Ultrasonic-Driven Spreading of Liquid Solder on Nonwetting Substrates

Solder droplet was able to spread rapidly on a nonwetting substrate under ultrasonication, and the spreading dynamics were studied with high-speed photography

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ABSTRACT

In this work, the spreading of a solder droplet on a substrate agitated by ultrasonic vibration was recorded by a high-speed camera. The dynamics and physical processes of the spreading, such as corrugate formation and atomization, were investigated. Results showed the solder droplet was able to spread on a nonwetting substrate, and it presented periodic expanding-shrinking spreading characteristics with a periodicity of dozens of acoustic periods. Corrugates formed as a result of the capillary wave propagation on the droplet, and the formation became intensive on a violently vibrating surface. Atomization preferentially occurred at the spreading front during solder expansion, where the liquid solder appeared as a film and burst on the whole droplet with strong vibration. High ultrasonic power resulted in fast spreading and a large spreading diameter. In particular, the solder droplet exhibited fast spreading and a large spreading diameter on the TC4 alloy with high characteristic impedance. The Sn-4Cu solder with large viscosity spread slowly and exhibited a small spreading diameter.

KEYWORDS

- Spreading • Ultrasonic • Oxide Layer • Viscosity
- Atomization

Introduction

Power ultrasonication facilitates the bonding of a liquid solder to substrates with low surface energy because the cavitation inside the liquid solder caused by ultrasonication can remove the oxide layer on the substrate surface and activate the cleaned substrate surface (Ref. 1). Ultrasonic soldering is invented to join easy-to-oxidize alloys (i.e., aluminum and magnesium alloys) and hard-to-wet materials

(i.e., ceramics and sapphire) (Refs. 2–4). This joining does not require any flux, can avoid harmful gases when heating fluxes, and omit the subsequent flux cleaning (Refs. 5, 6). Since its invention in the 1950s, ultrasonic soldering has been widely explored as an option for joining advanced and dissimilar materials.

One of the most fundamental issues of soldering/brazing is the spreading and wetting of filler droplets on a substrate, in which both processes can help directly determine the productivity and quality of the soldering/brazing. Numerous studies have been carried out on this issue of static soldering/brazing systems (Ref. 7). By contrast, the literature on the ultrasonic spreading or wetting of liquid fillers on substrates remain inadequate (Refs. 8–12). Yu et al. (Ref. 9) studied the spreading of Sn-based solders on a porous graphite under ultrasonication and reported prolonged ultrasonication time decreases the contact angle of the Sn5Ag8Ti solder to the porous graphite from 14.5 to 40.5 deg. Soltani-Kordshuli et al. (Ref. 10) found the contact angle of a polymeric droplet to a glass substantially decreases under vertical ultrasonic vibration because of the increase in surface energy. Yang et al. (Ref. 11) studied the wetting of Sn-37Pb on a Cu substrate under an ultrasonic field and reported ultrasonication enhances the wettability of Sn-37Pb/Cu by promoting interfacial reaction. Lin et al. (Ref. 12) reported significantly improved wettability under ultrasonic vibration. The momentum transfer at the liquid/solid interface is a driving force of spreading, but this scenario is invalid for nonwetting systems with contact angles in the range near 90 deg.

In the above studies, the prevailing theory on ultrasonic-improved spreading is that ultrasonication can reduce the contact angle of the solder to the substrate. Our previous study focused on the wetting behavior of Sn-9Zn solder on a vibrating 2024 aluminum surface, and we found the solder droplet can spread readily on the substrate when the contact angle is greater than 90 deg (Ref. 8). We also examined the ultrasonic-

Fig. 1 — Schematic of ultrasonic-driven solder spreading.

induced filling of a liquid solder in its vertical and horizontal joints and found that solder filling can be completed even when the solder does not wet the substrates (Refs. 13–15).
The effect of ultrasonication on the spreading and wetting of liquid fillers on substrates continues to be a debatable topic. The underlying mechanisms of the spreading of ultrasonic-driven solders remain unclear. In this work, we studied the spreading behavior of a liquid solder on Al substrates by using high-speed photography. The physical processes of the spreading were recorded in situ, and the influencing factors of the spreading were analyzed. This work can serve as a reference about the attempt to observe solder spreading under ultrasonication.

