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SOLDERING AUTOMATION

By S. Landers

Published October 1978

Final Report

Prepared for the United States Department of Energy
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**Kansas City
Division**

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Published October 1978

Final Report
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SOLDERING AUTOMATION

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Prepared by S. Landers

A method of automatically selecting and placing chip capacitors for subsequent soldering using the automated soldering process was evaluated and found to be feasible. The solder used for attachment was 50Pb-50In, which had been chosen previously for its low gold dissolution rate when soldering to metallization 3 μ m and 6 μ m thick on ceramic substrates. The automatic soldering process provides a 70 percent reduction in soldering costs during production. The automatic capacitor placement machine also offers economic advantages when design is constant and production rates are sufficient to justify the purchase of the equipment.

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SUMMARY

Applique components are attached to the metallized substrate of hybrid microcircuits (HMCs) by preheating the substrate to 160°C and reflowing Pb-In solder in the joint area by applying localized heat with a pulsed resistance-loop heating element. This process is manually controlled and is best suited for soldering discrete components such as flat packs where the probe contact area is constant and for attaching small wires or terminals that cannot be soldered using mass reflow techniques.

Most of the soldering operations performed during HMC assembly involve the attachment of chip capacitors with metallized terminations. When a hand process is used to solder these components, the uniformity, wetting, and overall quality of the resultant solder joint is dependent on the skill level, experience, and training of the production operator. In addition to the wetting and heat transfer problems present when a hand probe is used to flow solder, the substrate sometimes is damaged whenever any object is brought into contact with the gold metallized surface, and there is a continuing danger of damage to adjacent components. These problems prompted study of a process to minimize the adverse consequences associated with a hand solder process while seeking to provide improved quality and lower costs.

A study was made to determine an acceptable method of holding capacitors to the substrate during the soldering process. Methods considered included solder paste, solder flux, and retaining plates.

Solder paste, solder preforms, solder coated substrates, and solder coated capacitor terminations were considered as means of supplying solder to the solder joint area. The temperature and time required to properly flow solder were determined, and a characteristic curve was established as a base line reference for future applications.

The use of an automatic reflow process was studied and found to be feasible. The process was implemented on the production line and is used by several production and development programs. The process involves placing the capacitor, solder preforms, and solder flux on the HMC and passing the HMC through a conveyORIZED solder machine that supplies heat from three resistively-heated sources. The heat is transferred to the HMC by conduction through a thin Teflon-fiberglass conveyor belt. This process has been found to be cost effective, to reduce the need for highly trained soldering operators, and to improve the overall appearance and uniformity of soldered connections.

The possible application of an automatic capacitor selection and placement machine was evaluated. Modifications were designed to tailor the machine to individual circuits.

Shear strength values of applique capacitor solder joints made during this evaluation were determined and compared to previously generated results for hand soldering. Samples were thermally aged, temperature shocked, and shear tested to determine joint strength degradation. Various cleaning processes were evaluated for use in conjunction with the belt reflow solder system, a necessity because of the increased difficulty of removing flux after exposure to higher substrate preheat temperatures. The need for an improved solder flux removal process was established.

The cost of hand soldered capacitors was compared to the cost of belt soldered capacitors using the process developed, and it was found that significant cost reductions can be achieved with belt soldering.

DISCUSSION

SCOPE AND PURPOSE

The specific goal of this project was to automate and simplify the soldering process used to connect ceramic chip capacitors to gold conductors on alumina substrates.

The gold metallization system used to produce the sample substrates for this endeavor was defined by Sandia Laboratories at Albuquerque, New Mexico. The system consists of a resistive layer of sputtered tantalum nitride approximately 60 nm thick, followed by approximately 20 nm of evaporated chromium for adhesion and 6 μ m of evaporated gold for a conductive layer. These metallizations were deposited on alumina substrates in accordance with normal production processes.

The solder used was an alloy of 50 percent lead and 50 percent indium that had been selected for use by Sandia Laboratories because of its relatively low gold absorption rate.

The manual process previously used to attach ceramic chip capacitors to thin films was established in 1974. It used a closed-loop resistance-heated solder probe in conjunction with a hotplate set at 160°C to preheat the substrate. The probe was used to bring a localized area of the substrate to the required 240°C soldering temperature. The probe temperature could reach 649°C momentarily if it were used improperly and could cause rapid oxidation of solder joint material with an obvious degradation of appearance and quality. The manual process also caused previously soldered joints to be reheated, reflowed, and disturbed when new joints were soldered. Rework was required as a result. It was felt that the rework could be avoided by using a mass soldering process.

This work was undertaken to develop a process which minimized the use of the manual process. Since the manual process is completely dependent on the skill level of individual operators and requires more time, it was often necessary to assign numerous operators of varying skill levels to the job of soldering the same assemblies. The result was to reduce the uniformity of soldered assemblies and increase visual and electrical reject rates.

An evaluation of automated component (capacitor) selection and location equipment was conducted to determine the feasibility of using such equipment with typical logic and RF HMCs. Dimensional considerations were identified to determine design limitations imposed on the use of automated equipment as well as the associated cost factors.

To verify the quality level that could be expected, the soldered connections produced using the developed automated soldering process were aged at 150°C for up to 125 hours and thermal shocked from -40°C to +125°C for 500 cycles. The components were periodically sheared off and metallographically examined.

PRIOR WORK

Previous work on lead-indium soldering at Bendix was limited to initial establishment of the manual intraconnection soldering process for attaching appliques to hybrid microcircuits. That development effort recommended that a mass soldering process be developed and this effort was designed to satisfy that need.

