CONF-9610172-- 1

SAN096-1590C

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Computational Modeling of On-Demand Solder Delivery for Fluxless MCM Packaging Applications

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JUL 02 1996
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Abstract

The development of smaller circuit volumes in microelectronic applications, particularly Multichip Module (MCM) technology, entails deposition of minute quantities of solder, with volumes on the order of nanoliters. We propose a system for fluxless solder deposition which uses on-demand solder jetting for deposition of 200 μm diameter solder droplets onto aluminum pads. This work details the computational modeling performed to provide design parameters for a magneto-hydrodynamic solder jetter (MHD). A dimensionless analysis was used to relate the fluid properties, the orifice length and width, and the droplet size to the amplitude and duration of the pressure pulse. These results were used as the initial inputs for the fluid dynamics model, and subsequent iterations were performed to determine the operational parameters that lead to the formation of stable, single droplets. Results show that a maximum pulse amplitude on the order of 0.5 Mdynes/cm^2 is necessary to dispense molten solder from a 200 μm diameter orifice. The size of the droplet was found to vary linearly with the applied pressure pulse. The duration of the pulse ranged from ~ 0.6 to 0.9 milliseconds. A theoretical description of the relationship between the orifice diameter, surface tension, and "pinch-off" time is given, and is in agreement with the results of the computational model.

Introduction

In the interest of developing a method of performing fluxless soldering for microelectronic applications, we proposed a system which uses laser ablative cleaning to remove the oxide layer from the surface of metallization pads, along with an apparatus which deposits molten solder droplets onto the pads. Droplet deposition takes place in less than one second after the pad is ablated. The system consists of a pulsed Nd:YAG laser and an on-demand magnetohydrodynamic (MHD) solder jetter. The MHD jetter was first reported by Smith.[1] A schematic of the laser ablative fluxless soldering apparatus is shown in Figure 1. A schematic representation of the MHD jetter is shown in Figure 2. The jetter principally consists of a solder reservoir (not shown), a drive chamber, and a permanent magnet. The drive chamber is positioned between the poles of the magnet, and a current is sent through the solder in the drive chamber, in a direction perpendicular to the pole faces of the magnet. This produces a force on the molten solder which can be used to displace the fluid from an orifice located at the end of the jetter. Determination of the operational parameters of the MHD solder jetter is crucial to the design of the apparatus.

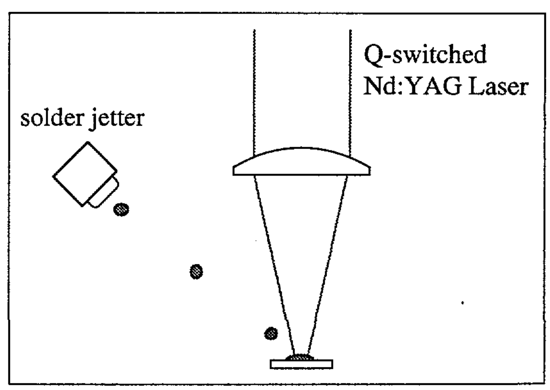


Figure 1: Laser ablative fluxless soldering.

Therefore computational simulations were used to determine the optimum shape, amplitude, and duration of the pressure pulse applied to the inlet of the orifice. The code used in this work was a commercially available fluid dynamics code, Flow

3D®, developed by Flow Sciences Inc., Los Alamos, New Mexico.

Theory

Simulation of the jetting of molten solder using magnetohydrodynamics was performed by applying a uniform pressure pulse across the inlet of a computer-generated cylindrical cavity filled with an incompressible fluid. The fluid modeled is the 60/40 tin/lead eutectic. The basic problem solving approach is:

(i) the fluid region is subdivided into a grid of rectangular cells.
(ii) flow quantities (velocity, pressure, density) are determined for the initial fluid configuration.
(iii) a finite difference approximation to the equations of motion and mass continuity is used to compute spatial and temporal evolution of flow quantities.
(iv) the free surface of the fluid is tracked using the volume of fluid method.