Experimental

Substrates and Solders

The substrates used in this work were pure Al, 5056 Al

alloy, and a titanium alloy (TC4), which were provided by Northeast Light Alloy Co. Ltd. The physical properties and chemical compositions of the substrates are listed in Tables 1 and 2, respectively. The meaning and calculation of the characteristic impedance of the solid materials were introduced in our previous work (Ref. 15). The substrates were cut into the dimensions of 50 × 30 × 3 mm. They were then polished using 500# emery papers and ultrasonically cleaned with acetone for 10 min before the experiment. Three different solders, namely, pure Sn, Sn-9Zn, and Sn-4Cu, were used. The diameters of the solders were approximately 6 mm.

Ultrasonic-Assisted Soldering Experiment

A self-designed ultrasonic vibration system named UPM-U-P1010A01 was used. The sonotrode with a diameter of 20 mm was operated in the frequency of 20 kHz. The ultrasonic vibration system had a maximum rated power (P_m) of 1000 W, and three modes of power output were used: 1/3 P_m (Mode I), 2/3 P_m (Mode II), and P_m (Mode III). Ultrasonic vibration was transmitted from the sonotrode to the substrate at 0.2 MPa. A schematic of the ultrasonic-induced spreading experiment is presented in Fig. 1. Ultrasonication vibration time was within the range of 1–5 s. Temperatures were set to 250°, 220°, and 300°C for Sn, Sn-9Zn (wt-%), and Sn-4Cu (wt-%), respectively. At least three samples were tested for each experimental condition. The viscosities of the Sn (250°C), Sn-9Zn (220°C), and Sn-4Cu (300°C) were approximately 1.8, 2.0, and 2.2 mPa·s, respectively (Refs. 16–18).
A high-speed camera (Phantom V12.1), equipped with a macro lens (Tokina 100 mm F2.8MACRO), was used to record the spreading. The images were obtained at the acquisition rate of 5000–10,000 frames/s and resolution of 256 × 256 dots per in. The microstructure of the wetting interface was observed with a scanning electron microscope (SEM, FEI-Quanta 200).

Table 1 — Physical Properties of the Substrates				
Substrate	Characteristic Impedance ($10^2\text{g/cm}^2 \cdot \text{s}$)		Density (kg/m^3)	Poisson's ratio
Pure Al	13.64×10^3		2700	0.31
5056 Al	13.76×10^3		2640	0.31
TC4	22.37×10^3		4440	0.31

Table 2 — Chemical Compositions of the Substrates									
Substrate	Element	Fe	Mn	Mg	Si	Zn	Ti	Cu	Al
	wt-%	0.35	0.03	0.03	0.25	0.05	0.03	0.05	Bal.
5056 Al	Element	Fe	Mn	Mg	Si	Zn	Cu	Cr	Al
	wt-%	0.4	0.05–0.2	4.5–5.6	0.3	0.1	0.1	0.05–0.2	Bal.
TC4	Element	Fe	C	N	H	O	Al	V	Ti
	wt-%	≤0.3	≤0.1	≤0.05	≤0.015	≤0.2	5.5–6.8	3.5–4.5	Bal.

Fig. 2 — Spreading of Sn droplet on 5056 Al at the ultrasonic power of: A — Mode I; B — Mode II; C — Mode III.

Simulation of the Vibration on Substrate Surfaces

ANSYS 15.0 software was used to analyze the vibration conditions on the substrate surfaces. During simulation, a model with the same dimensions as the substrate during spreading was used. The model was built using the element type of Brick 20 node 186 and then meshed using the element edge length of 1 mm. The physical parameters used to define a substrate were characteristic impedance, density, and Poisson's ratio (Table 1). The ultrasonic was applied on the upper surface of the substrates. Three power modes (Modes I, II, and III) and one fixed frequency of 20 kHz were used. After a series of calculations, the vibration status on the substrates were extracted and displayed as amplitudes.

Results

Spreading Under Different Ultrasonic Power Levels

Figure 2 shows the spreading of the pure Sn solder on the 5056 Al substrate. The images were acquired at the acquisition rate of 10,000 frames/s. The pure Sn solder was melted on the substrate by heating at 250°C. The solder droplet was maintained without ultrasonication, and its rounded morphology was retained because of the formation of an oxide layer on the surface. The contact angle between the liquid Sn and Al was higher than 90 deg (Ref. 8), indicating a spontaneous spreading of Sn on Al will be unlikely to occur.

