



Ultrasonic Soldering for Structural and Electronic Applications

Fundamental experiments and two case studies illustrate the feasibility of ultrasonic activation for fluxless solder processing

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ABSTRACT. A study was performed which examined the use of ultrasonic activation as a means of solder coating metal surfaces without the requirement of a fluxing agent. Fundamental studies on copper plates revealed that oxide removal and subsequent solder wetting resulted from both mechanical erosion and coupling of sonic energy from the source (horn) into the substrate. Cavitation was removed from the surface oxide layer. Coupling efficiency was dependent upon the power level, horn sample separation, and the substrate geometry. Inefficient coupling was characterized by a reduced area of solder coating and significant erosion of those regions that were wetted by the solder. In the absence of a flux, traditional meniscus rise and capillary flow processes were limited. Case studies illustrated the use of ultrasonic soldering in the coating of printed circuit board copper features and electronic package leads.

Introduction

Solder processing, whether for structural assemblies or the manufacture of electronic products, utilizes three principal components: 1) the solder alloy, 2) the substrate material(s), and 3) a fluxing

agent. The flux has multiple roles in the joining process. First, the flux is a corrosive agent that removes oxide film(s) from the substrate and solder surfaces, thereby promoting the solder/substrate metallurgical reaction. The flux also provides a protective film to prevent re-oxidation of the cleaned surfaces upon heating. Finally, the flux acts as a surfactant which reduces the solder surface tension, thereby facilitating flow on surfaces or through gaps and holes. Because flux residues left by the soldering process retain some level of corrosivity, it is necessary to remove them so as to ensure adequate service reliability of the final product. The traditional cleaning techniques have relied upon chlorinated fluorocarbon (CFC) and chlorinated hydrocarbon solvents as well as aqueous-based agents. The discharge of CFCs into the environment has been sus-

pected of damaging the stratospheric ozone layer, and is now severely restricted (Ref. 1). Waste water effluent from aqueous cleaning processes potentially pollutes drinking water resources (Ref. 2).

An alternative soldering technique replaces the flux's chemical activity for oxide removal, with mechanical energy in the form of sound waves. The sonic energy forces the liquid solder to cavitate, causing it to remove the oxide layer from the base metal surface. The solder can then form a metallurgical bond with the substrate; the solder is then said to wet the surface. This procedure is commonly referred to as "ultrasonic soldering." The frequency range of the sound waves generated by typical equipment today is 20 to 20,000 Hz. Although ultrasonic excitation can replace the oxide removal function of the flux, it cannot protect a freshly cleaned surface prior to soldering nor will it modify the molten solder surface tension to enhance spreading and capillary flow.

First mention of ultrasonic soldering dates back to pre-World War II Germany and includes the issue of a German patent for the ultrasonic soldering iron in 1939 (Ref. 3). Renewed interest was gained in ultrasonic soldering during the 1950s and 1960s as a means of joining difficult-to-solder metals such as aluminum or stainless steel (Ref. 4). This technique received large-scale manufacturing use during the 1970s for the join-

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Table 1 — Percent Area Wetted (left or right) of Copper Specimens Using 60Sn-40Pb Solder and the Commercial Ultrasonic Unit

Sample Thickness (mm)	Horn	Surface	25/5	Power (%)/Time (s)		50/15
				25/15	50/5	
0.51	both	left	27 ± 29	60 ± 12	58 ± 24	58 ± 24
		right	26 ± 31	76 ± 8	37 ± 16	45 ± 8
0.51	right only	left	37 ± 18	—	—	29 ± 15
		right	39 ± 6	—	—	59 ± 25
3.18	both	left	83 ± 7	85 ± 8	87 ± 7	86 ± 1
		right	85 ± 4	87 ± 8	83 ± 5	88 ± 3
3.18	right only	left	65 ± 26	—	—	66 ± 13
		right	63 ± 23	—	—	74 ± 12

