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Automated Twisted-Pair Wire Bonding

A need for highly dense and reworkable external interconnections with controlled characteristic impedance on high-performance printed-circuit boards led to the development of the process and equipment described in this paper. These interconnections are required to implement engineering changes, to install precise circuit delays, to repair printed-circuit defects, and to complete interconnections not possible with printed circuitry alone. As an economical way to meet the characteristic impedance requirement of 80 ± 10 Ω and the density requirement for terminations on a 2.5-mm "staggered" grid (twice as dense as a 2.5-mm-square grid), 39-gauge twisted-pair wire is used. A solder-reflow process bonds the wires to the printed circuitry and meets the need for reworkability. Computer-controlled equipment, developed to install twisted-pair wires at production rates, is now being used in several IBM plants worldwide.

Introduction

Major requirements of the interconnection system for a new printed-circuit board technology were high density, the capability for rework, and the capacity for high-volume production. These requirements helped to determine the described process and equipment. For example, these connections were required to implement engineering changes, to install precise circuit delays, to repair printed-circuit defects, and to complete interconnections not possible with printed circuitry alone.

In order to meet the system impedance requirement of 80 ± 10 Ω [1] economically, 39-gauge (0.089-mm-diameter) twisted-pair wire (approximately six twists per centimeter) with 0.04 mm of insulation was chosen as the interconnection vehicle. This wire was also chosen to meet pin-density requirements of the densest circuit boards under consideration at the time. These boards had terminations on a 2.5-mm staggered grid (twice as dense as a 2.5-mm-square grid). The required interconnection system density was determined by the pin density of the planned thermal conduction module (TCM) [2] and the input/output (I/O) connector systems on the TCM board [3].

An orthogonal wire routing system with wires held in place by accurately positioned wire guides was selected with an eye towards automation of the wiring process. Whenever wire terminations had to be made where bond sites were obscured by overlying wires, those portions of the wires were placed parallel to one another. This facilitated their separation for work on the underlying bond sites since previous work had shown it to be very difficult to clear away mazes of random wires from such bond sites without damaging the wires.

The wire attachment process selected was a low-melt solder-reflow method. This process looked attractive from two aspects. First, a low-melt solder process satisfied reworkability requirements. Second, application of the solder on surface metallurgy could be made at essentially no additional cost since a low-melt solder was already used to wave-solder components onto the boards. The overall wiring process was further simplified by the use of a heat-strippable polyurethane insulation for the twisted-pair wire. This insulation acts somewhat like a flux during the soldering step [4].

A *pre-twisted*, rather than *twisted-as-you-go*, approach was chosen because of its potential for higher wiring rates. After a small length of the twisted-pair wire is untwisted (in order to separate the ground and signal wires), a resistance-heated molybdenum solder tip is used to bond (solder-reflow) wires to pads on the board. The wire bonder first melts the insulation on the wire and then reflows the solder that was previously deposited on the pads. The wires are then automatically routed from bond site to bond site in either an orthogonal or point-to-point fashion; this depends on the product design. The computer-controlled machine has a net wiring rate of greater than sixty wires per hour.

The wiring machine actually used in production was developed after elementary concepts were validated on three earlier experimental machines, which we call Models 1 through 3. Model 1 was useful in developing the basic soldering process, as well as in establishing wire configurations. It was also used to wire the first development-level TCM board. This simple machine was built around a tape-controlled x-y positioning system and two power supplies, which were used to power the solder tip. Although this machine had no provisions for automatic wire handling (wires were placed under the solder tip manually), it was sufficient to develop the basic solder-tip configuration, solder process, and early product design.

The purpose of Model 2 was to prove that automatic handling of pre-twisted wire was possible. This machine used a four-axis positioning system and had an air-cylinder-driven wire-handling head. The machine had no automatic control logic; all motions were controlled individually by switches on the control panel. The machine proved that "hands-off" wire loop formation, placement, and routing between bond sites was possible. It was designed and built by an equipment engineering group at IBM Poughkeepsie [5].

Model 2 was converted to Model 3 by connecting it to an IBM System/7 computer in order to provide the required automatic control logic. The System/7 was also capable of communicating with IBM's manufacturing data system so that wiring data could be automatically accessed. Model 3 was used to obtain quality engineering approval of the automatic wire-bonding process. It was also used to wire the first engineering-level boards.