Figure 2A depicts the spreading of the pure Sn droplet at the ultrasonic power of Mode I (Movie I). Small-amplitude capillary waves corrugated the droplet surface when ultrasonication was applied. However, the droplet did not spread

immediately. The liquid solder breached the oxide film at the solder/substrate interface at 0.01 s and started to spread outward on the Al substrate. The spreading did not occur continuously though. The solder droplet expanded for a certain period and then shrank in the same period; that is, the expansion and shrinkage of the solder droplet occurred periodically and alternately. During the expansion, the spreading front moved forward. The solder at the spreading front retracted during the shrinking, but the triple line remained somewhat pinned. This phenomenon was mainly due to the cohesion and friction between the solder and the substrate. The triple line appeared to be in an alternating moving-stopping state (to be discussed in detail later). Thus, the spreading of the solder droplet on the substrate was in a stepwise mode. Capillary waves consistently formed on the solder with continued spreading. The droplet evidently collapsed at 0.03 s, and complete spreading was observed at 1.6 s. After which, the solder droplet did not spread further. The corrugate of the solder droplet did not disappear until the ultrasonic power was switched off.

Figure 2B illustrates the spreading of the solder at the ultrasonic power of Mode II (Movie II). When the inputted ultrasonic power was increased, the solder droplet continued to spread in the stepwise mode. Notably, the liquid solder broke through the oxide film and subsequently spread on the substrate at a shorter time (0.006 s) in Mode II compared with that in Mode I. The spreading of the solder droplet was relatively fast and evidently collapsed at 0.016 s, and complete spreading was observed at 1.5 s. The spreading area in Mode II was larger than that in Mode I, as previously shown in Fig. 2A. The spreading of the solder droplet was accompanied by the periodic atomization of the spreading front (to be discussed in detail later).

Figure 2C shows the spreading at the ultrasonic power of Mode III (Movie III). In this case, the liquid solder broke

Fig. 3 — Time variation of the spreading diameters of Sn on 5056 Al at different ultrasonic power levels.

through the oxide film and subsequently spread on the substrate at a much shorter time (0.003 s). Remarkable atomization occurred immediately when the droplet began to spread. Moreover, the atomization took place not only at the spreading front but also on the surface of the whole solder droplet. The capillary waves on the droplet were the most intensive and unstable in all cases. Droplet spreading also followed the stepwise mode, but it moved faster than that shown in Fig. 2B. The spreading area did not increase as expected. This phenomenon was attributed to the severe atomization, which led to the significant loss of the solder, and the droplet spreading ceased at an early time (0.06 s). The atomization continued even when the spreading stopped, and it did not disappear until the ultrasonic vibration was discontinued.

Figure 3 presents the time variation of the spreading diameters of the Sn droplet with different ultrasonic powers. The Sn droplet started to spread at a moderate rate at the ultrasonic power of Mode I. Spreading diameter followed a nearly linear relationship with spreading time. The diameter of the Sn droplet was approximately 9.54 mm after 1.5 s. The spreading velocity of the Sn droplet increased abruptly at the beginning when the ultrasonic power of Mode II was adopted. The spreading diameter was 9 mm after 0.021 s and reached approximately 10.16 mm after 0.048 s. Following, the spreading of the droplet slowed down and ultimately stopped. After 1.5 s, the solder diameter was approximately 14.25 mm, which was larger than that in Mode I. The spreading velocity of the droplet at the ultrasonic power of Mode III was the largest. The solder started to spread rapidly and obtained the diameter of approximately 13.51 mm within 0.06 s and then stopped. The droplet diameter of the solder in Mode III was fairly smaller than that in Mode II.

Spreading of Different Solders

Figure 4 depicts the spreading of Sn-9Zn and Sn-4Cu on the 5056 Al substrate. The ultrasonic power was set to Mode II. The liquid solder of the Sn-9Zn droplet (Fig. 4A) broke

Fig. 4 — Spreading of the following: A — Sn-9Zn; B — Sn-4Cu on 5056 Al surface under the ultrasonic power of Mode II.

