Ultrasonic-induced Rising and Wetting of a Sn-Zn Filler in an Aluminum Joint

The feasibility of ultrasonic-induced solder capillary rise above the bath level was demonstrated and the underlying mechanism was proposed

BY Z. XU, L. MA, J. YANG, J. ZHANG, AND J. YAN

ABSTRACT

The filling and wetting of a Sn-Zn solder in a vertical aluminum joint clearance under ultrasonic agitation was investigated and the mechanism underlying ultrasonic-induced capillary rise was explored. The liquid solder was pumped into the capillary and rose above the solder bath level to a constant height after 16 s of ultrasonication, even though the base material was not wetted. The surface oxides of the base material were gradually removed from the bottom of the clearance after prolonging the ultrasonic exposure time. This phenomenon resulted in the formation of a metallurgical bond between the solder and the base material. Solder rise increased roughly linearly with the increase in applied ultrasonic amplitude but decreased with the increase in joint clearance and heating temperature. A physical model comprising water and a glass capillary tube was used to examine the acoustic pressure inside and outside of the capillary. Results showed the ultrasonic-induced capillary rise may be attributed to the considerable drop in the acoustic pressure at the entrance of the capillary and the decline in the acoustic pressure gradient along the capillary.

KEYWORDS

• Ultrasonic Soldering • Capillary Rise • Wetting • Oxide Film • Acoustic Attenuation

Introduction

Ultrasonic soldering/brazing is a fluxless method of joining difficult-to-join materials, such as aluminum, magnesium, and titanium (Refs. 1–3). This technique has attracted considerable attention since its development in the 1940s and was used in the large-scale production of joining aluminum heat exchangers during the 1970s (Ref. 1). Interest in ultrasonic soldering/brazing has resurged in the last few years because of the increasing need for powerful and reliable methods to join new or dissimilar materials, such as metal matrix composites (Refs. 4, 5), ceramics (Ref. 6), amorphous alloys (Ref. 7), sapphires (Ref. 8), Ti/stainless steels (Ref. 9), and Cu/ceramics (Ref. 10), which are extremely difficult to wet and join.

Ultrasonic soldering/brazing studies have primarily focused on engineering applications (Refs. 1, 2). These investigations have been generally aimed at the engineering or commercialization of a particular procedure or product. Despite being considerably limited, fundamental investigations of solder wetting and joint formation are significant to guarantee or improve joint reliability. Noltingk and Neppiras (Ref. 11) first discovered that cavitation is a fundamental mechanism in ultrasonic soldering. Cavitation is induced when power ultrasonic is introduced into the molten solder. This process disrupts and disperses the oxide layer of a metal surface and allows the molten solder to wet the clean metal surface. The wetting mechanism in ultrasonic soldering has been firmly established and gained widespread acceptance (Ref. 12). However, capillary filling, another important aspect of ultrasonic soldering, has not been well documented, and studies on this issue still provide inconsistent results (Refs. 13–17).

Fuchs (Ref. 14) graphically illustrated the interaction of solder and capillary with flux or ultrasonic energy. He stated that flux chemically removes oxides and functions as a wetting agent to reduce surface tension and promote the flow of solder alloy. As a result, the solder climbs in the capillary sometimes to a height that exceeds that of the surrounding solder through wicking. Ultrasonic energy could effectively remove surface oxides but cannot duplicate the wetting agent effect of flux to allow the solder to fill and wet to a height above the level of the surrounding solder.

Vianco (Ref. 15) obtained similar results in his study on the wetting and capillary action between two parallel sheets of copper that were vertically dipped in an ultrasonic-activated Sn-Pb solder bath. A small volume of molten solder penetrated into the base of the joint clearance because of the hydrostatic pressure during immersion. Cavitation in the penetrated solder removed
the surface oxide films of the clearance. This process allows the solder to wet and protrude progressively toward the bath surface. However, rising of the solder to the bath level causes the hydrostatic pressure to disappear and leads to the lack of a prefilled solder to support oxide removal (cavitation). Therefore, further wetting and capillary rise could not occur. Vianco (Ref. 15) also suggested that the substrate should be immersed into the solder bath for ultrasonic soldering to produce a joint.