The production use of twisted-pair wire in the manufacture of TCM boards necessitated a wiring machine more sophisticated than Model 3 in terms of speed, reliability, and capability. We refer to this machine as the Production Wire Bonder (PWB). Model 3 even required two persons to operate it. The PWB is five times as fast, is much more reliable, and requires only one person to operate. In addition to the machine control software and data supply system, the PWB system consists of four basic boxes: an IBM Series/1 Model 4955 Processor, an IBM 4979 Display Station, an IBM Model 4974 Printer, and the PWB itself.

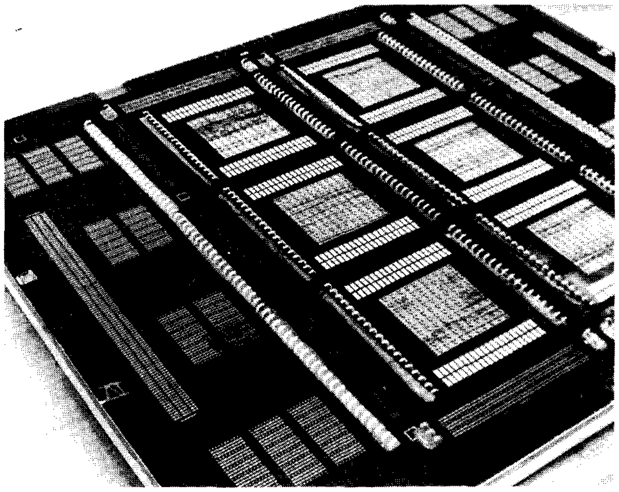

Figure 1 Six-module TCM board as used in the IBM 3081 processor models, showing discrete wiring changes.

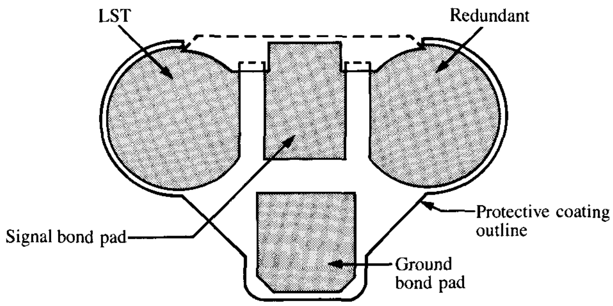

Figure 2 TCM board redundant bond pad printed-circuit configuration.

This paper provides a brief introduction to the TCM board and the methods by which additions and deletions (engineering changes) are accomplished. The workings of the PWB are then discussed in some detail, followed by a brief discussion of the control computer, the software, and the data supply system.

Engineering change methods

Board designs which utilize twisted-pair wire include at least one external wiring plane where overflow, engineering change (EC), and repair wires can be added. An example of a wiring plane of the type used in the IBM 3081 processor (six-module TCM board) is shown in Fig. 1. The wiring plane allows twisted-pair cables to be bonded to module, I/O, and terminating resistor locations by a solder-reflow technique. Two types of logic terminations appear here—double or *redundant*, and single or *nonredundant*.

The redundant external printed-circuit pattern consists of a logic service terminal (LST) via and a redundant via (Fig. 2). (Via is the term for a plated through-hole used to provide

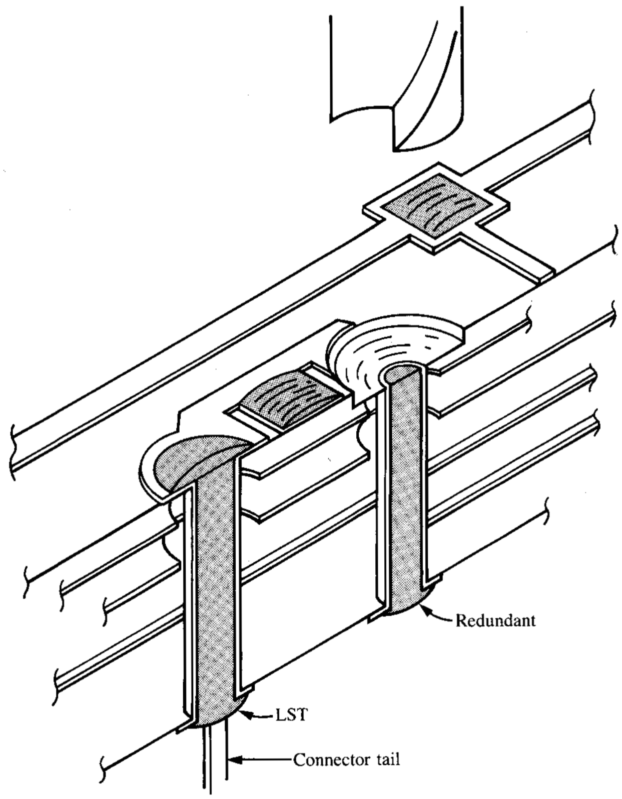

Figure 3 Cross section of TCM board showing redundant bond pad printed-circuit configuration with deleted logic service terminal (LST).