ACTIVITY

Equipment Selection

Mass reflow soldering processes are not uncommon, and many different equipment designs are available for automated processing of electronic assemblies. Three basic types of heat sources are available: infrared, radiant heat from a resistive source, and direct heat conduction from a resistive source. There are many variations and combinations of these basic sources.

The design constraints for lead-indium (Pb-In) soldering of applique components limits the substrate temperature to 250°C. Time-at-temperature is not considered a critical parameter. Data on solder joint strength versus time of molten solder at 250°C shows the strength to be constant through 32 minutes. Time-at-temperature for the mass reflow process developed on this project is less than 5 minutes but is dependent on several factors, such as circuit configuration, component size, and termination material and configuration.

To make sure the maximum temperature (250°C) is never exceeded during processing, the equipment chosen was of the direct conduction type with a resistive heat source (Figure 1). Depending on the circuit configuration and on protective handling devices, it is necessary to position a heat conduction block between the heat source and the HMC. Consideration must be given to the temperature profile to which each HMC configuration is subjected. Figure 2 shows examples of different HMC configurations and heat transfer blocks. Figure 3 shows the belt reflow machine used in this study.

Figure 1. Solder Machine Functional Diagram

Figure 2. Heat Transfer Blocks and HMC Configurations

Figure 3. Belt Reflow Solder Machine

Solder Flux Selection

Solder flux selection was found to be a significant step in developing a mass reflow solder process for HMCs with 6 μm and 3 μm evaporated gold films. Four types of flux were selected for comparison and evaluation: Type 1, Type 2, Type 3, and Type 4. The solder flux criteria included the requirement that the flux be non-activated Type R. The flux also had to be stable when subjected to temperature increases expected in the mass soldering process. Finally, the flux had to produce acceptable joints. The requirement that the flux be Type R was a part of the thin film soldering process defined by Sandia. Type 2 flux is an RMA type (mildly activated) with an alcohol-based solvent. Type 3 is a non-activated flux with toluene, benzene, and isomers of terpene as solvents for the rosin. Type 3 was not approved for use on HMCs and did not provide adequate fluxing action when evaluated during this effort. Even though Type 3 and Type 2 did not meet the design requirements they were evaluated to provide a broader experience level.

The only difference between the Type 1 and Type 4 is the solvent base: alcohol for Type 1 and terpene for Type 4. Both of these fluxes are Type R non-activated flux. Both Type 2 and Type 1 have been used to solder production units but the former was deleted to preclude the possibility that flux activators would be left on the HMC and chemically attack delicate components.

During the solder flux evaluation, the capacitor bond sites of sample substrates were coated with each of the four fluxes and a 50Pb-50In solder preform was placed on each prepared site. The substrates were then heated in the belt reflow machine and the fluxing action and preform wetting were observed. The Type 1 and Type 2 fluxes rapidly boiled, dislodging the preforms and floating them to random locations, which caused shorts and solder coated areas not intended for solder. Type 4 and Type 3 were more stable. Type 4 was clearly superior to Type 1 and Type 2 in holding characteristics and to Type 3 in wetting of the gold substrate surface.

Efforts were then diverted to the development of a mass reflow process using Type 4 which was approved for use on HMCs and showed promise of providing adequate retention of components.

Solder Paste

Since solder pastes are widely used for mass soldering operations, several capacitors were soldered to sample substrates using solder paste which was specially formulated with 50Pb-50In and Type R flux. Solder paste consisting of 60Sn-40Pb and an RMA flux manufactured in Great Britain that was provided with the soldering machine was used as a test of the acceptability of the solder paste. In addition, a solder paste consisting of Type R flux and 50Pb-50In was procured from a United States manufacturer for use in this evaluation.

The solder pastes consistently produced hundreds of small solder balls which floated across nonconductive ceramic spaces in the circuit. In addition, the solder pastes did not uniformly wet and did create resin joints (Figure 4). The foreign material generated during the use of the solder paste was unacceptable as were the soldered connections. The evaluation showed that commercially available solder paste cannot be used for thin film networks when conductor and resistor paths are closely spaced and components such as beam lead devices are present.

Retaining Plate

Retaining plates were fabricated with holes for locating capacitors and were found to be unacceptable because of the variation in component size, the alignment of the plates relative to the

Figure 4. Defective Joints Resulting From Use of Solder Paste

conductor-resistor pattern, and tolerances associated with the manufacture of the retaining plate itself. A typical retaining plate is shown in Figure 5.

Application of Solder

The manual process originally used to solder capacitors to HMCs included the application of a 50Pb-50In preform at the termination of the capacitor to supply sufficient solder for completion of a solder joint. No solder is available on the HMC. At least 75 percent of the solder joint perimeter is required to be wetted with a continuous coating of solder for a joint to comply with design requirements. The use of solder preforms permits precise control of the amount of solder required for any given joint. The production operator is then required to apply external heat to flow the solder using the manual process.

Any mass reflow process also must provide adequate solder to the joint area, and, with solder paste proving useless, the approach that appeared most feasible was to precoat the solder joint region with a preform. Another method that was finally settled on is discussed later in this report.

Figure 5. Retaining Plate

Sample substrates were first coated with Type 4, and a preform of 50Pb-50In was hand placed on each capacitor joint area. The substrates were then passed through the belt reflow machine to melt the solder and coat the joint area with sufficient solder to produce a soldered connection. Various sizes were cut by hand and a ratio of approximately 50 percent solder to a given bond area (when the preform is 127 μm thick) was found to provide a complete covering of the area and adequate solder to form a fillet between the substrate and the capacitor. This, of course, varies with different circuit path configurations, but it is a good starting point when starting production prove-in. It will be necessary and desirable to have more than one size preform available for soldering operations.