were exposed to the point source of ultrasonic energy, provided the initial, exploratory data. The values of A, B, and C for the horn/sample geometry (Fig. 1) were 3.18 mm (0.125 in.), 14.2 mm (0.559 in.), and 36.6 mm (1.44 in.), respectively. It was observed that a solder film had formed on both the front and back surfaces of the coupons after ultrasonic activation. Also, the wetted area extended well beyond the projected footprint of the horn (i.e., a 3.18-mm (0.125-in.) diameter circle for either test condition. Both observations indicated that oxide removal and solder wetting were not due entirely to the erosion generated by cavitation of the liquid solder between the horn and the substrate surface. Rather, sonic energy appeared to couple to the copper coupon and then be available to all of the surfaces. These results suggest that ultrasonic activation will depend as strongly upon the bulk properties of the specimen material as on its surface condition or the operating parameters of the source.

Significant erosion took place on the front surface of the specimen (i.e., the surface which faced the ultrasonic horn). Shown in Fig. 7 are two schematic diagrams. In each of views (a) and (b), a horizontal line represents the location of the solder surface at the time of testing. Vertical and horizontal sections are shown as A-A' and B-B,' respectively. A schematic of each section is illustrated at the bottom of each diagram. The case of the vertical cross-sectional view of a typical sample front surface following exposure to the ultrasonic horn is shown in (a). An abrupt thickness change was observed along the vertical section of the sample; the point of transition was the solder bath free surface. An optical micrograph (Fig. 8) of the same cross section from an actual specimen illustrates the change in surface morphology between the eroded and noneroded surfaces (operating conditions: 55–60 W, 15 s). An oscillation pattern can be observed in the sample surface, extending from the solder surface interface towards the wetted region for approximately 1 mm. The horizontal section, diagram (b) in Fig. 7, represents ero-

sion that reached a maximum at the center of the coupon. The back surfaces did not experience significant erosion. The solder film thickness was approximately 2 µm (79 µin.) in those areas which exhibited a continuous coating.

Ancillary tests had confirmed the presumption that the closer the horn was to the sample, greater was the degree of wetting and/or erosion. Otherwise, the value of A (Fig. 1) was unchanged throughout the test program.

The mechanism by which the solder coating formed on the copper surface was through the formation of annular or donut-like regions of solder wetting. Shown in Fig. 9 is an optical micrograph of the donut pattern morphology as viewed looking down upon the copper specimen surface. A more uniform solder coating would form over the surface through the creation of additional annular features as well as progressive wetting of the interior region of each donut. An optical micrograph (Fig. 10) shows the cross-sectional microstructure of the donut pattern. The wetted, annular region was accompanied by a modest erosion of the surface. It was hypothesized that the donut artifact was caused by the formation of cavitation bubbles at the sample surface. Oxide removal (and subsequent wetting) occurred preferentially at the bubble wall, which separated the two nonwetted regions interior and exterior to the bubble. Continued activation caused oxide removal to progress quickly towards the interior area, trans-

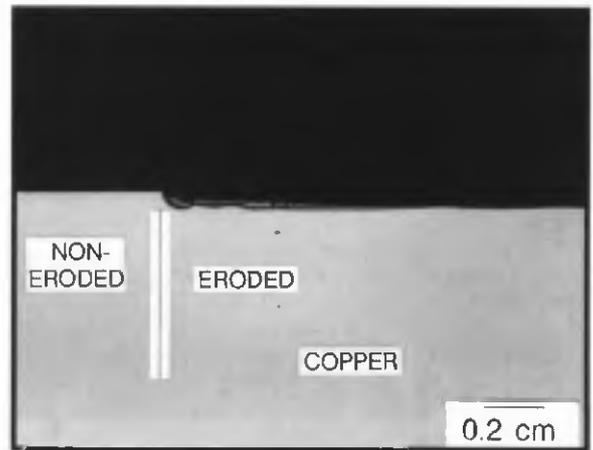


Fig. 8 — Optical micrograph of a copper sample cross section illustrating the transition zone between eroded and noneroded coupon surfaces. The noneroded surface was outside the solder bath; the eroded surface was immersed into the solder. The operating conditions were 55–60 W and 15 s exposure.

