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Thermal and ultrasonic bonding between planar polyethylene terephthalate, acrylonitrile butadiene styrene, and polycarbonate substrates

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A B S T R A C T

Polyethylene terephthalate (PET), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) have seldom been used as substrate materials in chemical and biochips. Here, identical planar PET, ABS, or PC substrates with a thickness of 1 mm were bonded thermally or ultrasonically. Thermal bonding conditions were found by increasing the experimental temperature above the glass transition temperature (T_g) of each polymer. The temperature of each bonding interface should reach T_g. Ultrasonic bonding was achieved when a longitudinal wave of ultrasonic vibration was changed efficiently to friction heat between the bonding interfaces. This phenomenon was promoted by attaching one of the polymer substrates to the ultrasonic horn by vacuum chucking. Using the developed bonding method, the bonding strength that was obtained was approximately ten times the maximum value reported previously. As choices for the substrate material of polymer chips increase, the experimental environments that can be realized in chips will greatly expand.

1. Introduction

Disposable polymer chips are widely used in chemistry, biotechnology, and medicine [1]. Numerous techniques to fabricate chips have been developed focusing on their function and manufacturing cost; for example, processing in microfluidic channels, bonding substrates together, and surface modification of microchannels [2]. In particular, in bonding where no foreign matter such as an adhesive agent is present, bonding between planar substrates is required to form a closed space by covering the microchannel. Direct bonding of chips can be roughly divided into thermal and chemical [3] approaches. In the latter method, chemically modified bonding surfaces are brought into contact with each other and then bonded. In contrast, the former method thermally welds contact surfaces by softening and then cooling them in the contacting state. Many heating methods have been developed, including using a heater, laser irradiation, microwave irradiation, and ultrasonic vibration [4]. Furthermore, a method combining a few of these techniques has also been proposed. In particular, ultrasonic bonding is used to manufacture three-dimensional structures such as connectors, and it is used for not only bonding but also molding. To form a closed microchannel, it is generally necessary to bond a polymer substrate containing a microchannel with a flat substrate. In the case of using microfluidic devices for fine chemistry or drug discovery, to completely eliminate the risk of microchannel contamination by an adhesive material, direct thermal bonding of the substrates is preferred. In thermal bonding using an ordinary heater, as shown in Fig. 1(a), two planar substrates (one of which has been prepatterned with microchannels) are sandwiched between upper and lower heaters, and the bonding surface is softened by heat transfer from the heaters. However, because the bonding surface is located at the farthest position from both heaters, the portion in contact with the heater heats up and is thermally deformed. As a result, the cross-sectional shape of the closed microchannel collapses. A bonding method in which the rectangular cross-sectional shape of the microchannel does not collapse needs to be developed. Applying a longitudinal ultrasonic vibration, as shown in Fig. 1(b), induces bonding by generating local frictional heat on the contact surface. In addition, the bonding method must achieve a sufficient bonding strength so that liquid or gas does not leak out of the microchannel.

Generally, polymers can be roughly divided into thermosetting and thermoplastic resins. The molecular structure of thermosetting resins is three-dimensional, and once molded, it will not melt even if heated again. In contrast, because thermoplastic resins are chain polymers, they can melt when heat is applied even after molding. Therefore, only thermoplastic resins can be used as thermally bonded polymers. Thermoplastic resins can be classified into amorphous and semi-crystalline resins. Amorphous resins have polymeric chains. Conversely, semi-crystalline resins have a regular molecular arrangement even of chain molecular bonds. Therefore, it is said that amorphous resins can be bonded more easily than semi-crystalline ones. In addition, semi-

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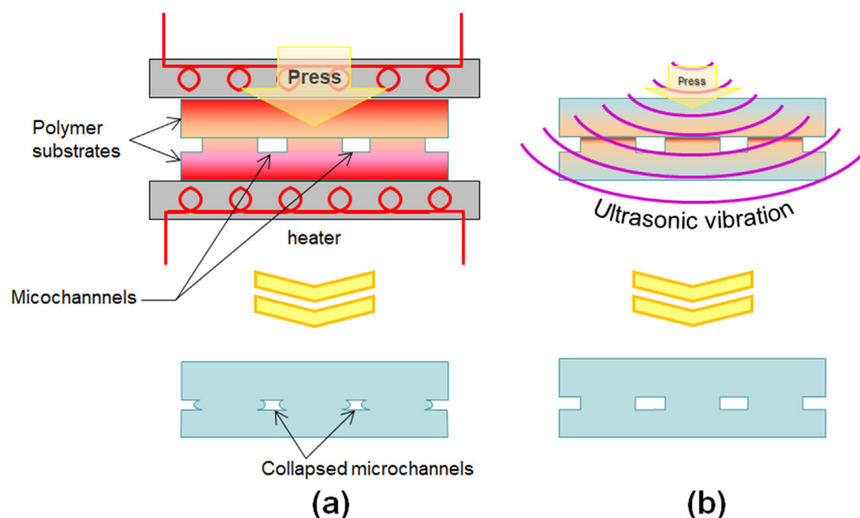

