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FLUID DYNAMICS AND SOLIDIFICATION OF MOLTEN SOLDER DROPLETS IMPACTING ON A SUBSTRATE IN MICROGRAVITY

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ABSTRACT

This program will investigate the fluid dynamics and simultaneous solidification of molten solder droplets impacting on a flat substrate. The problem of interest is directly relevant to the printing of microscopic solder droplets in surface mounting of microelectronic devices. The study consists of a theoretical and an experimental component. The theoretical work uses axisymmetric Navier-Stokes models based on finite element techniques. The experimental work is performed in microgravity in order to allow for the use of larger solder droplets that make feasible the performance of accurate measurements while maintaining similitude of the relevant fluid dynamics groups (Re, We) and keeping the effect of gravity negligible.

INTRODUCTION

A schematic of the two distinct stages (flight and impact) of the problem examined is shown in Fig. 1. The primary application of interest (solder microdroplet dispensing) employs solder droplets approximately 50 to $100\mu m$ in diameter, which collide, spread, recoil and eventually solidify on the substrate. Due to the small size of the droplets and the relatively high surface tension coefficient of solder, gravity effects are negligible. This solder application technology has shown great promise in microelectronic packaging and assembly, therefore, the development of a good understanding of the pertinent fluid dynamics and solidification phenomena is essential for its successful commercial implementation. However, progress in this area has been hindered by the small length scales of the problem (50 to $100\mu m$), which have made experimental measurements of the relevant transport phenomena difficult. Alternative approaches, which employed much larger (mm-size) droplets, yielded results that were affected by the masking effects of gravity. Hence, even though mm-size droplets yield significantly improved resolution, the applicability of the obtained results for much smaller droplets remains suspect. Conducting experiments in a microgravity environment eliminates the unwanted influence of gravity and makes the experimental investigation of large droplet dispension directly relevant.

The Reynolds, Weber and Froude numbers characteristic of the process shown in Fig. 1 are defined by

$$Re = V_0 r_0/\nu, We = \rho V_0^2 r_0/\gamma, Fr = V_0^2/r_0 g \tag{1}$$

where V_0, r_0 denote droplet impact velocity and radius, while ρ, ν, γ correspond to the density, kinematic viscosity and surface tension coefficient of the liquid. To exemplify the disparity in the importance of gravity in the dispension of large and small droplets, the values of Re, We and Fr were calculated for a set of parameters corresponding to the real dispension process in normal gravity (50 micron diameter solder droplet impacting on a flat surface with a velocity 1m/s). These values were Re=78.5, We=0.6, Fr=4077, and illustrate the importance of inertia and surface tension, as well as the insignificance of gravity effects. If a larger (1mm) drop is used in normal gravity experiments, a slower impact velocity V_0 is required for similitude based on Re. In turn, similitude in terms of the Weber number requires a smaller surface tension coefficient. To maintain similitude in this specific example, the surface tension coefficient as well as the impact velocity of the larger droplets need be reduced by twenty-fold. The resulting values of the above dimensionless groups are then Re=78.5, We=0.6, Fr=0.5. Clearly, the drastic decrease in the value of the Froude number proves that gravity effects become significant for mm-size droplets, and that the presence of a microgravity environment is necessary in large solder-droplet impact experiments.

OBJECTIVE

The study will be aimed at identifying the degree of influence of the dominant process parameters on specific aspects of solder droplet dispensing. These parameters are: droplet size and velocity; droplet, substrate and ambient gas temperatures; and contact angle between the solder and substrate before and after solidification. The sensitivity of the final bump shape and size to variations in the above parameters is critical because solder bump volume, position, and height variation are key metrics for solder jet technology. The data produced in this program will be analyzed to define the domains of solder microdroplet dispensing operational parameters that result in optimal and consistent production of solder bumps as needed for specific industrial applications. At the same time, through a series of numerical simulations, the effect of the dimensionless groups defined in Eq. (1) (and the physics they represent) will be thoroughly documented.

