to the advantages of high efficiency, local heating and no need for implants, ultrasonic bonding is a potential key technology for the automatic production of polymer-based MEMS.

Traditional ultrasonic bonding process was controlled by time, pressure, electrical energy or collapse displacement. There were studies in improving the ultrasonic bonding control method. Mazuzawa et al. [7] studied the information contained in the radiating ultrasound during ultrasonic bonding and made the radiated ultrasound related to the mechanical impedance as a control parameter. Qiu et al. [8] proposed an ultrasonic method with an interposed sheet to impose longitude ultrasound, which is effective for heterogeneous materials weld.

Ultrasonic bonding was applied in micro assembly for the first time in 2006. Truckenmüller et al. [9] applied plastic ultrasonic bonding in the sealing of microfluidic chip and the assembly of micropump. In their research, micro channels made of PMMA were sealed and a piezo-driven micro pump made of PMMA (poly methyl methacrylate) and PEEK (Polyether Ether Ketone) was successfully assembled. In 2009 Kim et al. [10] studied two ultrasonic bonding methods respectively for metal wire and polymeric MEMS devices. It achieved wafer level packaging at low temperature. Ng et al. [11] applied ultrasonic bonding in the assembly of connectors to microfluidic devices. PMMA rod connector with external diameters of 3 mm and a 1 mm diameter conduit was bonded on a microfluidic chip, which was able to withstand a minimum of 6 bars pressure for at least 10 min. To improve the interfacial fusion controllability for micro assembly, an ultrasonic bonding method based on ultrasound propagation was designed in the author's early work [12]. In this process, ultrasonic propagation through polymer parts was measured. The vibration amplitude changes with the transition of interfacial polymer components. Then the change rate of ultrasound propagation was made as a primary parameter to control ultrasonic energy, the interfacial fusion degree could be controlled much more precisely.

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Ultrasonic bonding is a fusion bonding process, which realizes the interfacial polymer fusion by repeated impact of two surfaces at high frequency under ultrasonic load. For this process, Benatar et al. proposed a five-part model including mechanics and vibration of the parts, viscoelastic heating, heat transfer, flow and wetting, and intermolecular diffusion [13]. The model was verified by measuring the dynamic mechanical impedance via measurements of both the power and the acceleration on the base. Zhang etc. [14] measured the interfacial temperature in the ultrasonic bonding process. Two heating stages based on friction heat and viscoelastic heat were proposed based on experiments. Results indicated that there was a great gap in the heating speed between the two stages. It was found from the interfacial temperature curve that viscoelastic heating speed was much higher than friction. Villegas [15] carried out an experimental analysis of the transformations and heating mechanisms at the welding interface. The effects of friction heating initially in the elastic interface and then in the viscoelastic body were considered by analyzing the dissipated power and the displacement of the sonotrode. Generally, it is considered that the interfacial heat is mainly generated from two aspects. One is the friction heat caused by the high-frequency impact of the contacting surfaces. The other is the heat converted from the dynamic mechanical energy loss in the viscoelastic body, which leads to a much faster temperature rising speed.

Based on the two heating mechanism, a two-step ultrasonic bonding process at non-constant ultrasonic amplitude is proposed in this paper to balance the temperature rising speed and improve the parameter tolerance Experiments are carried out to study this method and explore the parameters. This paper is organized as follows. Section 2 introduces the control flow of this method and the test bench. Parameters are studied and the experiment results are discussed in Section 3. Finally, conclusions are drawn in Section 4.

2. Method and experimental

A two-step ultrasonic bonding process at non-constant ultrasonic amplitude is designed. Based on the literature, the ultrasonic bonding process can be divided into two stages based on frictional heating and viscoelastic heating. In friction heating stage, temperature rising occurs in some partial areas initially. Under ultrasonic load, heat accumulated with the temperature rise up to T_g (glass transition temperature) in some regions. In this condition, the polymer in these regions gets melted and viscoelastic heating begins to work. In viscoelastic heating stage, ultrasonic cavitation becomes effective as the fluidity of interfacial polymer increases at high temperature, which causes the cavities easily. In traditional ultrasonic bonding method, the amplitude is constant in the whole process. Once some regions get melted by friction heating, ultrasonic cavitation happens easily in the following viscoelastic heating process at high heating speed. Nevertheless, extra ultrasonic energy is needed to melt the whole interface, but it is redundant for the initial melting regions, which leads to the uneven distribution of fusion degree eventually.