After the substrates were precoated with solder they were rinsed in trichloroethylene for 15 seconds and in isopropyl alcohol for 15 seconds and then dried using dry nitrogen to remove residual solder flux. The substrates were then returned to the original assembly station for the addition of capacitors. Two types of capacitor terminations, gold and lead-indium coated, were evaluated for solder joint wetting and overall visual appearance. Visual appearance is of prime importance as it is the sole basis for final acceptance during production. The gold terminations were found to be solderable in most instances, although the presence of glass at the gold surface caused some solder joints to have high contact angles at the gold interface.

Figure 6 shows both the gold and the lead-indium terminations after soldering. The lead-indium coated terminations were found to produce consistently good wetting and low contact angles. It was noted that the quantity of solder flux was crucial to the final appearance of the joint. If too little flux was applied the solder joint exhibited a clearly defined line and, in some cases, incomplete joints between the substrate solder and capacitor terminations. There was inadequate flux to provide necessary protection, fluxing action, and heat transfer during soldering. Figure 7 shows incomplete joints. It should be noted that components to be soldered with non-activated Type R flux must be extremely solderable. Adequate precautions must be taken to obtain and maintain clean, oxide-free components.

Temperature Profile

After initial test samples were soldered, efforts were directed toward the determination of an optimum set of operating parameters for the machine. Machine parameters subject to control are belt speed, temperature of each of three stages, and exhaust rate.

Another critical item which must be considered along with the machine operating set points is the configuration of the heat transfer block on which an HMC may be placed during soldering. These devices may be of numerous types and consideration must be given to the cross sections of heat transfer paths when designing any such device. As the block becomes larger, the temperature rate of change with respect to time becomes less, and the belt speed must be reduced, or the temperature increased, to provide an equivalent temperature profile.

A standard handling method for HMCs at Bendix is to hold the HMC by the leads in a non-conductive test fixture and not remove it until the HMC is ready for installation in next assembly (Figure 8). This carrier holds the HMC in a position that requires that a heat transfer block be placed between the HMC and the belt to provide heat conduction. A typical heat transfer block is shown in Figure 9.

Indium-alloy solders must be held at soldering temperature longer than tin alloys to obtain comparable results in wetting. A temperature of 30°C to 40°C above the liquidus of the solder is required for consistent wetting. Therefore, it is necessary to minimize the thickness of any heat transfer block that may be required or longer solder times or higher heater temperatures in the machine will be required to produce good solder joints. An exception to this is when one HMC presents a larger heat sink to the machine than another and it is desired to operate the machine at the same temperature and belt speed. In such

Figure 6. Gold (Top) and Lead-Indium Coated Terminations After Soldering

a situation a larger heat transfer block can be designed to compensate for a smaller heat sink capacity. A temperature profile can thus be developed to solder several different sizes and types of HMCs with one set of machine parameters, one belt speed, and one temperature for each of the three heaters.

A typical temperature profile necessary to produce good solder joints was determined and is shown Figure 10. The initial temperature rate of change is 4°C/s , which is slow to permit the drying of the solder flux and ensure retention of capacitors on the HMC. A faster heat cycle is possible, depending on the accuracy required. Once the solder has begun to melt, the surface tension of the solder tends to align the capacitor to cancel unequal physical forces. If excessive flux is applied to the HMC, the capacitors can be moved. An even brush coating of flux is usually adequate to produce good solder wetting and not cause misalignment of the capacitors.

Figure 7. Incomplete Joints

Figure 8. Typical HMC in Nonconductive Carrier

Figure 9. Heat Transfer Block

Figure 10. Typical Temperature Profile

The temperature setting for each of the three heat zones is listed below the temperature profile in Figure 10. The temperature gradient from the bottom of the HMC carrier to the substrate surface was found to be dependent on the individual carrier and HMC design, thus requiring, in some cases, machine settings higher than the design limit of 250°C to produce a soldering temperature of 240°C. This must be considered as each heat transfer device or HMC changes configuration.

Preparation of Sample Solder Joints

Once the initial profile needed to produce consistently uniform solder joints had been established on the basis of visual criteria only, approximately 2000 capacitors were soldered to sample HMCs with production type resistor-conductor networks. The production HMCs typically have 127 μ m wide lines and spaces. The mass soldering process developed is compatible with these relatively narrow lines and spaces. Five different patterns were used in the evaluation to ensure an adequate cross section of the types of HMCs and exposure of the process to several circuit configurations.

The following sequence was used to process these HMCs for subsequent environmental conditioning and testing.

1. Set machine controls and preheat until temperature stabilizes.
2. Coat capacitor bond sites with Type 4 flux.
3. Place a 50Pb-50In solder preform on each bond site.
4. Place HMC on solder fixture and transfer to belt of machine.
5. Reflow solder preform, precoating the HMC capacitor bond site.
6. Allow HMC to cool as it exits from the machine.
7. Rinse in trichloroethylene for 15 seconds to remove flux.
8. Rinse in isopropyl alcohol for 15 seconds to remove flux.
9. Blow dry with dry nitrogen.
10. Recoat solder coated bond sites with Type 4 flux.
11. Select and place Pb-In coated capacitors in respective positions.
12. Place HMC on solder fixture and transfer to belt of machine.

13. Reflow the solder on the HMC and the capacitors, forming a solder joint from the capacitor to the bond site.
14. Allow HMC to cool as it exits from the machine.
15. Clean the HMC by repeating Steps 7, 8, and 9.

This process was used to produce approximately 4000 soldered connections on 2000 capacitors. These capacitors were then subjected to a two-part environmental conditioning program designed to prematurely degrade the soldered connection and push-off tests were conducted to profile joint degradation.