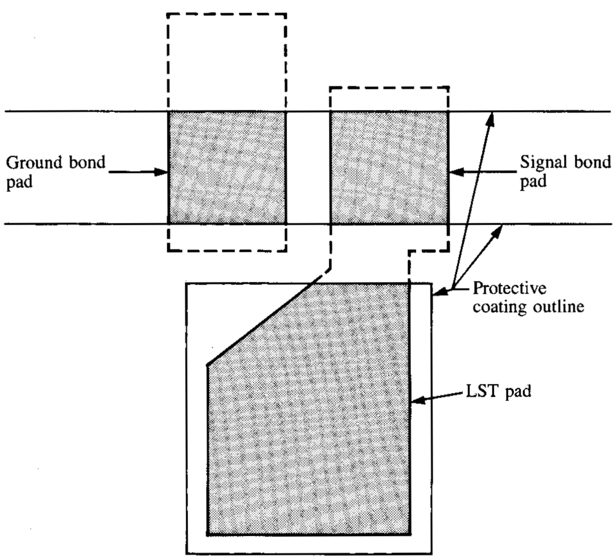

Figure 4 TCM board nonredundant bond pad printed-circuit configuration.

electrical interconnections between layers of a printed-circuit board; see Fig. 3.) An interconnection includes the signal bond pad where a signal wire can be connected.

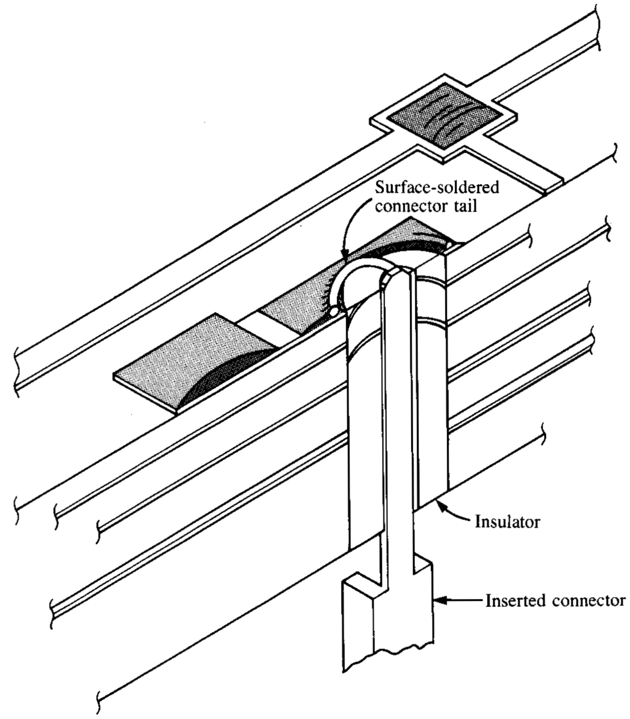

Figure 5 Cross section of TCM board showing nonredundant bond pad printed-circuit configuration with a special insulated connector inserted and its tail soldered to the remaining, previously deleted, LST.

Opposite the signal bond pad, and electrically isolated from it, is the ground bond pad, which is used to connect the ground wire of the twisted-pair cable.

The purpose of the redundant via concept is to facilitate the deletion of internal board printed-circuit lines from the LST and wiring plane side of the board by surface techniques. Deletion is accomplished simply by the use of an end-mill to remove the redundant via surface area (land). When deletions are made, the internal printed circuitry and any overflow wire that might be bonded to the signal bond pad are eliminated from the LST connector (Fig. 3).