Hirt has given a detailed description of the mathematical methods and computational techniques used by Flow 3D®.[2-4] A typical pressure pulse is shown in Figure 3. A negative pulse is first applied to the fluid. This pulse lasts about 10 - 15 % of the total pulse duration and is used to force pinch-off above the orifice. The positive pressure forces the fluid out of the nozzle. After some volume of fluid V_0 has been ejected, the pulse reverses direction. This overall pulse shape can be used to control the volume and speed of the ejected droplets. An initial shape and duration of the pressure pulse was determined using a dimensionless analysis developed by Fromm [5]. This analysis gives the magnitude and duration of the pulses needed to form droplets, in terms of the fluid properties (i.e., density, surface tension, and viscosity) and the size of the orifice. The amplitude of the pressure pulse is directly proportional to the applied current, so that operating parameters may be determined using the computer simulations.

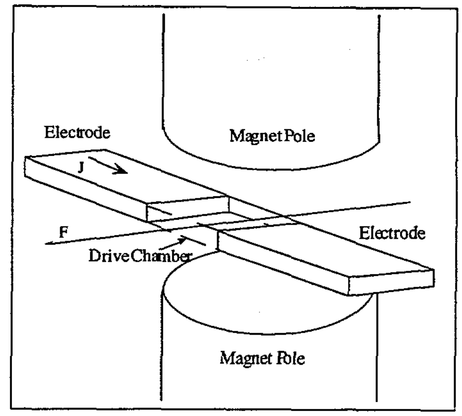


Figure 2. The magnetohydrodynamic solder jetter.

Approach

Flow 3D® was first used to determine an approximate pressure pulse amplitude sufficient to jet molten solder from an orifice with a diameter of 200 µm and length of 500 µm.

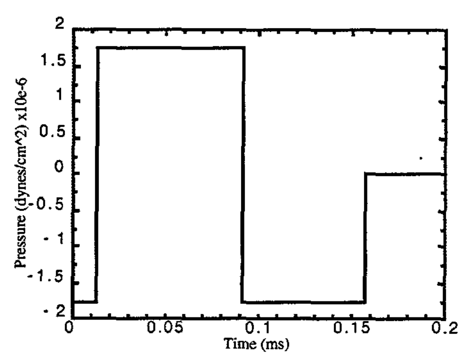


Figure 3. Typical pressure pulse use for solder jetting simulation.

It was found that the amplitude of the positive pulse is linearly related to the length of the orifice. Following the notation of Fromm, the dimensionless pressure, $\hat{P}$, is given by

$$\hat{P} = \frac{r}{\sigma} P \qquad (1)$$

where r is the orifice radius, σ is the droplet surface tension and P is the applied pressure. The dimensionless time is given by

$$\hat{t} = t\left(\frac{\sigma}{\rho r^3}\right)^{\frac{1}{2}} \qquad (2)$$

$$\tau = \sqrt{\frac{\rho r^3}{\sigma}}$$

where t is the absolute time and ρ is the fluid density. The dimensionless time is scaled using τ, the characteristic time for the growth of capillary waves on an inviscid liquid jet. [6] Table 1 gives the pulse amplitude and duration for the case of the 60Sn 40Pb near eutectic alloy jetted from a 200 μm diameter orifice. For 60Sn 40Pb solder, ρ=8.0 g/cm^3 and σ=440 dyne/cm. The results obtained from the pressure history of Table 1 is shown in Figure 4. Necking of the fluid has begun by 0.2 milliseconds and continues until pinch-off occurs at about 0.3 milliseconds. At 0.349 ms a free droplet has been formed with a trailing fluid region (tail) which is subsequently drawn into the body of the droplet by surface tension.

Table 1. Non-optimized pressure history for the 60Sn 40Pb eutectic solder jetted from a 200 μm diameter orifice.

