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Immersion Wave Soldering Process

Immersion wave soldering is a new technique for soldering advanced printed circuit boards. In this process, an assembled and fixtured printed circuit board is immersed in a fluxing fluid and preheated to the soldering temperature. The fluxing fluid is glycerine activated with ethylenediamine tetra-acetic acid (EDTA). After preheating and while still immersed in the fluxing fluid, the fixtured board is passed over a tin-bismuth eutectic (42% Sn, 58% Bi) solder wave. This technique has several advantages over conventional soldering processes, including elimination of solder dross formation, improved control over solder deposition, reduced thermal shock, easier cleaning after soldering, and improved flux effectiveness.

Introduction

As printed circuit boards become thicker and more complex, the need to minimize thermal stresses during processing and the need to obtain completely filled solder holes become conflicting requirements. In general, more difficult solder requirements are satisfied by increasing the soldering temperature of the board. Unfortunately, such an increase also increases the occurrence of board delamination and cracking of the plated "through holes." In addition, rework of the solder on printed circuit boards requires process temperatures and cycle times that increase with board thickness and complexity. Dissolution of the copper plating by molten solder during rework is an added detrimental factor in board survival and reliability.

There are two approaches available to reduce or eliminate these board degradation mechanisms. The usual approach is to reduce the peak temperature encountered by changing from a high-speed system (generally, wave soldering) to a batch system (oil immersion, oven reflow, or vapor-phase reflow) [1–3] that permits lower temperatures but requires longer exposures and expensive solder preforms. The second, less common, approach is to use a solder with a lower melting point than the normal eutectic tin-lead solder (63% Sn, 37% Pb), which has a melting point of 183°C.

Our process, called the *immersion wave soldering process* [4], combines both approaches in a way that avoids the use of high-cost solder preforms and the low throughput of batch processing. The process consists of a fairly conventional solder wave submerged in a heated flux bath. The bath is glycerine with 5% (by weight) added EDTA (ethylenediamine tetra-acetic acid) [5]. The mixture serves as a preheat medium, a flux, and a protective blanket. In addition to using the glycerine/EDTA mixture, the normal Sn-Pb solder is replaced by a eutectic mixture of tin and bismuth (42% Sn, 58% Bi), with a melting point of 138°C. With this soldering process, the fixtured board is first immersed and preheated in the hot glycerine/EDTA flux. While still immersed, it is passed over a Sn/Bi solder wave. The board is then removed from the flux bath, quenched, and cleaned.

Description of printed circuit boards

The printed circuit boards used in recently announced IBM intermediate and large computer systems present several difficult soldering problems. The first involves filling small (0.36–0.46-mm), high-aspect-ratio (12–14 to 1) plated through holes in complex printed circuit boards with solder. Some of the boards are up to 5 mm thick and contain six signal planes and twelve 0.036-mm-thick copper power planes. As a result of the small size of the holes and the heavy construction of the board, solder wave compression is ineffective in achieving complete fill of the holes with solder. The large number of power planes mandates a board preheat temperature above the melting point of the solder used for assembly.

The second major assembly problem presented by these board designs is the need to control the height of the

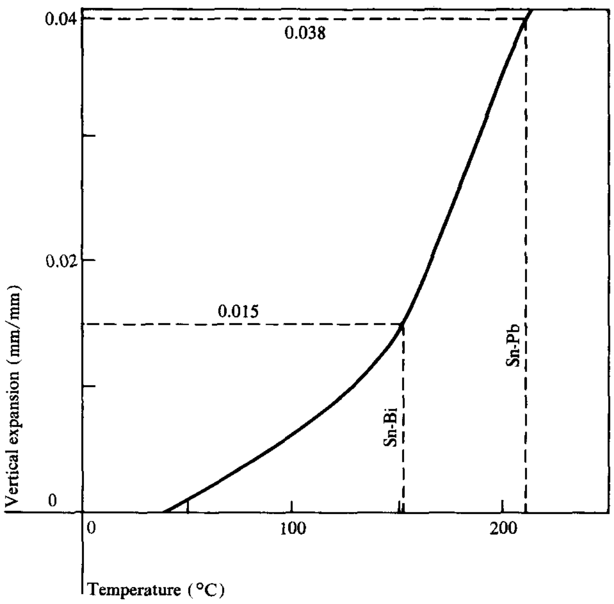

Figure 1 Vertical expansion of the epoxy-glass printed circuit board as a function of temperature.

Table 1 Comparison of properties of Sn-Pb and Sn-Bi solders.