The nonredundant external circuit pattern consists solely of an LST and its signal/ground bond pads (Fig. 4). Although this can reduce the number of holes that must be drilled in a multi-layer printed-circuit board to make engineering changes, it complicates the EC process. Here, a deletion is accomplished by drilling out both the LST and its connector, thus removing the electrical continuity between the internal printed circuitry and the external wiring pattern. A special insulated connector is then epoxied into the drilled-out pattern and its "wire tail" is soldered to the external land. As a result, any overflow wire bonded to the signal bond pad is electrically continuous with the board connector (Fig. 5).

Production Wire Bonder

Figure 6 shows the mechanical portion of the machine, which consists primarily of a four-axis positioning system and a bonding head. The printed-circuit board to be wired is located on a table which moves horizontally (y axis) and vertically (z axis). The twisted-pair wire spool and tension-control system are mounted on top of a carriage that moves horizontally in the x direction. A spindle, which also is mounted to the carriage, holds the bonding head and moves rotationally (angle θ). Also attached to the carriage is a microscope for inspecting the wire bonds as they are made and for making maintenance head adjustments.

The positioning system, except for the drive, was designed by IBM especially for the wire bond application. The electronics connecting the machine and the control computer are packaged in four IBM System/7 gates located on the left end of the machine. The primary function of the interconnect electronics is to multiplex the various data (position, solder tip voltage and current, wire length, etc.) coming from or going to the control computer. The bonding power supplies which drive the solder tip are located behind the x axis to minimize cable lengths between the supplies and the tip.

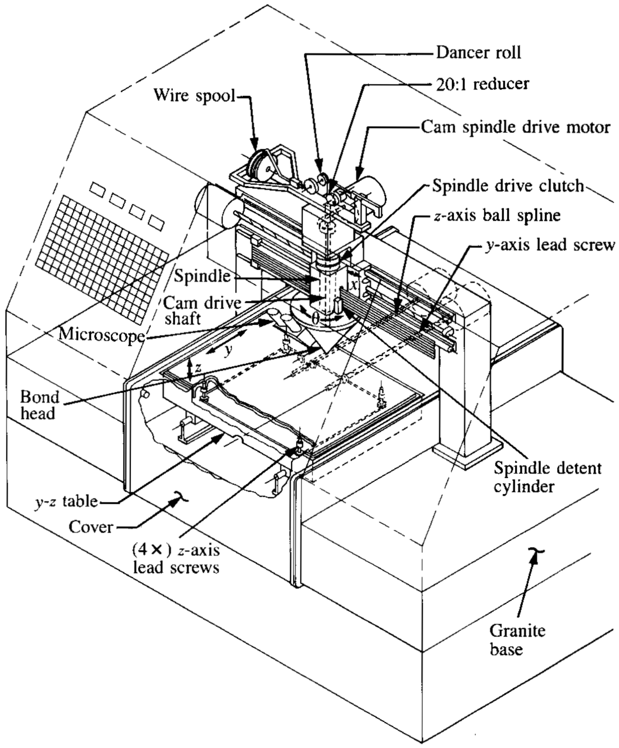

Figure 6 Isometric drawing of the Production Wire Bonder.

Bonding and routing sequence

To install a wire, the bonding head forms a loop in the wire while the positioning system drives the head to the initial bond site. The board is then driven up and the initial bond is made. After this, the board is lowered and the positioning system moves (x, y, and θ) to route the wires around the wire guides (in the case of orthogonal wires) to the terminal bond site where the bonding process is repeated. The wire is then cut off and the board is lowered to complete the single wire cycle. See Fig. 7 for a close-up picture illustrating the result of bonding and routing wires. The machine also has the capability of making any number of intermediate or stitch bonds along the wire before it is cut.

The preceding sequence description is a simplified overview; many process and machine checks and functions that actually occur have not been mentioned. The most important of these are discussed in some detail in subsequent sections.

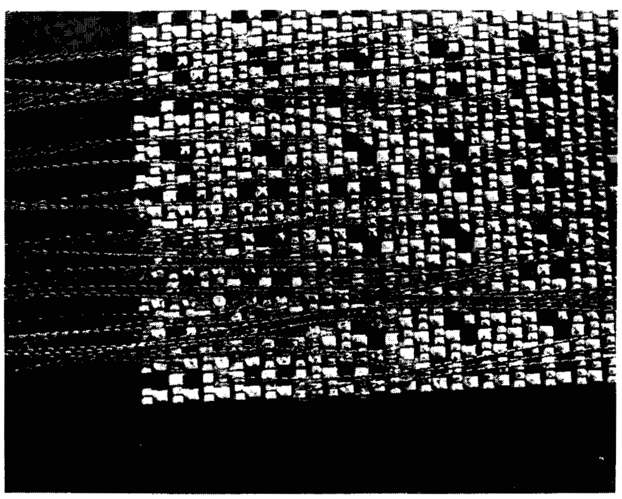

Figure 7 Close-up of TCM board showing examples of routed wires.