METHODOLOGY

The research consists of both a theoretical and an experimental component. The theoretical component investigates the fluid dynamics and solidification of a molten solder droplet during its impact on the substrate, in order to attain an understanding of the miniature solder deposition process. The experimental component tests the numerical predictions and provides necessary input data (such as wetting angles) for the theoretical model. Details of both components are given below.

Theoretical

A schematic description of the impacting droplet problem was presented earlier in Fig. 1. In this figure, a microscopic liquid-metal droplet is shown after impact, while it spreads on the substrate. Cooling of the liquid metal takes place almost entirely by conduction through the substrate, and solidification ensues some time during this process. The theoretical model for the fluid dynamics, which uses a Lagrangian formulation to solve the axisymmetric Navier-Stokes equations accounting for surface tension effects, has been outlined and tested in [1, 2]. The model takes into account the important effect of wetting in the advancement of the contact line, if the dynamic contact angle is known from experiments.

Wetting: In order to model the wetting phenomenon, knowledge of the contact angle ψ_C is necessary. A number of issues relevant to static and dynamic contact lines on solid surfaces have been reviewed by Dussan [3] and de Gennes [4] who showed that a clear distinction exists between the static and the dynamic values of contact angle. The value of the contact angle in this work will be measured experimentally. With the contact angle known, the following boundary condition is satisfied at the contact line

$$\tilde{\sigma} \cdot \vec{n} = -(2\gamma H_C + p_0)\vec{n} \tag{2}$$

where $\tilde{\sigma}$ is the stress tensor, γ the surface tension coefficient, p_0 a reference pressure, H_C the mean surface curvature, and $\vec{n}$ the normal vector (Fig. 2). The mean curvature of the free surface is defined by

$$H = \frac{r^2(r'z'' - z'r'') + [(r')^2 + (z')^2]rz'}{2r^2[(r')^2 + (z')^2]^{3/2}} \tag{3}$$

All symbols in Eq. (3) are defined in Fig. 2 with the primes denoting differentiation with respect to the free surface coordinate, s. At the contact line $r' = -cos\psi_C, z' = sin\psi_C$, thus the mean curvature expression becomes

$$H_C = \frac{1}{2}(-z''cos\psi_C - r''sin\psi_C + \frac{sin\psi_C}{r}) \tag{4}$$

Solidification: With the velocity field provided by the fluid dynamics simulation, the axisymmetric energy equation will be solved both in the liquid metal droplet and the substrate, in order to attain the temperature field. Convection will be taken into account in the energy equation for the liquid solder and conduction in the substrate. Typically, the substrate consists of a number of layers each of different material, parallel to the exposed surface (Fig. 1), a fact that will also be taken into account in the substrate conduction model. Continuity of temperature and heat flux will be imposed at the substrate/droplet interface. After the initiation of solidification, the contact resistance at this interface will be taken into account to the extent allowed by the currently existing limited data for relevant contact resistance values [5].

The solidification modeling will focus on eutectic solders (for example Sn63/Pb37 which is commonly used by manufacturers of microelectronic components) to circumvent additional complexities associated with the possible presence of a mushy zone in non-eutectic solders. When solidification is initiated during the impact process, it does so in the presence of undercooling and recalescence. Several issues regarding the modeling of solidification with undercooling and recalescence are discussed in [6]–[9]. Given the parametric domain of the solder dispension process (low to moderate impact velocities and temperature differences), it is speculated that the effect of undercooling will not be significant. In the absence of undercooling, the freezing front velocity will be determined from an energy balance at the interface, with the interface temperature being the freezing temperature of the eutectic solder.