Fig. 1. Thermal deformation caused by (a) thermal bonding and (b) ultrasonic bonding.

crystalline resins bond only with themselves. For example, polyethylene terephthalate (PET), which is widely used industrially, is classified as a semi-crystalline resin, while poly methyl methacrylate (PMMA), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC) are classified as amorphous resins. In fact, heterogeneous bonding between PMMA and ABS/PC has been achieved. Among these polymers, PMMA, which has high transparency, has already been used as a material in microfluidic devices and many other applications [5,6]. However, there are few reports of chips made of PET [7], ABS [8], or PC [9]. PET displays excellent transparency, toughness, and gas barrier properties. Meanwhile, ABS and PC exhibit high impact resistance, and PC can be used in harsh environments like acid and high temperature. Also, because ABS contains butadiene rubber, its characteristics differ greatly from those of PC even in the same amorphous resins. Thus, PET, ABS, and PC are representative thermoplastic materials with different thermal characteristics.

In this paper, we focus on polymer bonding, which is indispensable in polymer chip manufacture. We evaluate polymer bonding by comparing the thermal and ultrasonic bonding behavior of PET, ABS, and PC under the same conditions.

2. Experimental procedure

2.1. Thermophysical properties of PET, ABS, and PC

Among commercially available thermoplastic resins, three types of polymers, PET as a semi-crystalline resin and ABS and PC as amorphous resins, were selected. Planar polymer substrates with dimensions of 50 × 50 × 1 mm were prepared. The PET and PC substrates were transparent in the visible light region, while the ABS one was opaque with low transparency. To determine the heating temperature to use in bonding experiments, the glass transition temperature (T_g) of each polymer substrate was measured by differential scanning calorimetry (DSC) using a DSC-60 Plus calorimeter (Shimadzu, Kyoto, Japan). First, a circular tip with a diameter of 4.8 mm was cut as a sample for DSC measurements from a 1-mm-thick plate fixed on chemical wood by double-sided tape. A cutting operation was performed at 3000 rpm with a 3-mm-side-length square end mill (ZHS-300, Roland DG, Hamamatsu, Japan) using a three-dimensional milling machine (Modela MDX-40A, Roland DG). The tip was placed in an Al crimp pan designed for the DSC-60 Plus, and then pressed and sealed with an Al lid. The results of DSC measurements using α-alumina powder (20 mg) as a reference sample for each polymer are shown in Fig. 2. Regardless of the kind of polymer, the DSC heating rate was set to 10 °C/min. The heating temperature ranges used for PET, ABS, and PC were 50–120, 50–150, and 100–180 °C, respectively. The middle value between the upper temperature (T_{a1}–T_{a3}), which is just before the heat flow curve descends, and the lower temperature (T_{b1}–T_{b3}) was taken as T_g for each polymer. The estimated T_g of PET, ABS, and PC were 77, 112, and 152 °C, respectively. These values and densities calculated from the mass of each DSC test piece measured by a semi-micro analytical balance (GR-202, A&D Company, Tokyo, Japan) are presented in Table 1. In addition, because the surface roughness of bonded substrates greatly affects their bonding strength, the surface roughness of each polymer substrate before bonding was measured using a surface profiler (Surfcorder ET 4000M, Kosaka Laboratory, Tokyo, Japan). These results are also shown in Table 1 together with values of thermal conductivity, specific heat capacity, coefficient of thermal expansion, and emissivity obtained from Refs. [10–13]. This table reveals that there is not much difference between these values for PET, ABS, and PC.

2.2. Instrument setup for thermal and ultrasonic bonding

An ultrasonic nanoimprint system (ASUN0101, Engineering System, Matsumoto, Japan) was used for thermal and ultrasonic bonding experiments. This system contained a lower loading stage fixed on a frame, an upper loading stage that could move vertically driven by two ball screws and a servomotor, a load cell capable of measuring a contact force of up to 500 N applied between the two stages, and a personal computer used to control the functions. Furthermore, as shown in the upper row of Fig. 3, the ultrasonic head mounted on the upper loading stage could be replaced. The operator could choose between a heating head that could be heated up to 250 °C by a ceramic heater combined with a vacuum chuck groove (Fig. 3(a-1)) or an ultrasonic head capable of applying ultrasonic vibration at a frequency of 20 kHz by combination with a controller (Branson 2000bdc/20:3.3, Emerson Electric, St. Louis, Missouri, USA) and Ti ultrasonic horn connected to a piezoelectric element. Two types of ultrasonic horns were used: the first had a vacuum chuck groove on its bottom surface (Fig. 3(a-2)) and the second was a normal horn (Fig. 3(a-3)). The bottom surfaces of both the heating and ultrasonic heads were 50 × 50 mm. The size of the polymer substrate used in bonding experiments was also adjusted to the head size.

Under the lower loading stage, a gimbal mechanism (Toshiba Machine Co., Ltd.) was constructed [14]. In this mechanism, a hemispherical ball fixed under a lower loading stage floats slightly in a bowl fixed to a frame by compressed air supplied from a compressor. This mechanism makes it possible to adjust the slope of the lower loading

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