By contrast, Antonevich (Ref. 13) reported that ultrasonic-agitated zinc solder fills the vertical aluminum capillary to a maximum height of 2 mm above the normal liquid level at a specific immersion depth. However, no alloying or metallurgical bonding occurs between the solder and the inside tube diameter above the immersion depth.

We recently examined solder capillary in the the level joint clearance under ultrasonic activation (Refs. 16–18). The use of a solder droplet instead of a solder pool eliminated the effect of hydrostatic pressure created after sample immersion on the capillary filling. The solder droplet located at one end of the clearance readily filled an oxide-covered joint clearance under ultrasonic activation. Thus, either in vertical or horizontal joints (Refs. 13, 16–18), the solder filled the capillary before wetting or alloying the capillary wall, suggesting that forces other than surface tension act during ultrasonication. This phenomenon is different from that in flux soldering, in which solder filling depends on wetting (Ref. 19). However, the possible mechanisms underlying ultrasonic-induced capillary rise remain ambiguous.

Accordingly, the present study investigated the capillary rise of liquid solder in a vertical joint under ultrasonic activation and identified the influencing factors of this process to acquire in-depth information about the ultrasonic-induced capillary filling of liquid solder. Considering the difficulty of observing

| Table 1 — Chemical Compositions (wt-%) of 2024 Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Alloy | Mg | Cu | Si | Fe | Mn | Ag | Cr | Ni | Al | Zn |
| 2024 Al | 1.2–1.8 | 3.8–4.9 | <0.5 | <0.5 | 0.3–0.9 | – | <0.1 | – | Bal. | – |
capillary effects in a liquid metal system, we conducted a simulation experiment involving water capillary rise in a glass tube under ultrasonication. The driving force for nonwetting filling and the relationship between wetting (i.e., surface oxide removal) and ultrasonic capillarity were determined.

**Experimental Procedures**

An Al-Cu-Mg alloy (2024 Al-T3) was used as the base material in this study. The chemical composition of the base material is given in Table 1. Rectangle coupons with a dimension of 40 × 10 mm and a thickness of 6 mm were machined, and their surfaces were ground with a 500-grade emery paper prior to ultrasonic cleaning. A capillary parallel to the long surface of the coupon was prepared in each coupon through electric-sparking wire-cutting. The capillaries possessed sizes ranging from 300 to 800 μm and a constant length of 30 mm. A Sn-9Zn alloy was used as the filler metal. This alloy is a highly potential lead-free solder that presents a melting point (198°C) close to that of a Sn-37Pb solder (183°C) but exhibits superior shear strength and fatigue resistance. The base material and filler metal were ultrasonically cleaned in acetone for 30 min before the capillary rise test.

The experimental conditions are summarized in Table 2.

![Fig. 5 — Overall appearance of the filler metal in the clearance under different ultrasonic exposure times: A — 4 s; B — 8 s; C — 16 s; D — 24 s.](image)

![Fig. 6 — Microstructure of the wetting interface after 4 s of ultrasonic exposure.](image)

The experimental conditions are summarized in Table 2.

**Table 2 — Experimental Test Matrix**

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<th>Description</th>
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was transmitted to the solder bath by coupling the sonotrode to the solder container at 0.2 MPa. The sonotrode was operated at 20 kHz, with amplitudes of 10–22 μm on the top surface. The dwell time of the ultrasonic vibration ranged from 4 to 24 s, and the heating temperature ranged from 250° to 350°C. The soldering temperature of Sn-9Zn is generally about 250°C when using flux. The viscosity of the liquid solder would increase without flux since the solder is easily oxidized and covered by an oxide film in air. Heating temperatures higher than 250°C were used in this work. Moreover, examination of the effect of a wide range of heating temperature on soldering is beneficial for fundamental research. Each capillary was cut after the filling test, and the filling height was measured. The microstructure of the filler/base metal interface was observed under an optical microscope and a scanning electron microscope equipped with an energy-dispersive x-ray spectrometer. Specimens for microstructural analysis were prepared using conventional metallographic techniques.