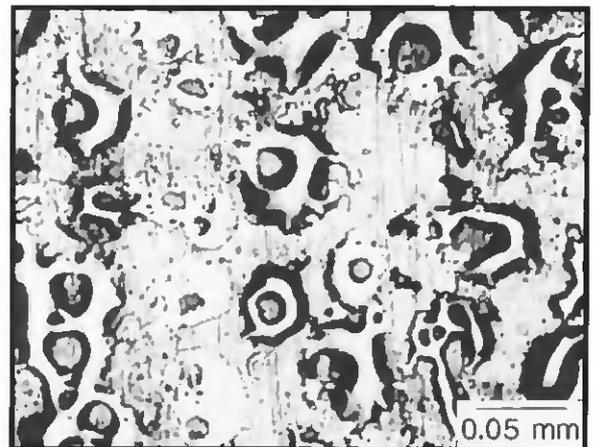


Fig. 9 — Optical micrograph illustrating the annular (donut) morphology of the solder wetting patterns on the copper plate surface.

forming the annular geometry into a wetted circle on the surface.

A quantitative assessment was performed which determined the extent of solder wetting on these samples as a function of the power level. The data scatter was established by subjecting five samples to an activation of 55–60 W for 15 s in 100Sn (282°C); an error term rep-

on the back surface, losing some of the preference for the projected position of the horn.

The 3.18-mm (0.125-in.) thick plates exhibited complete wetting of both the front and back surfaces of the plate. (The side surfaces were likewise coated with tin.) A comparison with the nonwetted areas did not indicate that erosion of the copper surface had taken place. The improved coupling of the thicker substrates meant that the solder-free surface caused less erosion at the interface with the surface of the larger plates. In addition, as the coupling efficiency improved with sample thickness, the edge of the wetted area extended closer to the free surface position of the solder bath.

Several points were confirmed from the test results depicted in Fig. 12: 1) Solder wetting need not require line-of-sight between the surface of interest and the source. 2) The ultrasonic source can be physically smaller than the substrate geometry. 3) Sample geometry had a significant role on the extent of wetting on the front and back surfaces. 4) Oxide removal (and subsequent wetting by the solder) is based upon either mechanical erosion, a coupling and distribution of sonic energy within the material, or a combination of these two phenomena. Energy coupling was the preferred mode since good coupling (as observed with thicker, wider samples) was accompanied by an increased extent of wetting as well as wider spatial distribution of solder coated regions, and a decrease in the degree of erosion, particularly on the surface facing the horn.

Further experiments were performed on the larger copper plate geometry in order to observe the effect of power level. All other operating parameters were unchanged. Shown in Figs. 13A and 13B are the reproduced images of wetting by 100Sn on the (a) front and (b) back surfaces of test samples exposed to 25–30 W; these samples are compared alongside those exposed to 45–50 W (from Fig. 12). The lower power value caused only slight differences in wetting magnitude between the front and back surfaces. However, the spatial distribution of wetted area on both surfaces appeared to be greater at the lower power values. This observation suggests that the amplitude of the sonic energy has a role in solder wetting.

Besides the specimen geometry and operating parameters, the third factor of importance in ultrasonic wetting is the surface condition of the base material. Copper samples 5.18 x 5.18-cm (2.0 x 2.0-in.) square and 3.18-mm (0.125-in.) thick were exposed to one of the three following surface conditions prior to test-

ing: 1) etched, 2) etched and stored in the laboratory environment for three months and 3) etched and air annealed at 250°C (482°F) for 25 min. The degree of surface oxidation was inferred to increase in the listed order of the treatments above. Three samples were evaluated per surface condition. Each plate was immersed in 100 Sn at 275°C (527°F); the power-on time was 40 s. The area percent wetted for the front surfaces are shown in Fig. 14 for tests run at two power levels. It is evident that as the degree of oxidation increased, wettability diminished. The back surfaces showed a similar trend and, in general, exhibited an overall lower degree of wetting as compared with the front surfaces.

Prepared surfaces caused the extent of wetting to be less dependent upon the power level so that similar degrees of wetting were realized with lower power levels.