Reducing amplitude is a way to weaken the ultrasonic cavitation effect in viscoelastic heating stage. But in friction heating stage there is critical amplitude to achieve interfacial melting. If the parameter is less than this value, the heat will be offset by dissipation, thus the interface is maintained at an equilibrium temperature below T_g. Above all, the amplitude bigger than the critical value is demanded in the friction heating stage and a smaller one is preferred in the viscoelastic heating stage. Therefore, providing ultrasonic energy in different amplitude for the two heating stages is a way to balance the heating speed.

In this method, ultrasonic energy at different amplitude is provided for the two steps. There are three key points, the first is dividing the two steps, the second is providing ultrasonic energy with the amplitude bigger than the critical value in the initial step to make the contact surface melted, and the last is reducing amplitude in the following step to weaken ultrasonic cavitation effect. For the division of the two heating steps, ultrasonic propagation through polymer components is employed to monitor the status of the interface. From our previous work, the ultrasonic propagation increases first and then decreases with the mechanical property change of the interfacial polymer [12]. So the ultrasonic propagation change rate could be the parameter to divide the two steps.

As shown in Fig. 1, in the ultrasonic test bench dynamic force sensor is fixed in the anvil to measure the vibration from the bottom of the workpiece. Piezoelectric dynamic force sensor (CL-YD-301, SINOCERA PIEZOTRONICS, INC.) with measuring range of 0–50 N, sensitivity of 4pC/N, resonant frequency of 70 kHz and linearity less than 1%FS is employed. The peak to peak value ($v_{p\text{-}p}$) of the measured vibration is calculated in real-time marked as $v_{p\text{-}p}$ (*real time*). In the bonding process the initial $v_{p\text{-}p}$ is recorded as a reference marked as $v_{p\text{-}p}$ (*ref*). Then the $v_{p\text{-}p}$ change rate of the vibration is calculated by Eq. (1) to divide the two steps.

$$R_c = v_{p-p}(real\ time)/v_{p-p}(ref) \times 100\% \tag{1}$$

For the amplitude control, instructions are transmitted to ultrasonic generator through RS232. The amplitude can be adjusted from 10% to 100% with the maximum value of 10 μm, with the resolution of 1%. The amplitude for step I and II are marked as A_I and A_{II} respectively.

In the test bench, an ultrasonic system in 60 kHz including the sonotrode, the ultrasonic transducer, and the ultrasonic horn are employed to provide ultrasonic vibration. The ultrasonic horn is fixed on linear motion guide rail and the movement is controlled by the stepper motor. In this mode the force from horn loaded on the workpiece is controlled more precise and also the disturbance from pressure float is avoided. Weighing sensor (BK-3, China Academy of Aerospace Aerodynamics) with measuring range of 0–10 kg, sensitivity of 1.5–2.0 mV/V, linearity of 0.02%FS is installed below the anvil to measure the static force. A fixture is designed to avoid the horizontal movement of the workpieces.

The ultrasonic bonding procedure in this method is as follows:

- Adjusting pretightening force;
- Setting ultrasonic amplitude to A_I (the amplitude for step I);
- Turning on ultrasonic generator (Bonding step I);
- Measuring vibration and calculating R_c (the $v_{p\text{-}p}$ change rate of the vibration);
- Setting ultrasonic amplitude to A_{II} (the amplitude for step II) when R_c reaches the setting value (Bonding step II);
- Keeping bonding for a while (15 s and 30 s);
- Releasing ultrasonic horn.

Experiments are carried out to study this method. In many microfluidic devices, there are connectors to be the inlets or outlets to connect the pipe fluid and microchannels [11]. Accordingly, the bonding experiment of the connector to the substrate as shown in Fig. 2 is carried out. The external and internal diameters of the connector are 4 mm and 1 mm respectively. The substrate is a square of 7 mm × 7 mm. Both parts are 2 mm in thickness, which is in the range of near-field ultrasonic bonding. As a kind of amorphous thermoplastic polymer commonly used in MEMS, PMMA is chosen for the study.

In experiments, the critical amplitude for interfacial melting is explored firstly. Then the relation between fusion degree and ultra-

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