A glass tube with a length of 325 mm and dual inner diameters/capillaries was used for simulation. The top capillary was 1.5 mm in diameter and 8 mm in length, followed by a capillary with a diameter of 5 mm to the end. The glass tube was immersed gradually and vertically into the deionized water activated in a normal ultrasonic cleaning tank, and the water rise in the capillary was observed. The maximum power of the ultrasonic cleaning machine was 99 W. The deionized water bath was 50 mm deep. In particular, an acoustic pressure gauge with a customized probe was used to test the acoustic intensity inside and outside of the capillary. The acoustic-intensity measuring device was based on the direct piezoelectric effect of the piezo-
electric ceramic. Piezoelectric ceramics were installed in a stainless steel probe with a diameter of 4 mm, which was smaller than the inner diameter of the glass tube applied.

The acoustic pressure test in the ultrasonic-activated water rise process is illustrated in Fig. 2.

Results

Characteristics of the Ultrasonic-Induced Solder Rise

Figure 3 illustrates the capillary rise of the filler metal without exposure to ultrasonic vibration. Limited solder rise was observed in the capillary; specifically, it was markedly lower than the solder bath level. Evident cracks appeared between the solder and the base material, demonstrating a nonwetting status between them. When the capillary was immersed in the molten solder, the solder rise was depressed because the surface oxides of the base material hindered the wetting and the capillary force did not work. However, solder rise still occurred under this condition. In fact, the rise resulted from a competition between dewetting effect and hydrostatic pressure.

Figure 4 shows the effective capillary rise of the filler metal as a function of dwell time for the 6-mm-thick specimen exposed to 20 μm of ultrasonic vibration. The clearance value was 300 μm, and the heating temperature was 300°C. In all cases, the filler metal reached a level that exceeded that of the bath. The filling height increased with ultrasonic exposure time and reached a relatively constant level when the ultrasonic exposure time exceeded 16 s.

Figure 5 reveals the overall appearance of the filler metal in the clearance under different ultrasonic exposure times. Except at the capillary bottom, the filler metal was not compact and remained unbonded to the base metals when the ultrasonic exposure time was 4 s — Fig. 5A. The filler metal appeared to be injected from the capillary bottom in this case. The filler metal in the clearance was compact and did not contain any void or porosity when the ultrasonic exposure time exceeded 4 s.

Whether or not the solder wet the base metal is difficult to detect in Fig. 5. Detailed examinations of the wetting interface between the solder and the base metal are illustrated in Figs. 6–8.

After 4 s of ultrasonic exposure, poor wetting was observed along the solder/base metal interfaces; this phenomenon involved a number of small cavities and oxide inclusions — Fig. 6. The wetting of the solder to the base metal at the bottom of the capillary was markedly improved when the ultrasonic exposure time was prolonged to 8 s.

The solder/base metal interfaces were free of oxide inclusions and contained nearly negligible cavities — Fig. 7A. In fact, only one suspected cavity of less than 50 μm was observed at the wetting interfaces (inset of Fig. 1). The backscattered image of the clearance bottom shows that aluminum dendrites nucleated at the wetting interfaces and grew into the solder — Fig. 7B. This finding indicates that wetting occurred between the solder and the base metal. However, the diffusion of solder into the aluminum substrate was limited. This result can be inferred to the Sn-Al and Zn-Al phase diagrams (Refs. 10, 18) showing that the solder constituents (i.e., elemental Sn and Zn) do not react with the aluminum substrate to form intermetallic compounds and that the solubility of Sn in pure Al is very low from ambient temperature to 300°C. In stark contrast to the bottom of the capillary, poor wetting was still observed at the solder/base metal interfaces of the solder head — Fig. 7C. Numerous oxide inclusions and pores were present at these zones, preventing metal-metal contact.
contact between the solder and the base metal.

The solder rise reached a maximum height when the ultrasonic exposure time was prolonged to 16 s. Comparative results between Figs. 7 and 8 show that solder wetting to the base metal was markedly improved not only at the clearance bottom but also at the solder head under prolonged ultrasonic exposure time. The amount of cavity and oxide inclusion was markedly reduced at the wetting interfaces of the solder head with prolonged ultrasonic exposure time.