For the finite element implementation of the solidification process the exact specific heat method proposed by Bushko [10] will be adopted. This method demonstrated superior accuracy over the enhanced specific heat method in energy conservation tests. It is especially suited for materials with specific heat functions that can be represented by Dirac delta functions in the neighborhood of phase transition

$$C(T) = [C_s(T), C_l(T)] + L\delta(T - T_m) \tag{5}$$

where C is the specific heat, L the latent heat of fusion, T the temperature, the subscripts s, l, and m denote the solid phase, liquid phase and melting point, respectively, and δ is the Dirac delta function [10]. Many metals and alloys, including solders, exhibit this characteristic which makes this method attractive for the planned research. Figure 3 shows a bump shape as obtained during experiments in 1-g utilizing an initially $50\mu m$-diameter Sn63/Pb37 solder droplet. This picture depicts the final state of a single droplet after complete solidification. The ripples on the surface of both solidified bumps may be explained as follows: After impact the droplet spreads and recoils (oscillates) several times prior to achieving its sessile state. As the droplet oscillates, solidification initiates at the bottom of the splat and advances upward. The dynamic interaction between the flow oscillations and the advancement of the solidification front yields the ripples on the surface of the solder bump shown in Fig. 3.

Experimental

Since this is a new program, the experiments have not commenced yet. Molten-metal single droplet impaction tests will be conducted in a low-gravity environment. The 2.2 second drop tower at the NASA

Lewis Research Center will be used to conduct these studies. Our estimates of the characteristic times for the various stages involved (droplet deployment, oscillations decay, impaction and solidification) have shown that 2.2 seconds of microgravity are sufficient for the single droplet experiments. In addition to the direct information obtained from the experimental results, this component of the study will serve to generate wetting-angle information, necessary to the theoretical work, and will provide specific criteria to validate the model predictions.

Measurements of the wetting angles and the splat dimensions will be made from high-speed films. The films will be used also to calculate the droplet preimpact velocity required for the simulations. A photoelectric method (Fig. 4) will be used as a means of providing data on the transient behavior of splat radius and spreading velocity for comparisons with theoretical predictions. This technique has been proven feasible in 1-g laboratory environments and does not involve recording of the droplet image; yet it is accurate, despite the short time scales of the experiment.

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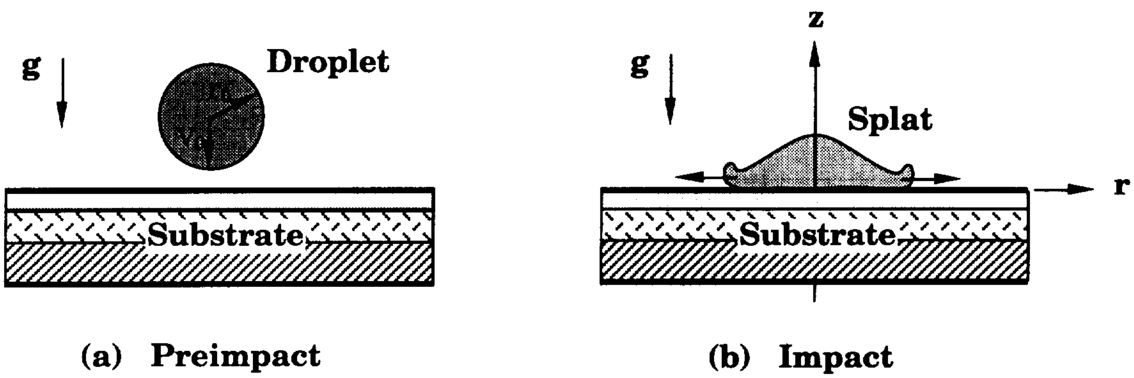

Figure 1: Schematic of the problem of interest. a) Flight stage, b) Impact stage. The multiple layers of the substrate represent practical situations of interest.

