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The effect of the echo-time of a bipolar pulse waveform on molten metallic droplet formation by squeeze mode piezoelectric inkjet printing

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ABSTRACT

The effect of the echo-time of a bipolar pulse waveform on pressure propagation in a tube is investigated. Micro droplets of molten lead-free solder, Sn–3.0 wt%Ag–0.5 wt%Cu, are ejected at 230 °C using a piezoelectric ink-jet printing process. The numerical model is used to calculate for the detailed information concerning the formation of droplet after the reliability of the numerical model has been verified by finding the simulated modes of droplet formation consistent with the experimental observations. The echo-time of a bipolar waveform plays an important role in determining when the pressure variation induced at the finalrise-time influences the pressure variation induced at the fall-time. A single droplet can be obtained by applying a negative pressure variation to reduce the pressure shock in the negative pressure period which influences the contraction and break-up of the liquid thread in the droplet formation.

1. Introduction

The ink-jet printing process is a non-contact and direct forming technique for micro-pattern fabrication. It is widely used in printing, biochip arraying, and the fabrication of transistors. In electronic packaging industry, lead-free solders have been adopted for the past few decades. By the demand of small scale, many techniques such as evaporation, electroplating and screen printing have been developed. The molten metallic droplet of lead-free solder by ink-jet printing technique has been developed for the reasons of reduction of copious fabrication procedures, time consumption and cost efficiency of traditional processes. In order to obtain a stable droplet formation, parameter adjustment is necessary when operating a piezoelectric device at high temperature. Therefore, an understanding of pressure variations influenced by process conditions is essential for operating ink-jet printing.

Researchers have optimized the t_{dwell} of a single polar waveform shown in Fig. 1(a) by determining periodic variation from droplet velocity, droplet size, or meniscus motion [1–5]. The relations between voltage waveforms and pressure wave propagation have been described using an idealized model. Chen and Basaran [6] and Gan et al. [2] discussed the effects of various waveforms on the morphologies of droplets. Kwon [3] measured the meniscus motion, which corresponds to the wave propagation of pressure. Kwon and Kim [7] also applied a self-sensing technique to measure the pressure in a tube. The pressure variations were explained using Bogy's idealized model and t_{dwell} was optimized. Kim et al. [8] measured the bending deflection of the piezoelectric actuator of a bending mode ink-jet printing using a Laser Doppler Vibrometer (LDV) and input the data into a simulation to optimize the fabrication conditions. Tsai et al. [9] discussed the effect of the transfer rate in the pulse waveform on the droplet formation through a series of experimental tests. Besides experiments made to clarify the effects of process conditions on the droplet formation, simulations were also applied to discuss the ink-jet process. In Wu's research [10], the ejected droplet was simulated to impact on the substrate, and it was found that the interfacial heat transfer coefficient between the droplet and the substrate is proportional to the sum of the potential energy and the kinetic energy. Wu et al. [11] and Chang et al. [12] simulated the droplet formation through providing given pressure curves on the top of the nozzle model.

In this study, the ink-jet process was simulated from the pressure generation to the droplet formation. First of all, the pressure was generated by simulating the actuation of the PZT material. Then, the induced pressure propagated through the tube and led to the pressure variation at the top of the nozzle. With various process conditions, the effect of pressure variations on droplet shapes was then discussed. Most studies discussed t_{dwell} of a single polar waveform; the second part of a bipolar waveform shown in Fig. 1(b) was rarely considered. However, t_{echo} in a bipolar waveform plays a decisive role in determining when the pressure induced at $t_{\text{finalrise}}$ influences the propagating pressure within a tube. It is then desirable to understand what role t_{echo} plays in

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the formation of droplet. Therefore, the aim of the present study is to investigate the effect of t_{echo} of a bipolar pulse waveform on the liquid pressure variation which influences droplet formation by a squeeze mode piezoelectric ink-jet printing using a simulation in Flow-3D, the reliability of which was verified by finding the simulated modes of droplet formation consistent with the experimental observations.

2. Numerical model

2.1. Description of the physical phenomena

Consider a fluid in a tube squeezed by a moving object in the radial direction, as shown in Fig. 2. In this study, a commercial print-head manufactured by MicroFab was used to produce droplets experimentally. Based on the cross-section of the real print-head, the model of the piezoelectric material was designed as a moving object with about half of the tube length and located close to the nozzle in the numerical model, as shown in Fig. 2. The moving object was considered as a moving wall simulating the expansion and contraction of the piezoelectric material. The pressures generated by the moving object propagated toward both ends of the tube, namely the reservoir end and the nozzle end. For the end connected with the reservoir, a boundary condition of specific pressure was set, which was used to simulate the back pressure in practice. The other end was connected with the nozzle, which was constructed with an orifice of a diameter of 50 μm allowing the liquid to be pushed outward. A finite-difference method was used and an axisymmetric and cylindrical coordinate system was built.