Further extension of the ultrasonic exposure time did not enhance solder rise but improved the wetting between the solder and the base metal — Fig. 9. On the one hand, most oxide inclusions were removed from the wetting interfaces, and the solder presented a close contact with the base metal at the solder head — Fig. 9A. On the other hand, the interaction between the solder and the base metal became more intense either at the bottom or in the middle of the clearance, as evidenced by the increased number of aluminum dendrites being transferred into the solder — Fig. 9B. However, a focus on the filling front revealed that an approximately 500-μm-long solder exhibited poor wetting to the base metal — Fig. 9C. No obvious oxidation occurred at the wetting interfaces, and most of the solder shared an intimate contact with the base metal in this region. Nevertheless, the several microcracks and limited aluminum dendrites that grew from the solder/base metal interfaces indicated that no alloying or metallurgical bonding occurred between the solder and the base metal.

The above observations illustrate several distinctive aspects of solder rise under ultrasonic agitation compared with those found in previous ultrasonic soldering applications (Refs. 13–15) or in the conventional soldering process (Ref. 19). First, liquid solder filling can exceed the normal solder level and reach a stable height after 16 s of ultrasonication. Second, filling is not dependent on the removal of the surface oxides of the base metal; that is, the liquid solder rises between the two layers of the surface oxide regardless of the absence of simultaneous wetting. In addition, the surface oxides of the base metal are gradually removed from the clearance bottom to the solder head with prolonged ultrasonic agitation time, and metallurgical bonding is formed between the solder and the base metal.

**Influence Factor of Ultrasonic-Induced Solder Rise**

Figure 10 shows the effective capillary rise of the solder as a function of ultrasonic intensity. The filling height of the solder increased, roughly linearly, with the ultrasonic amplitude applied. The solder rise was 4 mm when the input ultrasonic was approximately 11 μm, which is only 2 mm over the solder pool level. The level reached 8 mm when the ultrasonic input was increased to 20 μm.

Figure 11 shows the variation in solder filling height with the joint clearance value. Solder rise was favored when the joint clearance was less than 500 μm and became negligible when the joint clearance exceeded 700 μm. Therefore, the solder filling height decreased with increasing joint clearance. This decrease was more significant for capillaries with diameters lower than 500 μm.

Figure 12 illustrates the variation in solder filling height with heating temperature. In the range of 250°–350°C, the solder increased to a lower level at an elevated temperature.

**Discussion**

**Driving Force of Sonocapillarity**

In addition to the ultrasonic soldering system, a similar abnormal ultrasonic-induced capillary filling has also been observed in several other fields, and several hypotheses in terms of
sonocapillarity have been formulated (Refs. 13, 20–23).

Lobova (Ref. 20) found the use of high-intensity ultrasound, which exceeds the cavitation threshold, facilitates the infiltration of the vertically placed quartz capillary with a poorly wetting Ga-In melt (its contact angle on quartz in air at 60°–70°C is 85° ± 5°C) to a height of 0.8–38 mm. This infiltration is due to a sharp increase in liquid pressure at the capillary base.

Antonevich (Ref. 13) and Malykh (Ref. 21) attributed the sonocapillary effect to ultrasonic cavitation at the end of the capillary. The researchers observed that the height of the liquid rise is a power more than that resulting from the surface tension when a capillary end is located in a developed cavitational area. This finding is in contrast to the observation that the capillary liquid nonsignificantly increases when the ultrasonic pressure is below the cavitation threshold.

Hu (Ref. 22) experimentally confirmed the transportation of water through a bundle of metal wires and its dependence on ultrasonic vibration parameters. However, he inferred that acoustic cavitation is unnecessary for ultrasonic capillary action and argued that ultrasound may weaken the cohesive force among liquid molecules. Thus, the adsorption force between the capillary tube and the liquid may become larger than the cohesive force, thereby enhancing capillary action.

Cecchini (Ref. 23) demonstrated that atomization within the fluidic channel followed by surface acoustic wave-assisted coalescence could lead to a net fluid movement.