Positioning system

Though less convenient from an operator's point of view, it was decided to use a *split-axis* (y on table, x on head) rather than a *piggyback* (x and y on table) approach to minimize positioning inertia. High point-to-point speed was the primary positioning system requirement. Secondary needs for moderate accuracy and ease of set-up were also more easily met by the split-axis approach.

The drive for the positioning system is a commercially available four-axis open-loop stepping motor system. An open-loop stepping system was chosen because it cost less than an equivalent dc servosystem and also because of known maintenance problems that were associated with dc drives and encoders. The drive system consists of a four-axis logic unit, two double-axis translators, and four stepping motors.

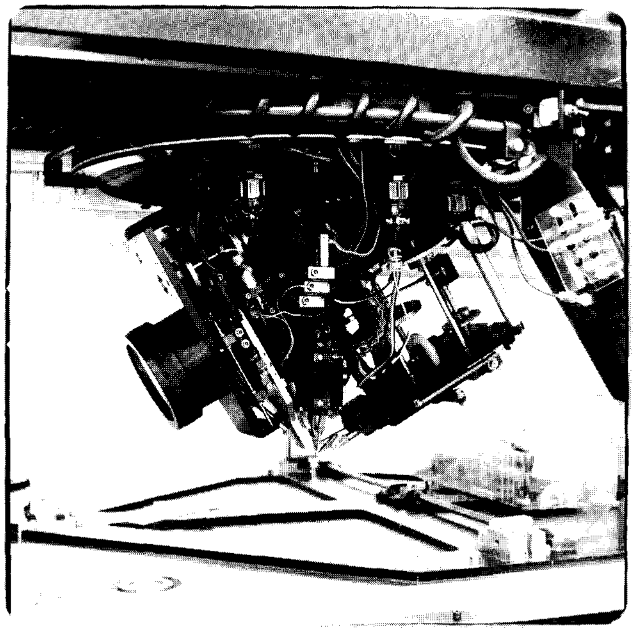

Figure 8 Close-up view of bond head.

Three of the stepping motors drive the x, y, and z axes by means of precision ball screws. The fourth stepping motor either rotates the bonding head as a unit or selectively drives the wire handling tools on the head by means of a clutch and detent arrangement.

Each stepping motor has a simple encoder attached to its shaft which produces an electrical signal when the motor is in the *home* position. The signal is used not only to home the machine after power-on, but also to check periodically that positioning integrity has been maintained during processing. After each wire has been completed, each stepping motor is driven to where its nearest home position should be. If a home signal is not obtained from a motor, positioning integrity on that particular axis has been lost and a search routine is initiated. The motor is driven back ten steps and then driven forward twenty steps, one step at a time, checking for the home signal after each step. If the home signal is found, position integrity has been re-established and board wiring continues. If the home signal is not found, the operator is required to re-home the machine as if the power has just been turned on. This re-establishes a starting point for the open-loop system.

• *Length-measuring tension-control system*

A system for measuring the wire length was required because certain external wires are used in timing circuits and the length of these critical wires must be controlled closely. A system for controlling the tension was also required to minimize and stabilize wire tension in order to make the wires less susceptible to damage during handling.

When the wire is pulled out of the bonding head (described in the next section), it turns the wire-measurement wheel attached to an encoder that emits one pulse per millimeter of wire. These pulses are amplified and drive the step motor and drive wheel, which in turn drive the wire at a rate of 1.04 mm per pulse. This ensures that the loop of wire over the dancer roll always gets longer when the motor is running.

The drive wheel pulls wire from the wire spool by means of a low-inertia rotating wire bale. The wire spool is kept stationary to prevent wire damage due to table acceleration and to facilitate an electrical connection to the buried end of its wire (the importance of this is explained later).