Fig. 5 — Time variation of the spreading diameters of Sn-9Zn and Sn-4Cu on 5056 Al substrate under ultrasonic power of Mode II.

through the oxide film and began to spread on the substrate at 0.006 s, similar to that for the pure Sn droplet (Fig. 2A). The spreading occurred in the stepwise mode, and slight atomization was observed at the spreading front. Droplet collapse was observed at 0.02 s, and the solder spread quickly thereafter. The droplet spread to a large area at 0.06 s, and the atomization and corrugate became intensive on the solder surface. By contrast, the atomization was not so obvious for the pure Sn droplet — Fig. 2. The Sn-9Zn droplet completed sufficient spreading after 0.1 s, and atomization continued until the ultrasonic vibration was stopped. Figure 4B shows the spreading of the Sn-4Cu droplet. The Sn-4Cu solder required a prolonged time (0.011 s) to break through the oxide film and spread on the substrate. The stepwise spreading did not advance outward uniformly, and the spreading presented a flower-like morphology with the absence of the solder at the center. Negligible atomization was observed during the spreading. The time needed by the Sn-4Cu droplet to complete the spreading was 1 s, which was much longer than those by the pure Sn and Sn-9Zn droplets.

Figure 5 shows the time variation of the spreading diameters of the different solder droplets. A comparison of Fig. 5 with Fig. 3 indicates the Sn-9Zn droplet has the largest spreading area, among the three droplets. The pure Sn droplet obtained a larger spreading area compared with the Sn-4Cu droplet, but it also presented a lower average spreading velocity during the entire spreading. The Sn-4Cu droplet

Fig. 6 — Spreading of Sn solder on: A — Pure Al; B — TC4 substrates under ultrasonic power of Mode II.

spread quickly at the beginning, but the spreading became extremely slow after 0.08 s.

Spreading on Different Substrates

Figure 6 presents the spreading of the pure Sn droplet on pure Al and TC4 substrates. The ultrasonic power was set to Mode II. The time for the pure Sn solder to break through the oxide film and spread on the pure Al substrate was 0.02 s, which was longer than that on the 5056 Al substrate — Fig. 6A. No atomization was observed during spreading. The solder droplet evidently collapsed at 0.04 s and showed clear spreading at 0.07 s. The spreading was completed after 0.2 s. The time for the solder to break through the oxide film was only 0.002 s (i.e., when the droplet began to spread on the TC4 substrate), which was shorter than that on the 5056 Al substrate. Significant atomization, accompanied with fast solder spreading, was observed instantly after the solder broke through the oxide film. The droplet collapsed after 0.014 s and nearly stopped spreading at 0.074 s. The solder continued to atomize during the entire spreading stage. The solder droplet underwent stepwise spreading on all substrates regardless of the different spreading velocities. A comparison of Figs. 2 and 6 suggests the corrugates of the droplet on the TC4 substrate are the most intensive.

Figure 7 shows the time variation of the spreading diameters of the pure Sn droplet on different substrates. The solder droplet underwent rapid spreading on the TC4 substrate. The solder diameter increased to approximately 13 mm at a time, shorter than 0.065 s. The diameter of the solder was approximately 13.51 mm after 0.1 s. The solder did not further spread because of the solder loss caused by severe atomization. The solder presented slow spreading on the pure Al substrate. The spreading diameter of the Sn droplet reached 7.82 mm after 0.02 s, and it grew slowly to 15.62 mm after 0.2 s. The spreading at the beginning stage was slower than the spreading process of the pure Sn droplet on the 5056 Al surface, and the spreading diameter

Fig. 7 — Time variation of the spreading diameters of pure Sn on different substrates under the ultrasonic power of Mode II.

of the Sn droplet reached 9 mm after 0.021 s, as previously shown in Fig. 3.