Environmental Conditioning

Soldered connections were evaluated in the "as-cast" condition by section and metallographic examination techniques. After artificial aging of the joints, additional samples were examined to determine changes that occur during such aging.

The HMCs were divided into Groups A and B for environmental conditioning. Group A was subjected to thermal aging at 150°C and samples were shear tested at intervals of 5 hours, 25 hours, 75 hours, 100 hours, and 125 hours. Group B was subjected to temperature shock cycles consisting of a cold cycle at -40°C for 15 minutes and a hot cycle at 125°C for 15 minutes with the transfer time between each cycle being approximately 4 seconds. The measured temperature rate of change when going from 125°C to -40°C was 83°C per second. The rate of change after transfer from cold to hot was approximately ten times slower because of the design of the temperature shock chamber. The temperature rate of change experienced by the HMC during soldering is approximately 4°C per second during heating. The temperature shock testing is obviously quite severe compared to the solder process.

The shear strength data obtained during these tests were plotted as a function of time-at-temperature and at intervals during temperature cycling. Figures 11, 12, 13, and 14 show temperature aging and temperature cycling data for two different size capacitors.

At the start of the environmental conditioning program for Groups A and B, a sample of "as-cast" solder joints was shear tested. Data is shown on the respective graphs as the values at time zero. On larger capacitors measuring 3.175 by 2.28 mm, the force at failure was found to be 62 to 66 N for as-cast solder joints.

Capacitors that had been thermally aged at 150°C for 125 hours and temperature shocked for 500 cycles were centrifuged at 5000 g's and no failures occurred. All HMCs with soldered connections were at one time required to pass a 5000-g centrifuge

Figure 11. Shear Strength Versus Time at 150°C (1.01 by 1.27 by 1.27 mm Capacitors)

test which has since been deleted because of a lack of failures of soldered connections during the test. Several sample HMCs were overtested in 1000-g acceleration increments until the substrate or capacitor solder joints failed. The substrates typically fail at 12000 g's with no failures of solder connections on capacitors.

Metallurgical Evaluations

Metallurgical evaluations of soldered connections were performed to determine joint condition at various stages of assembly and environmental conditioning. Figure 15 is a scanning electron micrograph of a cross section through only the metallized gold. Measurement of the gold indicates it to be approximately 6 μm thick (all joints soldered were on 6 μm gold). After soldering capacitors to the metallization using 50Pb-50In solder alloy and Type R solder flux, a second cross section was taken as shown in Figure 16. Three distinct layers are present. Energy dispersive X-ray analysis at Points A, B, and C indicates substantial

Figure 12. Shear Strength Versus Temperature Cycles (1.01 by 1.27 by 1.27 mm Capacitors)

differences in composition at these points. The X-ray results are shown in Figure 17. The layer containing Point A is most likely the gold-indium intermetallic AuIn_2 . Layers B and C are AuIn and pure gold, respectively.

From Figure 16 it can be concluded that there is approximately 1 to 2 μm of the original gold metallization remaining. The total thickness of these layers is about 9 μm .

The most significant result of the environmental conditioning, metallurgical evaluation, and visual inspection was the documentation of lifting and peeling of solder from the circuit paths after temperature cycling and thermal aging. Figure 18 shows gross examples of solder that had wetted down the circuit path during pretinning, and soldering is shown to be delaminated from the underlying metal. Auger electron spectrographic analysis of this region detected mainly gold and indium with a slight oxygen and carbon peak as shown in Figure 19. These samples had been subjected to 500 thermal cycles from -40°C to $+125^\circ\text{C}$ and had numerous areas where the solder coating and solder fillets were lifting off and pulling up.

Figure 13. Shear Strength Versus Time at 150°C (1.27 by 2.29 by 3.05 mm Capacitors)

Another analysis was made on solder joints that had been aged for 125 hours at 150°C. Several peeling joints were noted here also but the degree was not as severe as those on HMCs that had been thermal cycled. Metallographic inspection of cross-sectioned joints revealed the intermetallic layer to be lifting off the substrate as shown in Figure 20. The intermetallic compound layer thickness on these samples was approximately 16 μm . This is almost double the compound layer thickness observed on the as-cast solder connections.

It seems reasonable that the peeling and delamination are the result of stress caused by volume changes during solid state growth of the intermetallic layers. This phenomenon was also observed in an earlier soldering development study.

The reaction that forms the intermetallic layer is time-temperature controlled. To maximize the useful life of assemblies using lead-indium solder alloy, the time at high temperature during testing, environmental conditioning, and storage should be minimized to reduce layer growth. In addition, the storage temperature

Figure 14. Shear Strength Versus Temperature Cycles (1.27 by 2.29 by 3.05 mm Capacitors)

should be maintained at moderate levels (less than 80°C). Future work on Pb-In solder systems should include a life expectancy evaluation under a full range of possible storage conditions.

Profile Modifications to Reduce Solder Spread

The severity of the solder lifting problem prompted efforts to minimize the thinning out of the solder fillet tangent to the substrate interface in the hope that the solder lifting was the direct result of the formation of this section and not a more basic metallurgical problem as yet not fully understood. Several attempts were made to minimize the time-at-temperature. A profile was developed as shown in Figure 21. This profile reduced the time at liquidus (above 210°C) temperature from 138 seconds for one pass to 40 seconds for one pass. In addition, the process was revised to limit the number of passes to one versus two. Using the modified profile required the operator to carefully

Figure 15. Scanning Electron Micrograph
of Metallized Gold on Ceramic
Substrate (3000X)

Figure 16. Scanning Electron Micrograph
of Solder-Gold Interface (3000X)

AREA A

AREA B

AREA C

Figure 17. SEM/EDAX Analysis of Areas A, B, and C in Figure 16

Figure 18. Photomicrographs of Solder Peeling After Aging (80X)

place the preforms on each end of the individual capacitor. The resulting joints were virtually identical in appearance to those evaluated during this effort but did not exhibit much solder spread or thinning out of the solder fillet tangent to the TFN as was the case with the original process.