• *Bonding head*

In contrast to Model 3, all the wire-handling tools on the bonding head are cam-driven except for the cut-off blades. Although difficult to package and limited in versatility, a cam drive was chosen to achieve the high speeds and reliability desired. In order to provide selectivity and impact action, the cut-off blades are driven by small solenoids. Three other solenoids on the head also provide selectivity by driving interposers which lock out certain motions. Two of these solenoids are necessary to program the slight differences in tool motions required to make initial, terminal, and stitch bonds. The third is used to orient the loop of wire so that the ground and signal wires will be bonded to the correct pads.

Figure 8 is a photograph of the bonding head. Figure 9 is a drawing of the various cam-driven tools on the bonding head shown in their relative positions as they would be just after completing a wire. The motions of each tool are indicated by the arrows.

As shown in the sketch, the twisted-pair wire exits from the head through the wire-tracking feed clamp. The functions of this device are to route the wire between bond sites, to keep track of individual ground and signal wires, to untwist a short section of the wire to form a loop, to flip the loop 180° if necessary to orient the wire (this flip may be locked out by actuating one of the head solenoids), and to aid in the cut-off operation at a terminal bond site by pulling back on the wire after the cut. This motion is locked out during the initial bond and on stitch bonds by another head solenoid.

Keeping track of the ground and signal wires to allow automatic orientation of the loop was one of the major challenges in the design of the production wire bonder. By designing the tracking feed such that the tracking pins engage the twisted-pair wire much as a sprocket engages a chain [6], it is possible to clamp the wire so that for a given wire spool the ground and signal wires are always on the same side. This allows automatic orientation of the pre-twisted wire after the operator identifies to the machine (by means of a push button) which way the wire has been loaded through the tracking feed.

Referring again to Fig. 9, the functions of the receive clamp jaws are to grip the wire so that a loop may be formed and also to aid in the initial cut-off operation by pulling back on the wire after the cut. This pull-off is prevented on terminal and stitch bonds by the third head solenoid. After the initial cut, the jaws also place the small piece of generated scrap wire into the vacuum-operated scrap removal tube.

The probe *stabs* the loop and locates it accurately on the circuit board bond pads. The resistance-heated solder tip provides the energy to displace the insulation on the wire and reflow the solder on the bond pads. The solder tip also holds the wires in place during solder solidification.

The initial cut-off blade severs the wire on the receive clamp side of the bond after an initial bond is made. The terminal cut-off blade severs the wire on the feed clamp side of the bond after the terminal bond is made. The design of the cut-off blade system was complicated by the requirement for cutting at least halfway through the 0.089-mm-diameter wires without damaging the circuitry underneath. Further complicating the design was the fact that the solder surrounding the wires, which also had to be cut through, was highly variable in volume. This meant that the cut depth could not be controlled by simply controlling the blade driving force, because the energy absorbed by the cut-off operation was variable (solder variation). A positive stop for the cut-off blades was needed, and it had to be referenced to the board surface close to the cut since the flatness of the board was specified to no better than 1 mm maximum.

Due to the uneven topography of the board surface near the bond pads, the solder tip resting on top of the wires after bonding was found to be the most accurate height reference for the cut-off stops. The cut-off blades are now located in solenoid-driven blade holders in the head which slide in and are stopped by a surface on the probe. The probe is locked to the solder-tip holder during the cut-off operation so that the blade cut depth is controlled by the height of the solder tip.

As shown in Fig. 9, the function of the maze-penetration needles is to spread apart any wires which may be covering a bond site prior to bonding. The needles are mechanically constrained to move along their axes as shown by the arrows and are spring-loaded. After the loop has been formed, the needles are lowered simultaneously with the probe during loop stabbing to surround the loop, as shown in Fig. 10(b). Note that the end of the left needle is positioned lower and to the right of the end of the right needle (staggered). The reason for this will be explained later.

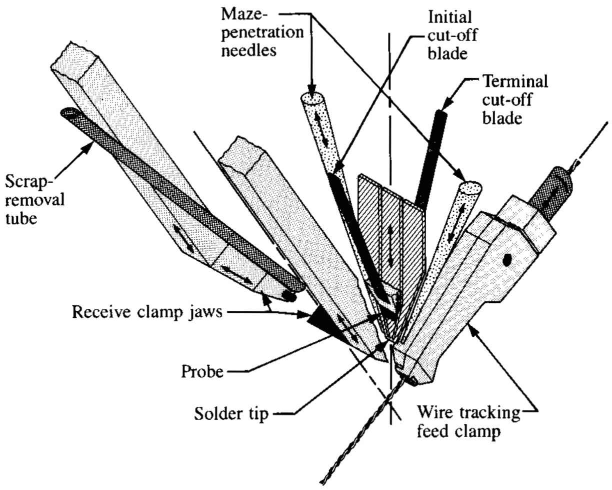

Figure 9 Schematic of the bond head tools. All tools are shown in home position. Their direction of motion is indicated by arrows.