$\hat{t}$	$\hat{P}$	t (ms)	P (MDynes/cm^2)
0.00-0.10	-40	0.00-0.013	-1.76
0.10-0.71	+40	0.013-0.092	1.76
0.71-1.21	-40	0.092-0.157	-1.76

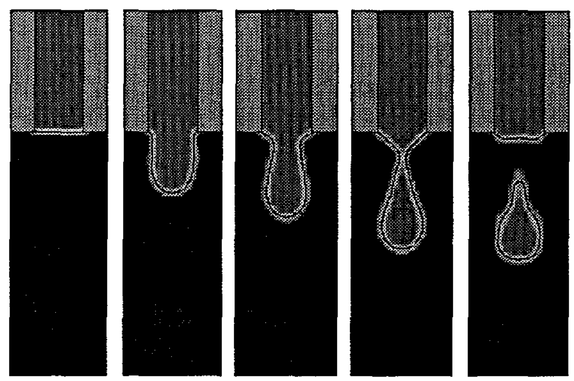
Results

To test the feasibility of using lower electrical currents for the MHD drive chamber, a simulation was performed for a pressure pulse with a decreased amplitude and increased duration. The area under the pressure curve (amplitude x time) was also altered to cause pinch off at a point closer to the orifice than in the case of Figure 4. A typical revised pressure history is given in Table 2.

Table 2. Revised pressure history. Dimensionless parameters are listed parenthetically.

t (milliseconds)	P (Mdynes/cm^2)
0.00-0.10 (0-0.77)	-0.20 (4.54)
0.10-0.30 (0.77-2.31)	0.54 (12.26)
0.30-0.65 (2.31-5.00)	-0.35 (7.94)

Figure 5 shows the results obtained with the pressure history of Table 2. Necking begins at about 0.4 milliseconds and continues until pinch-off occurs, well above the mouth of the orifice, at approximately 0.64 milliseconds. After pinch-off occurs, the droplet is formed with an elongated trailing fluid region (tail). The duration of the negative trailing pulse determines the length and speed of the tail region.



t=0.0 t=0.149 t=0.200 t=0.300 t=0.349

Figure 4. Solder jetting simulation obtained with the pressure pulse of Table 1. All times in milliseconds.

If the tail region of the droplet is too long, breakup may occur, leading to the formation of undesirable satellite droplets. A simulation was run to investigate the effect of the trailing negative pulse on the formation of satellites. The pressure pulse for this simulation is given in Table 3. The results are shown in Figure 6. By 0.79 ms, a droplet has been formed with an elongated tail. Surface tension then begins to constrict the region of the tail nearest the droplet, and a second pinch-off occurs just after 0.83 ms. By 0.88 ms a separate satellite droplet has been formed. Computational studies were also performed to determine the relationship between the amplitude of the positive pressure pulse and the size of the droplet. In each simulation the positive pressure pulse amplitude was varied, and a measurement of the droplet volume was performed. The results are plotted in Figure 7. This study shows that in the range of positive pulse pressures ranging from 0.48 to 0.60 Mdynes/cm^2, the droplet diameter increases linearly with pulse amplitude.

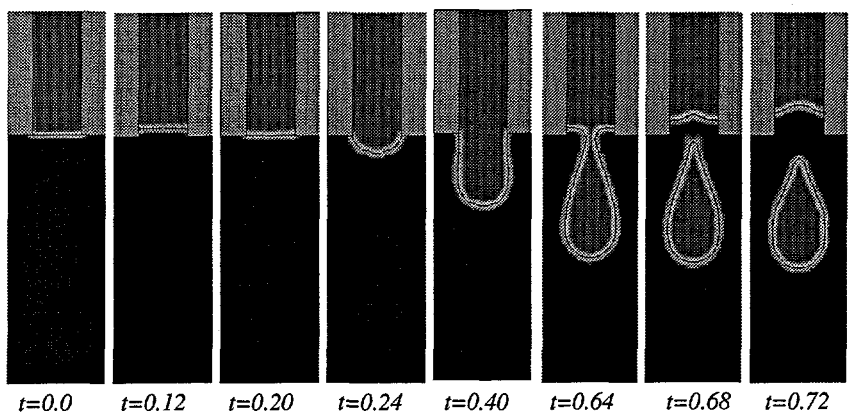


Figure 5. Solder jetting simulation obtained with the pressure pulse of Table 2. All times in milliseconds.