This illustrates the flexibility of the belt reflow process in being adaptable to a specific product or process restriction. The final definition of the failure mode is yet to be made; it was not within the scope of this effort to pursue this aspect. It is being recommended that future work include such an investigation to determine the advisability of applying lead-indium solder technology to future programs requiring long storage or process times at temperatures above 80°C.

Rework

With a mass reflow process, a typical problem is an incomplete or open solder connection. During this study less than 1 percent of

Figure 19. AES Analysis of Colored Area in Figure 18

the 2000 capacitors soldered exhibited open or incomplete solder joints which measured less than 75 percent wetting. If an incomplete solder connection does occur, it is easily repaired in most cases by simply refluxing all solder connections, adding a solder preform to joints with insufficient solder, and passing the HMC through the process again. If a capacitor is missing, the same approach can be used to add the capacitor. Recleaning is necessary after each rework or trip through the solder machine. Repeated heating of the solder flux causes it to become increasingly polymerized and more difficult to remove. The hand soldering method is currently being used to rework all defective solder joints.

For rework of capacitors that are found to be electrically defective or of improper value (necessitating removal of a capacitor), the rework can be accomplished by using a hotplate to preheat the substrate to 160° and a solder tip to apply localized heat to the capacitor to liquify the solder. The capacitor can then be

Figure 20. Cross Sections of Peeling Solder Joints After Aging at 150°C for 125 Hours (80X)

Figure 21. Modified Temperature Profile

removed using tweezers or a vacuum probe. This is the same process used during manual solder rework. Once removed the HMC can be reworked as described previously.

Automatic Selection and Placement of Capacitors

The belt reflow solder process minimizes cost and maximizes repeatability during the actual assembly sequence but it does not solve the problem of handling the capacitors during installation on the HMC. It is necessary for the production operator to select a capacitor and place it on the proper location. A visual aid is required during this process. The possibility of the operator making a mistake in selecting and placing the capacitor is 100 percent, given sufficient time and quantities. An automatic "pick-n-place" machine was thought to offer significant improvements in repeatability of placement while affording possible reduction in direct product costs. An electronically controlled "pick-n-place" machine was evaluated. The machine features a vibrator feed tray with several slots for different size and value capacitors, a substrate holding table, a programming console, and transfer mechanisms (Figure 22). The machine automatically selects a capacitor from the tray, uses a vacuum pickup chuck to transfer the capacitor to the HMC and orient it with its bond site, lowers the capacitor into position, and releases the vacuum.

The ability of the machine to follow a properly programmed sequence was virtually perfect. The problems encountered in the use of the machine were related primarily to the design of the individual HMCs and to operator experience and training. As designed, the machine was intended for use on substrates flat on the bottom and with solder pads large enough to allow for dimensional tolerance associated with the alignment of the conductor-resistor network relative to a pair of mutually perpendicular reference datums formed by two adjacent sides of the HMC.

A contour tolerance of 254 μm is required in the production of HMC substrates at Bendix. This means that any edge may vary 254 μm from a given maximum or minimum reference point. When all the tolerances associated were added together (as listed in A through E below) the resulting dimensional tolerance was in excess of that available. It was necessary to design an optical alignment system to bypass most of the buildup of tolerances by aligning directly with the conductor-resistor network. This was done as a part of the normal tooling efforts for the affected HMCs. With the modification in place, it is possible to select the capacitors from preloaded trays and position them on the HMC automatically. The smallest chip that can be consistently placed is 127 by 127 μm because of vacuum pickup problems, including dropping the component, failing to pick up the component, and shifting the component, that occur with small parts, small vacuum probes, and irregular surfaces.

Figure 22. Automatic Capacitor Selection and Placement Machine (Pick-n-Place Machine)

Manufacturer specifications for the automatic pick-n-place machine indicated that the machine was capable of selecting and placing within $\pm 25.4 \mu\text{m}$ capacitors 1.27 mm square or larger. This figure does not include several mechanical tolerances that are dependent on the design of the individual HMC. At Bendix two basic types of HMCs are currently being manufactured, including a "logic" HMC and an "RF" HMC. The RF HMC has a metal plate $5.08 \mu\text{m}$ thick soldered on the backside with several metal tabs turned down to form "feet" for connection to a printed wiring board. The logic HMC is flat on the backside with no appendages. On RF HMCs the following tolerances must be considered when determining the minimum size solder pads for a capacitor to be placed automatically.

- A. Dimensional variation of TFN pattern location to sizing line along edge $\pm 12.7 \mu\text{m}$.

- B. Pick-n-place machine tolerance $\pm 25.4 \mu\text{m}$.
- C. Pick-n-place pick-up error, best estimate $\pm 50.8 \mu\text{m}$.
- D. Pick-n-place align error, best estimate $\pm 50.8 \mu\text{m}$.
- E. Bilateral tolerance equivalent (variation between mounting plate leg and a TFN feature; see Figure 23 for deviation) $\pm 406 \mu\text{m}$.

The total error expected in positioning a capacitor on an RF HMC is $\pm 660 \mu\text{m}$.

This means that a given capacitor needs a pad $660 \mu\text{m}$ larger on each side than the maximum size capacitor to be positioned if every capacitor must be completely on the solder pad(s). For a typical 1.27 by 1.27 mm capacitor a 2.64 mm minimum pad width is required.