	Sn-Pb	*Sn-Bi*
Melting point (°C)	183	138
Ultimate tensile strength (kg/cm^2)	506	562
Elongation (%)	30	200
Lap shear at 60°C (kg/cm^2)	429	343
Stress rupture (min):		
24°C (70.3 kg/cm^2)	8.3	16.7
60°C (63.3 kg/cm^2)	0.4	1.1
Slow cycle fatigue (cycles); 4 cycles/h, 3% strain, −4°C to 24°C	1900	8500
Lead pull (kg):		
Initial	1.40	1.09
After 25 solder cycles	1.04	1.31
After humidity	0.96	1.07
After 500 h at 60°C	0.93	0.55
Wire bonds (g):		
Plated	53	—
Immersion solder	—	45
Cu dissolution after 5-min immersion (μm):		
Cu	7.87	1.14
Be-Cu	11.43	1.78

solder-coated pads on the wiring side of the boards. These pads are used by a high-speed automatic-wire-bonding process in making repairs and engineering changes (ECs) to the boards. Each node of these repair/EC wire nets requires a ground and signal pad pair. The solder thickness on these pads must be precisely controlled to ensure successful wire bonding. These pads can be as small as 0.394 × 0.394 mm and the solder thickness on each pad must be controlled to within a 0.013- to 0.140-mm thickness range. It is also required that the ground/signal pad pair differential thickness range be held to within 0.076 mm. The pad pair differential range is particularly important since the signal and ground wires are bonded simultaneously with the same bonding tip.

Selection of low-melting-point solder

The motivation for using a lower-melting-point solder in place of the eutectic Sn-Pb was the differential thermal expansion of the component parts of the printed circuit board. The difference between the vertical expansion of the base epoxy glass laminate and the copper-plated through hole is the principal cause of board delamination and cracking of the plated through holes. Exacerbating the situation is the sharp increase in the thermal expansion coefficient of the epoxy resin above its glass transition temperature T_g (see Fig. 1). Reducing the peak board temperature to 152–163°C, the temperature range used for Sn-Bi soldering, results in a strain of 1.5×10^{-5} mm/mm, rather than the 3.8×10^{-5} mm/mm encountered with conventional Sn-Pb solder.

The Sn-Bi eutectic mixture was chosen because of all the available low-melting solders its mechanical properties most closely approximated those of Sn-Pb (see Table 1) [6, 7]. In addition, the six-to-seven-times reduction in the copper dissolution rate with Sn-Bi permitted a much greater capability for rework than that available with Sn-Pb.

Immersion wave soldering

In conventional wave soldering, the combination of wave compression, preheating of the board, and superheating of the solder are used to achieve hole fill by the solder. However, as previously noted, wave compression is relatively ineffective with small-diameter holes, and capillary forces control hole fill. Preheating of the board is limited by surface oxidation and the resulting degradation of the ability to solder. With Sn-Bi solder, superheating of a conventional solder wave is not feasible because of excessive dross formation; therefore, a process which excludes air from both the board surface and the solder wave was indicated. Thus, our task was to select a protective medium and to design a solder machine for its use.

A variety of natural and synthetic oils and fluids such as fish oil, peanut oil, glycols, and silicones have been used in the past with mixed success. The principal difficulties are post-solder cleaning and poor flux retention during solder reflow. A water-soluble fluid with fluxing properties that are stable at soldering temperatures is ideal for this type of operation. For Sn-Bi, glycerine containing up to 5% EDTA meets these requirements. Although the fluid quickly darkens in use and gradually becomes more viscous, the flux life appears to be limited only by the introduction of contaminants such as sulfur, oil, etc. The replacement cycle, which has been dependent on production quantities, is typically a month or longer.

A schematic of the solder machine is shown in Fig. 2. The machine consists of a large titanium tank with steam heating coils and a chain conveyor. A conventional solder wave is inserted through the bottom of the tank. A molten solder seal, which is dependent on the density differential between the solder and glycerine, is used to contain the working fluid and permit an external solder wave impeller. The preheat station contains a nozzle which directs flux against the bottom of the board to remove the entrapped air pockets from the board bottom and from the plated through holes, and allows the flux to fill the holes.

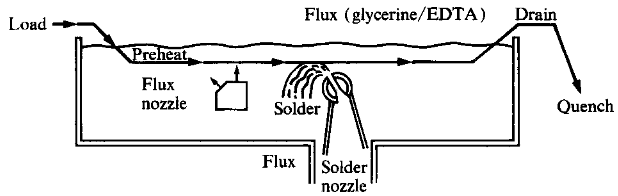

Figure 2 Schematic of immersion wave soldering.