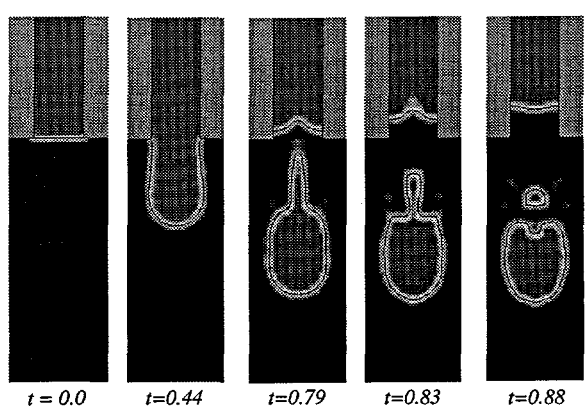


Figure 6. Solder jetting simulation showing the effects of an elongated trailing pulse. All times in milliseconds.

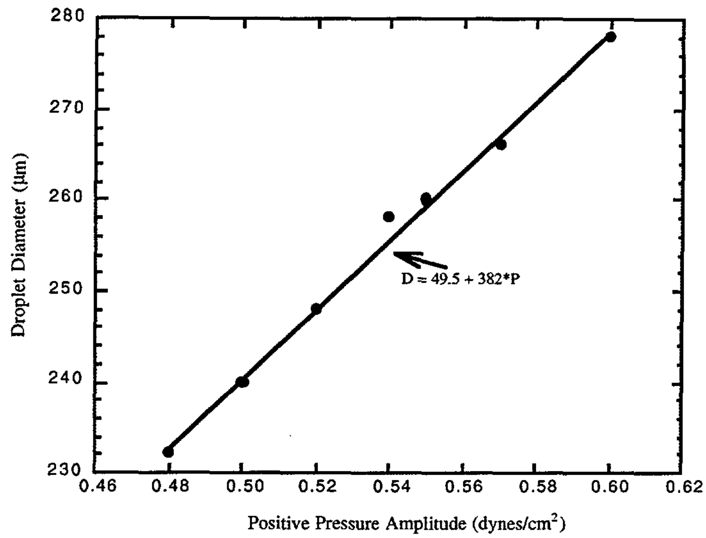


Figure 7. Droplet diameter vs. applied pressure for a 200 µm diameter orifice

Discussion

The characteristic time τ is important in on-demand jetting. Measured with respect to the time at which fluid first begins to leave the orifice, it gives the approximate time for the onset of necking. Necking may be defined as an inward constriction of the fluid column due to surface tension minimization of the free surface energy. For ideal droplet formation, the desired volume of fluid should be displaced from the orifice in a time $t \sim \tau$. The optimum pressure pulse is that in which the displaced volume has a spherical diameter which is ~1.0-1.5 times the diameter of the orifice. An example of this case may be seen in Figure 5, where a well-formed 260 µm diameter droplet is formed from a 200 µm diameter orifice. No satellites droplets are produced in this case. For the case of 60Sn 40Pb solder and an orifice diameter of 200 µm, τ =0.13 ms. At t_1=0.12 ms, the initial negative pulse has pulled the fluid the greatest distance into the nozzle. The fluid begins to leave the orifice at approximately t_2=0.22 ms, and necking begins to occur 0.18 ms later, at t_3 = 0.40 ms. Therefore $t_3 - t_2 = 1.38\tau$, so the simulation predicts necking after 1.38 characteristic time units. After necking has begun, the pressure applied at the nozzle inlet becomes negative, increasing the constriction of the fluid at the orifice until pinch-off is completed.

Conclusions

The conclusions drawn from this work are as follows:

(1) Computational studies of droplet formation have proven to be a valuable means of determining optimal pressure pulses for on-demand jetting.
(2) Stable droplet formation is produced for droplets with diameters that are 1.0-1.5 times the diameter of the orifice.
(3) Necking occurs at approximately 1.38 characteristic time units after solder begins to emerge from the orifice.
(4) Over the range of positive pulse amplitudes ranging from 0.48 to 0.60 Mdynes/cm^2, the droplet diameter increases linearly with pulse amplitude.

Acknowledgment

This work was performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract number DE-AC04-94AL85000.

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