The results in Fig. 14 appear to also indicate that the role of substrate geometry becomes less significant with an improved surface. However, consistent wetting was also observed with the controlled surface oxide film thickness — Fig. 15. It was shown that the as-received 0.51-mm (0.020-in.) thick samples exhibited very poor wetting. Samples were etched to remove the existing oxide layer, and then air annealed at 250°C (482°F) or 150°C (302°F) for 25 min. Poor wetting was realized with the 250°C (482°F) heat treatment temperature. However, a 100% surface wetting condition was achieved on the front and back surfaces after etching and heat treatment at 150°C (302°F). Similar results were recorded with the thicker 3.18-mm (0.125-in.) thick plates. These data sug-

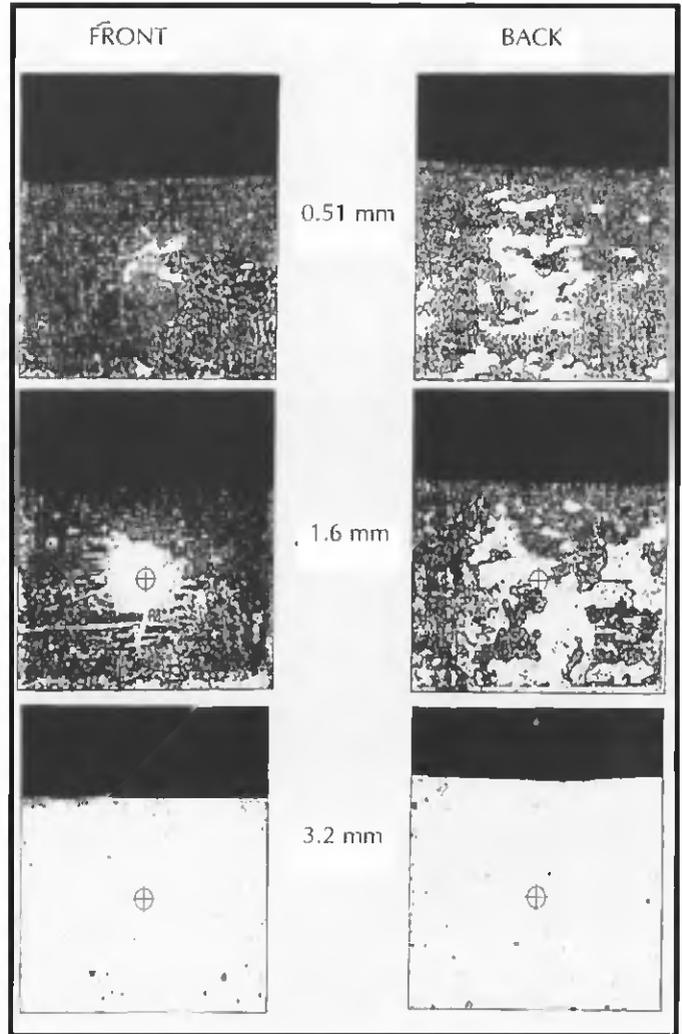


Fig. 12 — Solder film formation on the front and back surfaces of 5.08 x 5.08-cm square copper plates of thicknesses: 0.51 mm, 1.6 mm, and 3.2 mm. The power level was 45–50 W and a power-on time of 15 s.

gest that proper surface preparation, be it complete removal of the oxide layer, or at the very least, controlling its thickness, will likely promote uniform wetting on complex geometries that may have a varying power distribution within the substrate material.

Finally, experiments were performed to determine the role which the solder alloy had on the solder wetting of the copper plates. The 100Sn solder was replaced with the 60Sn-40Pb alloy. The substrates used in this evaluation were the 5.18 x 5.18-cm (2 x 2-in.) square copper plates with thicknesses of 0.51 (0.02) 1.59 (0.063), and 3.18 mm (0.125 in.). The samples were tested in the as-received condition (that is, no surface preparation steps were taken). The solder bath temperature was 225°–230°C (437°–446°F); all other parameters and procedures were similar to those described earlier. Overall, solder coverage was not as extensive as that observed with the 100Sn bath. The