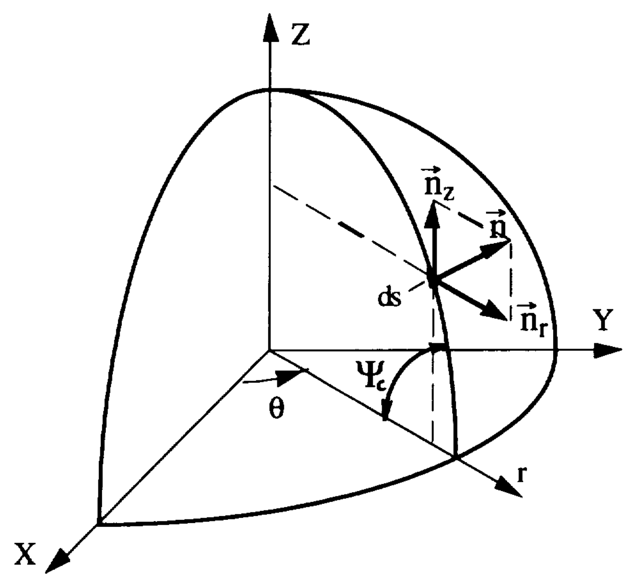

Figure 2: Schematic defining various symbols in the mathematical formulation of a droplet impacting on the X-Y plane in a direction parallel to the Z axis.

Figure 3: Solder microbump obtained experimentally in normal gravity. The solidified bump was produced by the deposition of a single 50 μm-diameter droplet.

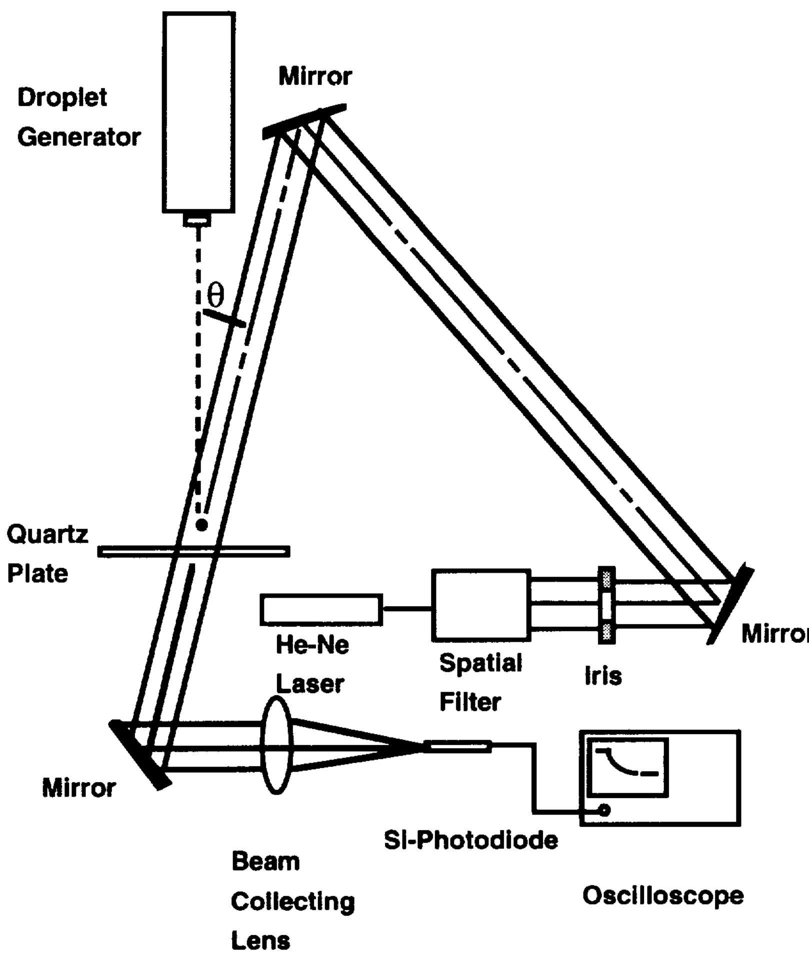

Figure 4: Photoelectric droplet spreading measurement system.