Figure 8 depicts the spreading of the pure Sn droplet on the 5056 Al substrates with different thicknesses. Figure 8A shows the spreading of the Sn droplet on an 8-mm-thick substrate (Movie IV). The solder broke through the oxide film at approximately 0.022 s after the ultrasonic vibration started, and the period in this case was much longer than that shown in Fig. 2. The solder droplet collapsed at 0.042 s, and solder spreading was observed at 0.152 s. Corrugates formed continuously on the droplet, and atomization was not observed during the entire spreading process. The solder was thick after the complete spreading at 0.552 s. The solder spreading using a 10-mm-thick substrate is shown in Fig. 8B. Increased time was needed for the solder to break through the oxide film. The solder did not atomize during

Fig. 8 — Spreading processes of Sn droplet on: A — 8-mm-thick; B — 10-mm-thick sheets under the ultrasonic power of Mode II.

the spreading under this condition. The solder continued to oscillate and corrugate under ultrasonication and then spread at an extremely low velocity. The solder in this case was much thicker than that by using the 8-mm-thick substrate after the complete spreading at 1.66 s.

Figure 9 shows the time variation of the spreading diameters of the Sn droplet on the substrates with different thicknesses. The droplet on the substrate with 8 mm thickness presented fast spreading and a large soldering diameter after the spreading. The diameter of the solder was approximately 11.63 mm after 0.552 s. The solder diameter in this case was smaller than that on the substrate with a thickness of 3 mm, as shown previously in Fig. 3. This finding can be attributed to the weak ultrasonic vibration intensity on a thick substrate. The solder diameter in this case was much smaller on the substrate with 10 mm thickness. The diameter of the solder was only 10.95 mm after 1.66 s. Atomization was not observed during the entire spreading when 8-mm-thick and 10-mm-thick substrates were used — Fig. 8. Consequently, the solder spreading on the 8-mm-thick substrate obtained a relatively large solder diameter after the complete spreading.

Table 3 summarizes the experiment results of the ultrasonic-driven spreading in this work. The atomization of the liquid solder became obvious when the ultrasonic power was increased. Obvious atomization was always accompanied by excellent solder spreading. However, severe atomization may cause excessive loss of liquid solder, leading to an inadequate spreading of the solder droplet.

Physical Process of Ultrasonic-Driven Spreading

Wetting of Liquid Solder on Substrate

The cross-section wetting interface was prepared to examine the wetting status of the liquid solder to the substrate during spreading. Figure 10A shows the cross section of the solder front after the ultrasonication time of 1 s. The oxide layer on the pure Al surface remained intact at the solder front (Fig. 10D), and the contact angle was greater than 90 deg. Figure 10B depicts the cross section of the solder

droplet after the complete spreading at the ultrasonication time of 5 s. The contact angle at the solder front remained greater than 90 deg even when the spreading was completed. Similarly, the oxide layer at the solder front remained intact — Fig. 10F. The results depicted by Fig. 10 clearly reveal solder spreading can be realized in nonwetting conditions under ultrasonication. The observations from this work differ somewhat from those in the literature (Refs. 9–11), in which ultrasonically improved wettability was achieved when the contact angle became acute under ultrasonication.

Figure 10 also displays the oxide layer at the droplet center that is partly removed after the ultrasonication time of 1 s (Fig. 10C) and then completely removed after the ultrasonication time of 5 s (Fig. 10E). No reaction layer was observed at the solder/substrate interface, as Sn solder remains stable to the Al substrate under the current heating temperature. We could deduce the solder droplet first spread on the nonwetting substrate covered by oxides, and then the oxide layer at the wetting interface was gradually disrupted under ultrasonication from the droplet center to the spreading front. The wetting interfaces at the droplet center were subjected to stronger cavitation intensity and longer ultrasonication time compared with those at the spreading front where the oxide layer was readily removed. The ultrasonic energy was dissipated in the form of capillary waves, and the acoustic pressure was relatively low at the spreading front (Ref. 19). The cavitation at the spreading front was weak, and it was unable to immediately eliminate the substrate surface oxides during the spreading.

In static wetting systems, solder spreading depends on its wettability on a substrate. However, ultrasonic-driven spreading is not a wetting-dependent process. This process is specifically useful for the surface metallization of hard-to-wet materials (Ref. 20). Liquid metals can be driven by ultrasonication to spread readily over the substrate regardless of their wettability, and then their wetting on the substrate is achieved by prolonging ultrasonication time.