Process optimization

A series of experiments and data analyses were conducted to determine the optimum process parameters for board assembly. The parameters studied were board velocity, solder wave angle and compression, solder and flux temperatures, and glycerine/EDTA flux pressure. A screening experiment was performed to determine the parameter limits that should be used in an optimization experiment. Based on the results, a model was developed using multiple regression analysis. The model has the form

$$\text{response variable} = K_1 + K_2V + K_3C + K_4A + K_5A^2 + K_6V^2,$$

where V is the velocity, A is the solder wave angle, and C is the compression.

The results of the preliminary analyses indicate that 1) ground and signal-bonding pad solder thickness is at a minimum when the solder wave angle is $\approx 50°$ from the horizontal, and 2) the standard deviation of ground and signal pads and the number of bridges are minimized when the velocity is ≈ 20 mm/s. Using this information, and plotting the response as a function of wave compression, the limiting value of wave compression needed to yield zero pad-to-pad solder bridges was chosen. From the results of the screening experiment, a five-variable, 32-treatment, rotatable experimental design was developed [8]. The response variables included solder fillet height on the connector tail, solder bridging between signal and ground bonding pads, pull strength of the connector, solder joints, non-wet pads, and hole fill.

Each board was inspected after soldering for the following response variables:

- Lack of hole fill in holes that contained connector springs. These values were normalized by determining the percentage of failures and multiplying by the number of connectors in a fully populated board.
- The number of connector spring tails that had high solder fillets. There were none found in any of the boards soldered.
- The number of solder bridges from signal-to-ground bonding pads. Bridging was nearly nonexistent and, consequently, was not evaluated.
- Pull testing of connectors. Ten connectors were pulled from each of 21 boards and the force required to "pull out" or break was recorded.
- Solder thickness on wire bonding pads. On each board, 66 ground and signal wire bonding pad pairs were measured.
- The number of de-wet holes (solder pull back).
- The number of non-wet pads.

The data were analyzed by developing a general second-degree least-squares regression model for each response variable. Each response variable was then plotted against each control variable while holding the other control variables at the central point of the rotatable design. Critical points were determined from the plots. With these variables as a starting point, all response variables were plotted against each control variable through several iterations for optimization of the control parameters. Optimization was keyed on the difference in solder thicknesses between signal and ground pads, on the number of non-wet pads, and on the lack of hole fill. Differences in board thickness, pad design, and pad density resulted in different optimal parameter values for board velocity and wave compression. For the board designs evaluated, parameter values were determined for an optimum soldering process. It was found that only board velocity and wave compression needed to be varied with the board design.

Using the parameter values established by the optimization experiments, excellent control of the solder height and defect level was obtained. All solder height values (Table 2) were within the desired range of 0.013–0.140 mm and all but one signal-ground pad difference were within the desired

Table 2 Wire bonding-pad solder height (mm); the data represent 288 readings from three boards.

	Signal	*Ground*
Mean	45.0	57.0
Variance (σ^2)	7.37	1.27
Standard deviation (σ)	13.7	18.0
Maximum	99	122
Minimum	13	15
Median	43	56

Table 3 Solder defects per board, averaged over seven boards.

	Risk sites	*Average number of defects*	*Average % defective*
Incomplete hole fill	28 800	26.0	0.09
Bridges	12 300	1.4	0.01
High fillets	16 500	0	0
Non-wet pads	45 300	9.9	0.02

0.076-mm maximum. The extremely low level of solder defects (Table 3) is indicative of the superior wetting obtained with the process.

In addition to the response variables that were optimized, several other positive characteristics of the immersion wave soldering process were observed. De-wetting, solder splatter, and dross formation were completely eliminated, and flux residue problems were greatly reduced (appearing only when board defects resulted in flux entrapment and subsequent bleedout after cleaning).

Conclusions

The immersion wave soldering process, when used with the low-melting-point solder, eutectic Sn-Bi, successfully filled the requirements for soldering advanced printed circuit boards. When this process is compared to conventional wave soldering using eutectic Sn-Pb, its advantages are significant. There is radical improvement in fluxing uniformity (elimination of de-wetting, reduction in bridging and non-wet pads, improvement in solder hole fill) and more controllable solder deposition (connector fillets and bonding pads). In addition, there is reduced board thermal shock as well as elimination of solder splatter and drossing, and the boards can be more easily cleaned.

It is recognized that the thermal limitations of the glycerine-base flux may preclude extension of this process (at least as it is presently equipped) to Sn-Pb processes. The requirement for total immersion also precludes utilization of this process for card assembly or for other components containing active but not hermetically sealed components.

Acknowledgments

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