From the hydrodynamic point of view, a pressure difference/gradient is a fundamental factor causing fluid flow. In the present study, the liquid solder flowed from the bath into the clearance and increased above the bath level. A pressure deviation may have existed between the solder bath and the solder in the clearance because the solder rise in the capillary under ultrasonication is nearly independent of its wettability to the aluminum substrate — Figs. 5–9. However, measuring the pressure of the liquid solder outside and inside the clearance is impractical. Thus, we used a sonocapillary system requiring deionized water and a glass...
capillary tube — Fig. 2. The capillary top was located 13 mm away from the bath bottom. The water in the capillary rose at an observable stable rate and reached a maximum height of 60 mm above the normal bath level under ultrasonication. By contrast, the water increased extremely slowly, and only 2 mm of a water head was observed in the absence of ultrasonication.

Acoustic pressure in water outside and inside the capillary was then measured by using an acoustic pressure meter, and the results are illustrated in Fig. 13. The data exhibited variance to a certain extent. However, the acoustic pressure from the outside to the inside of the capillary considerably declined. At the same time, the acoustic pressure in the capillary decreased with increased capillary height. These results indicate that the distinct capillary rise of liquid under ultrasonic agitation may be attributed to the decline in acoustic pressure gradient from the entrance of the capillary to the capillary surface.

For a glass tube located in an ultrasonically agitated liquid bath (Fig. 14), most of the ultrasonic waves were reflected by the end of the tube when travelling to liquid/tube interfaces. Only a small part of the ultrasonic waves were transmitted into and propagated in the capillary by the prefilled liquid (this liquid fills into the capillary under the hydrostatic pressure). The propagation of ultrasonic waves in the capillary induced liquid flow. The viscous resistance of the liquid itself and the friction forces of the liquid on the capillary wall promoted the gradual dissipation of ultrasonic energy through conversion into heat energy, which led to ultrasonic attenuation. The propagation of acoustic waves in a capillary can be expressed as follows:

$$P = P_0 e^{-\alpha x} e^{j(\omega x - kx)}$$

(1)

where $P$ is the acoustic pressure at a traveling distance $x$ in the capillary, $P_0$ is the initial acoustic pressure at the entrance of the capillary, $\omega$ is the angular velocity, $k$ is the wave number in the capillary, and $\alpha$ is the attenuation coefficient. $\alpha$ can be expressed as

$$\alpha = \frac{1}{dC} \sqrt{\frac{\mu \omega}{2\rho}}$$

(2)

where $d$ is the capillary diameter, $C$ is the acoustic velocity, and $\mu$ and $\rho$ are the dynamic viscosity and density of the liquid, respectively (Refs. 24, 25).

Equation 2 shows that the coefficient of acoustic attenuation is proportional to the square root of liquid viscosity and acoustic frequency, and inversely proportional to the diameter of the capillary. These characteristics indicate that a higher frequency and smaller capillary size correspond to an acoustic energy with a higher dissipation ratio. Thus, immersing a capillary with a diameter of hundreds of micrometers in an ultrasonically agitated liquid decreases the acoustic energy from the outside to the inside of the capillary and leads to the formation of a decreasing gradient of acoustic energy along the capillary. In consequence, capillary rise of the liquid occurs to compensate for this acoustic energy difference (as acoustic pressure difference) regardless of the wetting status of the liquid to the capillary material. In other words, the liquid is ultrasonically pumped into the capillary without the driving force of surface tension.

When a capillary end is located in a developed cavitation zone, the capillary rise would be considerably higher than that in the noncavitation zone because of the great acoustic pressure difference between the outside and the inside of the capillary. Previous studies (Refs. 13, 20, 21) have shown that a sharp increase in liquid pressure at the base of a capillary, which manifests in the presence of cavitation bubbles, is unilaterally responsible for nonwet-
ting capillary rise. However, the acoustic propagation characteristics (i.e., acoustic attenuation) in the capillary should also be considered because both of these aspects contribute to the capillary rise of the liquid. To calculate the height and speed of the capillary rise of the liquid, we should resolve a hydrodynamic equation of the liquid movement with the integral acoustic pressure from the cutoff point to the capillary surface.