Periodic Expansion and Shrinkage of the Spreading

Our high-speed photography revealed one of the most important characteristics of ultrasonic-driven solder spread-

ing is the periodic expanding-shrinking process, which is too fast to be detected directly by the eye. The solder droplet underwent periodic expanding-shrinking spreading in all conditions, indicating that this characteristic is intrinsic. Figure 11 depicts the solder movement within 100 acoustic periods (T). The substrate used was 5056 Al, and the ultrasonication power was set to Mode II. Figure 11A shows the spreading of the solder from 884 to 998 T after the start of the ultrasonication. Figure 11B shows a magnified view of the solder front in different moments. The solder front was located at the position of approximately 0.75 mm at 884 T. At 910 T, the solder front retracted to the position of 0.7 mm. This result indicates the solder is within the shrinking stage of 884–910 T. Then, the solder front moved forward to 0.8 mm at 938 T, indicating another expansion process. Another shrinking stage was observed thereafter, in which the solder front retracted to 0.75 mm at 954 T. The solder front further advanced to 0.95 mm at 978 T and retracted again to 0.85 mm at 998 T. As shown in Fig. 11, the solder undergoes periodic expanding-shrinking spreading under ultrasonication, and the transformation between expansion and shrinkage is at a periodicity of dozens of acoustic periods. The spreading distance during the expansion stage is always larger than the retracting distance during the shrinking stage; therefore, achieving solder macroscopic spreading. The solder spreading was closely related to atomization (to be discussed in the next section).

Figure 10 shows the substrate oxide layer always presents at the spreading edge, mainly because the spreading is so fast that the cavitation in the solder front does not have sufficient time to disrupt the oxide layer. This means wetting does not occur at the spreading front. Thus, the expansion/contraction process is not dependent on the wetting condition at the spreading front.

Corrugates on Solder Surface

The competition between the energy supplied by the vibrating substrate surface and the energy of the droplet sur-

Fig. 9 — Time variation of the spreading diameters of Sn droplet on substrates with different thicknesses under the ultrasonic power of Mode II.

face leads to the creation of capillary waves, which corrugate the droplet surface (Ref. 21). The observed corrugates first formed at the solder/substrate interface and then propagated upward. The formation of these corrugates is likely related to the periodic expanding-shrinking spreading process of the solder droplet. The corrugates were clear and regular when the solder began to spread at a low velocity (Fig. 8A and Movie IV), and they were disorganized when atomization occurred (Fig. 2C). The corrugates manifested as surface tension waves when ultrasonic vibration propagated on the solder surface (Refs. 22–25). In theory, the frequency of the surface tension wave should be half the frequency of the ultrasonic vibration. During the actual spreading, the frequency was affected by the surface morphology and physical characteristics of the solder, thus obtaining a deviated value. The frequency of the corrugates in Fig. 8 is approximately 300 μ s, which is six times the acoustic period of 50 μ s.

Table 3 — Summary of the Experiment Results of Ultrasonic-Driven Spreading

		Obvious atomization ▲			Negligible atomization △			Excellent spreading ●			Inadequate spreading ○		
Substrates		Pure Al			5056 Al alloy					TC4 alloy			
Ultrasonic power	Solders	Mode I	Mode II	Mode III	Mode I	Mode II			Mode III	Mode I	Mode II	Mode III	
	Sn		3 mm ▲ ●		3 mm △ ○	3 mm ▲ ●	8 mm △ ○	10 mm △ ○	3 mm ▲ ○		3 mm ▲ ●		
	Sn-9Zn					▲ ●							
	Sn-4Cu					△ ○

Fig. 10 — Cross section of a solder droplet after the ultrasonication time of: A — 1 s; B — 5 s; C–F — magnified views of regions C–F.

Atomization During Spreading

Another typical phenomenon during the solder spreading was the atomization of the solder droplet during significant spreading. Atomization first occurred on the forward-moving triple line because the liquid film at this location was thin enough to be easily atomized. Atomization occurred on the entire solder surface when ultrasonic power was increased (Fig. 2C) or when the substrate had high characteristic impedance (Fig. 6B). The sound intensity in the substrate is proportional to its characteristic impedance or to the square of the excitation amplitude, when the sound wave frequency is constant (Ref. 15). Thus, the application of increasing ultrasonic power (i.e., increasing excitation amplitude) or the substrate with high characteristic impedance may result in stronger vibration on the substrate surface and easily atomizes the spreading liquid film.