The maze penetration is effected by driving the board up into the needles. The wires on the board are first contacted by the needles and move up along their sides to the left and right. The board then comes in contact with first the left and then the right needle, forcing the needles to move up along their axes. This further spreads the wires. When the maze-penetration operation is finished, the bond area looks like Fig. 10(c). Before the "staggered" configuration was conceived, the needles started at the same height before the board was driven up. With this configuration, many wires which fell directly under or between the points of the needles as the board was raised ended up between the needles when the maze-penetration operation was over. The staggered configuration [7] greatly reduces these failures because the central part of the swept area is swept twice, first by the left needle and then by the right.

Figures 10(a)–(f) show the head tools during various points in a complete initial bond sequence. Although some details have been omitted, Table 1 lists the major actions and checks performed for each part of the figure. Stitch and terminal bond sequences are similar.

Solder tip circuit

A schematic of the solder tip circuit is shown in Fig. 11. Two constant-voltage power supplies, which are computer-controlled for both pulse voltage and time, drive the solder tip. Two power supplies and a dual solder tip were required to adjust for the different heat-sink properties of the ground and signal pads. The power supplies were connected to the

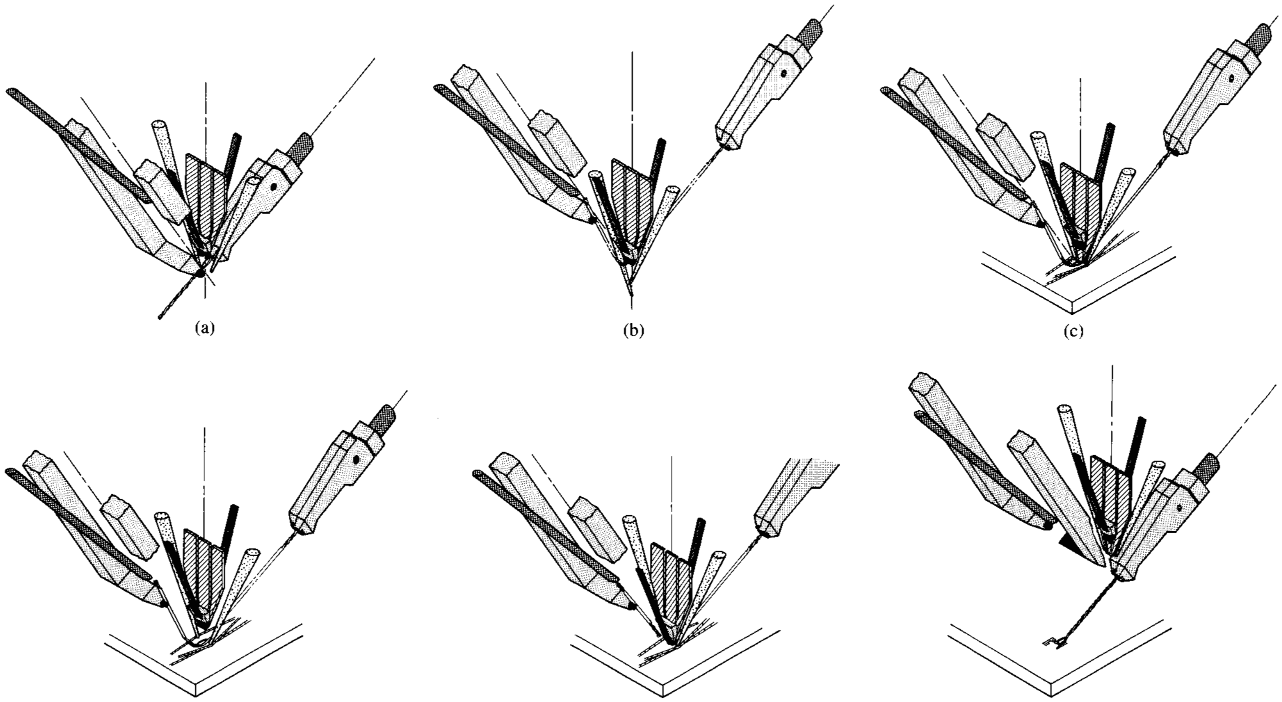

Figure 10 Bond head sequence. See Table 1 for a list of the major actions and checks performed before each point shown.

solder tip as shown in order to minimize current (and therefore minimize power losses in the trunkline) and power losses in the center leg (I_{center}).