On the basis of the above analysis, ultrasonically induced capillarity is not wetting based but rather significantly dependent on the acoustic pressures at the cutoff of the capillary $P_c$ and in the capillary $P$. $P_c$ is generally a function of the input acoustic power, the acoustic velocity in the liquid, and the location of the capillary end. $P$ is illustrated in Equations 1 and 2. Considering these conditions, we can easily understand the nature of the abnormal capillary phenomena occurring in ultrasonically agitated water or liquid metal systems mentioned in Refs. 13, 20–23.

**Effect of Soldering Variables on the Solder Rise**

A high ultrasonic amplitude markedly improves the solder rise. The mentioned ultrasonic amplitudes were those on the top surface of the sonotrode. The vibration of the sonotrode was transmitted through the titanium plate to the bottom of the vessel and finally injected into the solder bath. That is, the vibrating bottom surface of the vessel served as the agitator for the solder bath.

Our previous study (Ref. 26) revealed that the surface vibration of a solid plate agitated by a sonotrode follows a linear relationship with the input amplitude. Thus, the input energy to the solder bath increases with increasing sonotrode vibration, resulting in a significant elevation of the acoustic pressure level of the solder. Given that the ultrasound incident into the capillary would be dissipated, the difference in acoustic pressure between the outside and the inside of the capillary is enlarged when the acoustic pressure in the solder pool is increased. Thus, solder rise improvement is associated with an increase in applied ultrasonic amplitude.

Solder rise is highly sensitive to the variation in joint clearance. Decreasing the joint clearance not only decreases the volume of the ultrasonic energy transmitting into the capillary but also accelerates the dissipation of the ultrasonic waves inside. As depicted in Equation 2, the acoustic attenuation coefficient $\alpha$ is mainly dependent on the diameter of the capillary for a given ultrasonic system. Figure 15 shows the variation in acoustic attenuation coefficient $\alpha$ with capillary diameter $d$ for the Sn-9Zn solder. $\alpha$ increases significantly when $d$ is reduced from 500 $\mu$m to 0. By contrast, $\alpha$ presents an extremely small value and changes minimally with the variation in $d$ when $d$ exceeds 500 $\mu$m. Therefore, the acoustic pressure difference in the liquid outside and inside the capillary, as well as the acoustic pressure gradient along the capillary, is substantially augmented when the capillary is sufficiently small. In other words, the driving force of solder rise is increased in the capillary with a diameter under a critical value. Combining Figs. 11 and 15, we conclude that the critical capillary diameter in the current study is 500 $\mu$m. In addition, smaller clearance contains less liquid to be driven, resulting in a decrease in driving resistance, which also contributes to the enhancement of solder rise when the capillary dimension is reduced.

The effect of heating temperature on solder rise is apparently complex. The physical properties of the solder, the base material, and the vessel vary with the temperature. These variations consequently influence the propagation characteristics of the ultrasonic waves in the system. For example, temperature elevation normally reduces the solder viscosity and density, which strengthens the cavitation effect in the solder bath by lowering the cavitation threshold. However, this condition also declines the elastic modulus of the vessel and thus reduces the ultrasonic energy transmitted to the solder bath. To date, clarifying which factor behaves dominantly during ultrasonication remains challenging, and further investigation is necessary.

**Conclusions**

The rise and wetting of liquid filler in a vertical joint clearance under ultrasonication was investigated, and the following conclusions could be drawn.

1. Filling of liquid solder in a vertical joint above the normal solder level was realized under ultrasonic agitation regardless of the presence of oxide layers on the surface of the base material. Surface oxides were gradually removed from the clearance bottom to the solder head by prolonging ultrasonic agitation time, which resulted in metallurgical bonding between the solder and the base material.

2. The mechanism for the ultrasonically induced capillary rise of liquid was proposed. The propagation characteristics of acoustics in the capillary significantly decreased the acoustic pressure at the entrance of the capillary and the acoustic pressure gradient along the capillary. This phenomenon was basically responsible for the nontraditional capillary rise of the liquid under ultrasonic agitation.

3. Solder rise increased roughly linearly with the applied ultrasonic amplitude and decreased with increased joint clearance and heating temperature. The acoustic pressure at the entrance of the capillary and the acoustic pressure gradient along the capillary depended on ultrasonic intensity and joint clearance. The process by which heating temperature influences the propagation characteristics of ultrasonic waves in the solder warrants further investigation.

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**References**