The atomization exhibited a periodicity trend similar to that during the expanding-shrinking spreading. Figure 12 shows the atomization period of the solder at the ultrasonic power of Mode III. The atomization period started at 200 T after ultrasonication — Fig. 12A. Slight atomization was observed at the solder front. We assume that the solder front is located at the position of 0 mm at this time. Strong atomization was observed after 12 T — Fig. 12B. The solder front advanced to 0.3 mm, indicating that atomization occurred during the solder expansion stage. Then, atomization paused after another 12 T — Fig. 12C. The solder front did not move forward at this stage. The solder front retracted to 0.1 mm at 248 T without atomization at this stage — Fig. 12D. Thereafter, the solder front further moved forward to 0.5 mm without atomization — Fig. 12E. Another atomization period occurred at 288 T when the solder front moved to 1 mm. These observations demonstrate that atomization, which has occurred periodically, depends on the expanding-shrinking spreading of the droplet.

Strong atomization occurred at the high ultrasonic power

and on the substrates with high characteristic impedance. However, excessive atomization was not beneficial to the spreading or joint formation during ultrasonic soldering for two possible reasons. The first is related to solder loss caused by severe atomization. Solder loss during soldering can result in porosities, voids, or incomplete bonding in the joint. The second is related to the joint contamination caused by solder spatters. Tiny solder spatters can pollute the unsoldered region of the joint, thus reducing its anticorrosive resistance.

Discussion

Schematic of Ultrasonic-Driven Solder Spreading

The observed phenomena discussed above are represented in Fig. 13 as a schematic of solder spreading under ultrasonication, in which the solder spreading is classified according to several stages.

Figure 13A illustrates the solder morphology after melting. The solder droplet was round after melting because an oxide film formed on its surface. The contact angle between the solder and the substrate was larger than 90 deg, indicating a typical nonwetting condition. Capillary waves corrugated the droplet surface after ultrasonic vibration (Fig. 13B) and propagated upward. Additional corrugates formed and propagated upward over time — Fig. 13C. The solder first broke through the oxide film at the triple line and began to spread on the substrate. This process was accompanied by atomization. The solder droplet evidently collapsed after an amount of the solder broke through the oxide film and subsequently spread. Atomization continued to occur at the triple line during the spreading — Fig. 13D. Atomization was not observed at the solder center in this condition because the solder was thick and the oxide

Fig. 11 — Solder spreading from 884 to 998 T: A — General morphology; B — solder front under the ultrasonic power of Mode II.

film remained on this solder. The solder droplet shrank, and the atomization stopped — Fig. 13E. The solder droplet underwent periodic expanding-shrinking spreading — Fig. 11. The expansion and shrinkage of the droplet occurred alternately. Thereafter, the droplet evidently collapsed — Fig. 13F. After the solder droplet spread completely, significant atomization might have occurred on the entire solder surface — Fig. 13G. Solder thickness decreased over time, and the solder droplet stopped spreading after a certain ultrasonication time. Atomization can result in solder loss, which can then shorten the time needed for the complete spreading of the solder. The contact angle of the solidified solder to the substrate remained obtuse after the spreading, and the spreading of the ultrasonic-induced solder was achieved in a nonwetting condition — Fig. 13H.

Effect of Ultrasonic Power on Solder Spreading

An analysis of Fig. 2 indicates ultrasonic power exerts significant influence on the spreading and atomization of the solder droplet. The spreading velocity and the atomization were largely determined by the vibration condition on

the substrate surface. Subsequently, the vibration condition on the substrate surface was analyzed using the ANSYS software, and the authors studied the vibration condition at the right side of the substrate, where the solder droplet was located — Fig. 14. Figures 15 and 16 show the simulated results of the surface vibration of the substrate under different conditions.