These figures apply to RF HMCs. For logic HMCs similar conditions apply, except Item E is reduced to $\pm 254 \mu\text{m}$. The reduction is a result of the deletion of the mounting legs on the backside (logic HMCs do not have mounting legs), but does not allow for the presence of the logic carriers.

These tolerances necessitated a different approach to the alignment of the HMC to the machine. An optical alignment system was designed to bypass the $\pm 406 \mu\text{m}$ tolerance caused by stackup from the TFN pattern to the mounting legs. The optical system permits alignment to the TFN pattern itself rather than an edge or leg. The operator adjusts the position of the HMC (TFN) using a micrometer-adjusted X-Y- θ stage. Unless such an alignment system is used, automatic selection and placement is not practical.

Another limiting factor in the use of such a machine is the time required to set up for a production run. Time study information indicates that it takes 0.058 hours to set up the machine and load the first part before starting. As shown in the following calculations, automatic placement of capacitors should not be used unless a minimum of two typical HMCs can be processed at one time. A typical HMC is defined as one having 15 capacitors.

The following factors and equations were used to determine the break-even point of the automatic pick-n-place when compared to the hand placement process.

- A. Turn on machine, clear memory, and establish reference points for five-position control axes = 0.02 hr/run
- B. Reference zero = 0.02 hr/HMC
- C. Load and clear leader of magnetic tape = 0.015 hr/HMC

LEG THICKNESS = NOMINAL 508, MAXIMUM 559, MINIMUM 457

LEG WIDTH = NOMINAL 683, MAXIMUM 762, MINIMUM 508

MAXIMUM LIMIT DIAMETER, LEG = 1090

DEVIATION FROM TP = $1092 - 683 = 409$

HMC LIMIT - MAXIMUM LIMIT DIAMETER, LEG = $1194 - 1092 = 102$

A. POSSIBLE TOTAL DEVIATION DIAMETER = 510

HMC/TFN SIZE VARIATION: EXAMPLE HMC-R

1. MAXIMUM SUBSTRATE SIZE: 22606

2. ASSEMBLY ALLOWANCE: 152

3. MAXIMUM SIZE LIMIT (1+2): 22758

4. MINIMUM SUBSTRATE SIZE: 22098

B. POSSIBLE DEVIATION DIAMETER (3-4): 660

TOTAL DEVIATION POSSIBLE AROUND TP CENTER (A+B)

= $510 + 660 = 1170$ DIAMETER POSITIONAL TOLERANCE

C. BILATERAL TOLERANCE EQUIVALENT = $414 = \pm 406$

*ALL UNITS ARE μm

Figure 23. Bilateral Tolerance for HMC Location

- D. Program transfer to memory = 0.003 hr/cap
- E. Machine cycle time = (1400 cap/hr) 0.0007 hr/cap
- F. Hand placement time = 0.005 hr/cap
- G. Average number capacitors per HMC = 15.0
- H. Time required to hand place one HMC (15 cap/HMC x 0.005 hr/cap) = 0.075 hr
- J. Total time to set up one typical HMC (A + B + C + D) = 0.02 + 0.02 + 0.015 + (0.003 x 15) = 0.055 + 0.045 = 0.100 hr
- L. Time to load HMC in machine = 0.01 hr
- M. Time to run actual or trial HMC (0.0007 hr/cap x 15) = 0.0105 hr
- N. Time to run first HMC and trial 2 x 0.0105 = 0.0210 hr
- P. Time to run one typical HMC 0.131 = J + L + N (0.131 = 0.100 + 0.010 + 0.021)

The time required to place the capacitors on one typical HMC by hand is 0.075 hour. The time required to automatically place capacitors on the same HMC is 0.131 hour. Obviously more than one HMC per production run is required to justify the use of an automatic "pick-n-place" process. Additionally, design changes must be at a low level to minimize engineering support. The relationship between the cost of hand placing and automatic placing can be expressed by the break-even relationship. The typical number of capacitors per HMC (15) will be used to simplify the equation.

Where

K = Constant

The time to place 15 capacitors by hand = 0.075 hr/HMC.

(K) HMC x 0.075 hr/HMC = J + L + M + (K) HMC x M = 0.100 hour + 0.010 hour + 0.0105 hour + (K) HMC + 0.0105 hr/HMC.

(K) 0.075 hr/HMC = 0.1205 hr + (K) 0.0105 hr/HMC.

0.1205 hr = K (0.075 hr/HMC - 0.0105 hr/HMC)

K = (0.1205 hr) + (0.0645 hr/HMC).

K = 1.868 HMC

Therefore, exactly 1.868, or a maximum of 2, HMCs with 15 capacitors each are required to operate the machine on a cost effective basis.

Alternatively, if an HMC has 25 capacitors, only one HMC is required to justify the automatic "pick-n-place" machine.

$$\begin{aligned} K &= (0.1205 \text{ hr}) + (26 \times 0.005 \text{ hr/HMC} - 0.0105 \text{ hr/HMC}) \\ &= 0.1205 \text{ hr} + 0.1145 \text{ hr/HMC} \end{aligned}$$

$$K = 1.008 \text{ HMC}$$

These calculations do not allow for engineering time required to program and support the machine nor do they allow for machine costs such as calibration, repair, amortization of initial cost, operator training, and tooling costs. Obviously, high volume production is needed for this approach to be truly cost effective.

Good manufacturing practice would be to limit the number of HMCs produced at one time to a minimum of five to assure a margin of savings between the two methods. Another benefit of this automatic equipment is the reduction of operator errors in selection of the correct capacitor. If machine is properly set up, every HMC will be correct.