2.2. Governing equation

A commercially available computational fluid dynamics package, Flow-3D, was applied in this study. The behavior of the fluid flow was governed by the continuity equation, the momentum equation, and the equation for fluid fraction [10]. The fluid was taken to be a Newtonian fluid, and the Navier–Stokes equation was used as the equation of motion for the fluid velocity components [13]. In this study, the gravity was neglected due to its small influence compared to that of the fluid inertia given by the actuation of the piezoelectric device according to Chen's statement [6]. Free surfaces were tracked by using the volume-of-fluid method (VOF) [11,12]. The fluid configurations were defined in terms of a volume of fluid fraction, F, which tracked the location of the fluid. The fluid existed where $F = 1$, and did not exist where $F = 0$. When the function F was between 0 and 1, the cell contained both fluid and a void, and an interface existed in this surface cell. In order to apply the free-surface conditions, an approximate normal in a surface cell was identified first in accordance with the direction from the closest and empty neighboring cell [14]. Following this, a cell column containing three cells that were associated with the surface cell in the normal direction and its four principal neighbors, which located perpendicular to the surface normal, had their fluid fraction values summed up in the direction of the normal. This gave a discrete representation of the surface heights in five columns surrounding the surface cell. The heights containing the surface cells gave the location of the surface, and these can then be used to compute slopes and curvatures at the surface. The surface tension forces at the surface cell can be replaced by equivalent surface tension pressures in all three coordinate directions. By assigning the proper gas pressure plus the equivalent surface tension pressure, velocity components outside the surface can be determined to satisfy a zero shear-stress condition at the surface.

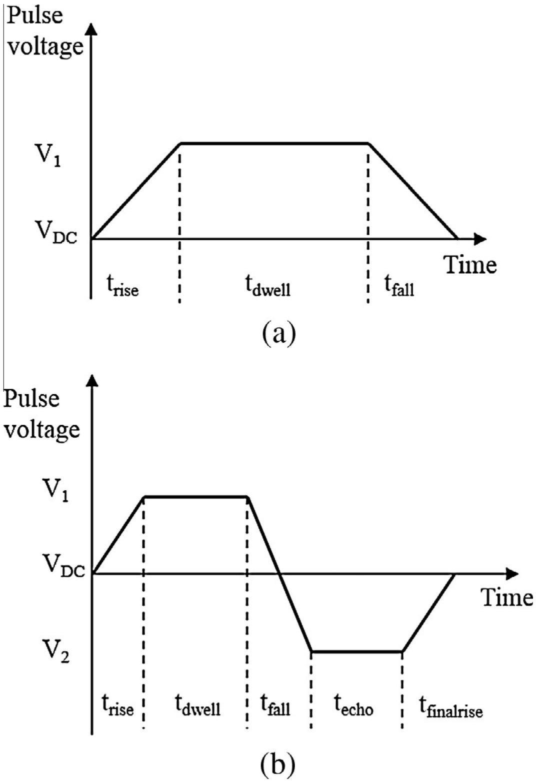

Fig. 1. Schematic diagrams of (a) a single polar pulse waveform and (b) a bipolar pulse waveform.

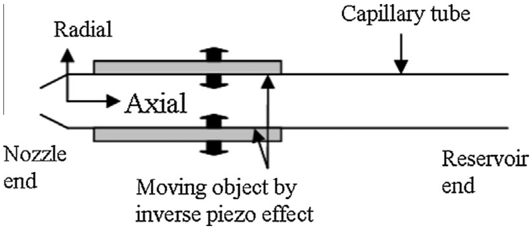

Fig. 2. A schematic illustration of a piezoelectric capillary tube model represented by a moving object around the capillary tube.

3. Experimental method

3.1. Apparatus

The experiment equipment comprised four interlocking functional blocks, namely pneumatic, heating, printing, and monitoring blocks [9]. The pneumatic control block used nitrogen gas as a back pressure in a molten solder reservoir to maintain a certain pressure in the chamber. It also provided a protective ambience near the nozzle of the piezoelectric print-head. The heating block was used to heat the chamber of the molten solder and piezoelectric print-head to the desired temperature. The printing block comprised a piezoelectric print-head and a pulse supply, which provided a pulse waveform of varying pulse time and voltage. The diameter of the print-head orifice is 50 μm. The piezoelectric print-head is suitable for fluid viscosities in the range of 1–100 mPa s and surface tensions in the range of 20–500 mN m^{-1}. It is capable of operating at a maximum temperature of 320 °C. The monitoring block which included a charge-coupled-device (CCD) camera and an LED flash that was triggered after a set time delayed after the voltage pulse was applied in each period. A jet device (MJ-SF-04-50) manufactured by MicroFab Technologies was used in this study.