Figure 15 illustrates the vibration amplitudes along the vibration analysis line of the substrate by referring to different ultrasonic powers. The substrate used was 5056 Al. Similar vibration trends were obtained because the same ultrasonic frequency was applied. The vibration amplitude along the analysis line showed a sine-like morphology in the direction from the sonotrode to the sheet border. The vibration amplitude by using the ultrasonic power of Mode I obtained minimum values. The maximum vibration amplitude at the solder position by using Mode I was approximately 5 μm . This value increased to approximately 6 μm when Mode II was adopted, and the value further increased to approximately 8 μm in Mode III. The solder droplet subjected to high ultrasonic amplitude obtained a fast spreading velocity and a large spreading distance. Consequently, the solder subjected to Mode III has the fastest spreading velocity, as shown in Figs. 2 and 3.

Fig. 12 — Atomization period: A — 200 T; B — 212 T; C — 224 T; D — 248 T; E — 264 T; F — 288 T.

Fig. 13 — Schematic of the solder spreading agitated by ultrasonication: A — Solder melts before ultrasonication; B — formation of corrugates; C — solder breaks its oxide film at the triple line; D — atomization occurs at the triple line; E — solder shrinks without atomization; F — solder collapses; G — severe atomization occurs after complete solder spreading; H — solder solidifies after spreading.

Effect of Substrate on Solder Spreading

Figure 16 presents the vibration amplitudes along the vibration analysis line by using different substrates. The ultrasonic power was set to Mode II. The vibration amplitudes by using different substrates in this case showed morphologies

similar to those in Fig. 15. The TC4 substrate, which had the highest characteristic impedance, obtained the maximum vibration amplitudes. Accordingly, the vibration on the pure Al sheet was the weakest because it had the lowest characteristic impedance. As previously discussed, the solder attained a fast spreading velocity and a much larger spreading

Fig. 14 — Testing line on the substrate.

Fig. 16 — Vibration amplitudes on different substrates under the ultrasonic power of Mode II.

Fig. 15 — Vibration amplitudes on 5056 Al surface with different ultrasonic powers.

Fig. 17 — Variation of average spreading velocity with solder viscosities during the first 500 T for different solders under the ultrasonic power of Mode II.

area for the substrate with the strongest vibration. However, unexpected atomization may also occur when the vibration is excessively strong. The spreading diameter of the solder was smaller than those of the other substrates because of the excessive solder loss caused by atomization. Therefore, balancing spreading velocity and atomization by adopting moderate agitating ultrasonic power is important.

Effect of Solder Viscosity on Solder Spreading

Figures 2 and 4 demonstrate the spreading varies greatly for different solder droplets. As viscosity is one of the critical factors that influence the flowability of the liquid from a fluid dynamics perspective, the relationship between the velocity and viscosity of the solder spreading was examined for each solder used. The viscosities of the liquid solders are excerpted from Refs. 16–18. The average spreading velocities of the different solders on the 5056 Al substrate during the first 500 T are shown in Fig. 17. The results reveal the spreading velocity of the solder is inversely proportional to solder viscosities. The pure Sn solder with the lowest viscosity attained the maximum average spreading velocity at approximately 0.14 m/s. The average spreading velocity of the Sn-9Zn solder was 0.13 m/s. The Sn-4Cu solder, which attained the highest viscosity, achieved the minimum average spreading velocity at approximately 0.11 m/s.

Conclusions

1) The ultrasonic-driven spreading of a solder droplet was observed on initially nonwetttable substrates. The solder droplet expanded and shrank reiteratively and alternately with a periodicity of dozens of acoustic periods. Corrugates formed at the solder/substrate interface and propagated upward during spreading. Atomization occurred periodically when high ultrasonic power and substrates with high characteristic impedance were adopted. The atomization occurred during the solder expansion stage but not during the shrinking stage. The periodicity of the atomization essentially relied on the expanding-shrinking process of the droplet.

2) The fast spreading of the solder was observed at the high ultrasonic power because of the strong vibration on the substrate surface. Small spreading diameters were observed at the ultrasonic power in Mode III because of the excessive solder loss caused by serious atomization.

3) Solder viscosity exerted an obvious effect on spreading. The pure Sn solder attained the lowest viscosity and the fastest average spreading velocity during the first 500 T. The Sn-9Zn solder attained the largest spreading area and optimal spreadability. The solder exhibited a fast spreading speed and a large spreading diameter on the TC4 substrate with high characteristic impedance. The substrates with increased thicknesses obtained weak vibrations on their sur-

faces and subsequently slow spreading velocities and small diameters.

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