Cost Effectiveness of Automatic Reflow Soldering

The cost of hand soldering each capacitor to an HMC has been estimated to be 0.048 hour per capacitor. The cost of belt reflow soldering the same capacitor is 0.0184 hour per capacitor. If an assembly with 210 capacitors is being assembled, the savings to the customer will be the difference between 10.08 hours and 3.86 hours or 6.22 hours per unit--a significant savings when applied over an entire production run. This process is applicable to several programs currently planned for production at Bendix Kansas City. The savings discussed here may be affected by other process constraints unique to individual assemblies. These figures demonstrate the savings possibilities given adequate consideration of design and process constraints.

Flux Removal

During the development of the automatic reflow soldering process, it was found that the flux residue was not as easily removed as with hand soldering. The solder flux became more difficult to remove as time-at-temperature or temperature increased. Limited efforts were expended to determine the extent of the problem. The Sandia specifications for soldering and for cleaning allow residual flux residue after cleaning procedures have been followed. There have been no documented failures of HMCs where

the cause was found to be flux residue present after mass reflow soldering. The presence of liquid flux (flux that has not been subjected to the belt reflow process) will cause electrical failure when power is applied to the HMC.

Efforts are now underway to define cleaning requirements and improve processes used to clean HMCs that have been soldered with non-activated flux, which is the only type used on HMCs at Bendix Kansas City. It was observed during this endeavor that hard-to-remove baked-on flux residue could be dissolved easily if the HMC were raised to a temperature of 160°C and liquid flux (particularly Type 1) were applied to the affected area. The elevated temperature and natural solubility of flux residue in fresh liquid flux is responsible for this result.

Several other solvents were used to remove flux that had been baked on at 230, 250, and 285°C and during the belt reflow process. The results were evaluated using Meseran numbers.¹ To ensure the consistency of these measurements, the entire surface of the HMC was coated with liquid flux applied with a small artist's brush. Some variation in thickness of the coating did occur but the results were consistent.

Solvents evaluated included Blend C, Flux Blend I, trichloroethylene, isopropyl alcohol, and TC cleaning. TC cleaning was required for soldered HMCs. TC cleaning is a multi-step process consisting of a boiling trichloroethylene (TCE) wash, a room-temperature isopropyl alcohol (IPA) wash, a boiling detergent wash in a solution of deionized water and non-ionic detergent, a hot deionized water rinse in a cascade washer, and a dry nitrogen drying (dew point less than 62°C). This process was required for cleaning soldered HMCs at the time this study was in process. Blend C is the designation given to a blend of four solvents consisting of 17 percent methyl chloroform, 33 percent n-butylacetate, 33 percent trichloroethylene, and 17 percent isopropyl alcohol by volume.¹ This solvent was used in a vapor degreaser while the Flux Blend I was used at room temperature. Flux Blend I consists of 50 percent Type 1 flux and 50 percent trichloroethylene by volume and was prepared in an attempt to use the flux removal characteristics of trichloroethylene and liquid flux. The circuits were rinsed in fresh trichloroethylene and isopropyl alcohol for 1 minute each immediately following the rinse in Flux Blend 1.

To establish cleanliness limits, control circuits were prepared by coating four circuits with Type 4 flux and baking two of them for 2 minutes and two of them for 3 minutes on a hotplate preheated to 230°C. The Meseran numbers were 1598 and 1231 for the circuits baked for 3 minutes and 1178 and 869 for those baked for

2 minutes. The substrates were not cleaned after flux application and baking. At the other extreme, a substrate was rinsed in fresh trichloroethylene and isopropyl alcohol for 1 minute and dried using dry nitrogen. The Meseran number for that circuit was found to be 52. This gives a range from 52 to 1598 for relative cleanliness levels from good to very bad (Table 1 and Figure 24).

In an attempt to determine the maximum degree of cleanliness that could be expected, several circuits were subjected to vapor degreasing for 1 minute using Blend C, followed by repeated cycles of vapor degreasing for 1 minute and ultrasonic cleaning for 1 minute in Blend C. The results are shown in Figure 25 and Table 2. Note that long time or elevated temperatures (285°C) raise the Meseran numbers.

The most significant observation during these evaluations was that the TC cleaning process is not producing the best results. If one were to choose a cleaning process from those evaluated, the choice would be between the vapor degrease process using Blend C--which yields Meseran numbers less than 100--or the Flux Blend 1 process followed by TC cleaning.

Combining solvents or flux blends holds great promise of producing a cleaning process that is more effective and less costly than TC cleaning, and possibly less detrimental to product, personnel, and environment.

Unless a procedure other than TC cleaning is used in conjunction with this process, some solder flux stain can be expected on assemblies and is allowed by the product definition. The TC cleaning process has been replaced by a process which uses a modified Flux Blend I wash (using IPA in place of TCE), a rinse in TCE, and a rinse in IPA. This process leaves very little stain but is not the most thorough cleaning process. It has been optimized for the current product requirements.

Mass Reflow Process Problems

This process requires that the components be solderable with non-activated Type R rosin flux. An activated flux would greatly enhance the tolerance of the process to varying degrees of solderability. To ensure the solderability of the capacitors, they are supplied to Bendix with terminations precoated with 50Pb-50In solder. A solderability test is performed on each lot received. Good results are also obtained using capacitors with gold terminations--provided the quantity of glass frit present in the gold is not excessive.

Table 1. Meseran Data on HMCs Baked for 2 and 3 Minutes

Circuit Serial Number	Flux Used	Temperature (°C)	Time (Minutes)	Solvent	Meseran Number
062132	None	None	None	TCE-IPA	52
062259	Type 4	230°C	2	None	1178
062258	Type 4	230°C	2	None	869
062251	Type 4	230°C	3	None	1231
062255	Type 4	230°C	3	None	1598
059434**	Type 4	Belt	--	TC	448
062134**	Type 4	Belt	--	TC	447
061508	Type 4	Belt	--	Flux Blend I and TC	79
061506	Type 4	Belt	--	Flux Blend I and TC	80
062217***	Type 4	Belt	--	TC and Ozone	230
062239***	Type 4	Belt	--	TC and Ozone	228
062113*	None	None	None	None	162
061933	Type 4	230°C	2	Blend C Vapor Degrease	107
061944	Type 4	230°C	3	Blend C Vapor Degrease	97

*Standard circuit; no cleaning and no flux; stored for extended period outside of clean room.

**Standard production process.

***Subjected to ozone treatment after cleaning for 90 seconds at 160°C; no exhaust.

Figure 24. Blend C Cleaning of HMCs Baked at 230°C for 2 and 3 Minutes

Another feature of the process that is less than ideal is the necessity of supplying solder to the HMC substrates. As previously discussed, a solder preform is used to perform this task. Although it does not generate foreign material such as solder balls and particulates, the preform itself may become dislodged during the first reflow needed to coat the substrate. This is the result of excessive flux or insufficient pressure being applied during application of the preform by the operator or deformed preforms that do not lie flat and seat themselves to the substrate. The operator must apply slight pressure to seat the preform without warping or bending it. The preform is best applied with a blunt-nosed stainless steel probe which will not penetrate the preform.

This is not a significant problem, but it is discussed here because of its dependency on operator skill and training. An objective of this endeavor was to reduce such requirements to a minimum and this represents a minor remaining dependency on the skill of the operator. Experience with training of operators used during this experiment showed that a relatively unskilled person can quickly be taught to properly position the preforms and components. It may be necessary to supplement the eyesight of the operator with a microscope of 10X magnification or greater, depending on the quality of the person's eyesight. Normally a 4X viewing glass commonly used for electronic assembly is adequate.

Figure 25. Blend C Cleaning as a Function of Cycled Baking

Table 2. Meseran Data on HMCs Contaminated With Type 4 Flux and Cleaned With Blend C

HMC	Baking Time for Type 4 Flux (Minutes)			Meseran Data: Diethylsuccinate Radioactivity Counts Per 112 Seconds						
	230	250	285	Vapor Degrease Only	Vapor Degrease--Ultrasonic Cleaning in Blend C					
					Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
061933	2			107	51	39	47	26	--	42
061944	3			97	43	39	46	42	--	35
061931		2		152	86	42	51	43	--	48
061941		3		507*	395	180	196	145	--	130
061934			3	493*	309	127	134	128	--	111
061945		3		65	60	30	54	47	--	41
*Stain present										

A positive feature of the preform is the lack of solder particle generation. Solder paste was found to produce thousands of the solder balls which caused the HMC to be contaminated beyond use.

In addition, it is necessary to rest the terminations of the capacitor on the precoated substrate solder pads during placement of capacitors or incomplete joints will result. This is also a problem if parts are uniform and properly designed to allow for maximum and minimum size capacitors. Too much solder creates large bumps in which capacitors must be positioned while too little solder results in insufficient soldering.

These problems do not represent serious difficulties. As evidenced by the cost effectiveness of the process, they are minor when compared to the total costs of training and developing experience, and the lower quality of the hand soldering process.

The major concern is the evidence of solder lifting from the gold conductor material. Such defects, if sufficiently severe, can cause failure in the units in which they are present. Future work should include further study of this problem to completely define it and determine a method of avoiding it. This type defect has also been seen on hand soldered units in the production area.

ACCOMPLISHMENTS

An automatic mass reflow soldering process has been developed and implemented. The new process significantly improves the processing of hybrid microcircuits by minimizing the contact of the HMCs with soldering tools with temperatures as high as 649°C, significantly reduces the skill level required of a production operator and thus minimizes the training needed to produce a skilled operator, and provides an improvement in the overall appearance and consistency of soldered connections.

By minimizing the contact between TFN film and metallic solder probes, damage to the TFN has been reduced and an HMC virtually free of probe marks and metallic scrape-off has resulted.

It has been estimated that a 72 percent reduction in the cost of soldering capacitors to production HMCs can be realized by using this process to replace the hand process.

The automatic selection and placement of capacitors was shown to be feasible under proper conditions--such as stable design, minimum lot size, and sufficient production rates.

HMCs have been built using the mass reflow process and have been shown to meet the functional and environmental quality requirements.

FUTURE WORK

Related future activity should include development of a more thorough flux removal process compatible with TC bonding techniques and the components used in the production of HMCs at Bendix. Present cleaning methods are inadequate to completely remove flux residue, so another aspect of such a development effort would be to show the possible acceptability of leaving flux residue on delicate components with no cleaning except drying to remove conductive solvents. Ozone cleaning has shown promise of providing improvements in cleaning and should be pursued.

During this development activity, the identification of the intermediate layer failure mechanism revealed the need for further work to define the exact mechanism of failure, which is believed to be related to indium starvation on sections of solder joints and to be dependent on solder spreading during reflow. It should be remembered that this mechanism has been seen at work on both belt reflow and hand soldered (resistance probe) HMCs.

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A method of automatically selecting and placing chip capacitors for subsequent soldering using the automated soldering process was evaluated and found to be feasible. The solder used for attachment was 50Pb-50In, which had been chosen previously for its low gold dissolution rate when soldering to metallization 3 μ m and 6 μ m thick on ceramic substrates. The automatic soldering process provides a 70 percent reduction in soldering costs during production. The automatic capacitor placement machine also offers

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