Voltage sense lines are connected as close to the solder tip as possible. The power supplies control the commanded voltage at these points. Current monitors installed on the right and left legs, as shown, are used in process control and in determining the end of tip life. Current readings are taken a few milliseconds after the start of a pulse. Voltage readings are taken at the same time through voltage monitors that are also installed on each leg.

- *Ground bond check*

After every bond is made, an electrical test for a good connection between the ground wire and the ground pad is performed. Because of the difficulty in automatically testing for good ground bonds after the board is wired, this check is done during the wiring process. The test also serves as an in-process check for the machine.

To perform the test, one side of a very accurate digital ohmmeter is connected to the ground plane of the circuit board and the other side is connected to the buried end of the wire on the wire spool (see Fig. 12). After an initial bond is made, the resistance is automatically checked to ensure electrical continuity. At subsequent bond sites, the resistance is checked immediately before and after bonding. The reading just after bonding should be lower than the reading just before bonding because the length of twisted-pair wire between the last two bond sites should have been shorted out of the resistance path by the bond.

The system is also used to detect when the spool of wire is nearly empty by checking to see when the total resistance goes below a certain value. By stopping the machine before the spool runs out and the wire breaks, the new wire may be loaded by tying the wire from the old spool to the wire from the new spool and pulling the knot through the system.

- *Performance*

The table size of the machine is 870 × 616 mm. The machine travels maximum distances of 835 mm in the x direction, 582 mm in the y direction, and 28.5 mm in the z direction. The head is capable of rotating ±1.25 revolutions. The net wiring rate (includes all operator inspection times, machine and operator efficiencies, and machine availability) is greater than sixty wires per hour.

Control computer and software

As was mentioned earlier, in addition to the wiring machine itself, each wiring system includes a control computer, display station, printer, and associated software.

The interrupt-driven control computer with its software provides all the sequencing logic for the wiring machine

Table 1 Summary of major actions and checks performed for points (a) through (f) shown in Fig. 10.

Figure part	*Actions and checks*
(a)	1) Feed clamp jaws grip wire. 2) Receive clamp jaws move down and grip wire. 3) Feed clamp rotates 1½ turns to form loop. 4) Receive clamp jaws open slightly and loop is flipped 180° if necessary for proper orientation.
(b)	1) Probe stabs loop. 2) Maze penetration needles move down to surround loop. 3) Receive clamp and feed clamp retract.
(c)	1) Board moves up and maze is penetrated. 2) Probe is retracted off board. 3) Solder tip is pulsed to bond wires. 4) Tip is left down on board sufficiently to allow solder to solidify.
(d)	1) Solder tip moves up off board. 2) Ground bond check is made. 3) Machine is stopped to allow operator to inspect bonds visually through microscope.
(e)	1) Solder tip is lowered onto bonded wires. 2) Loop probe is lowered to a fixed position with respect to solder tip. 3) Initial cut-off blade is actuated. 4) Receive clamp jaws pull off wire scrap.
(f)	1) Receive clamp jaws open to allow vacuum to remove wire scrap. 2) Probe, solder tip, and maze needles retract. 3) Solder tip is pulsed clean. 4) Board is lowered to route height. 5) Board is moved away from feed clamp as feed clamp is driven forward. Wire is now routed to the next bond site with the head in this position and the board at this elevation.

when it is running in the automatic mode. It drives all the actuators almost directly; the machine interconnect logic only decodes the multiplexed signals from the computer and transfers them to the proper actuators.

The control computer also provides interlock functions when the machine is being cycled in manual mode from the control panel for maintenance and debugging. All the control panel inputs are fed to the computer; the computer in turn drives each actuator as it does in automatic mode. This makes it possible for the computer to "track" the machine and to prevent "crashes" that would be caused by improper control panel inputs.

Another function of the control computer is to perform special computations for process checks. Some of these are the ground bond check, current and voltage checks, and positioning system checks.

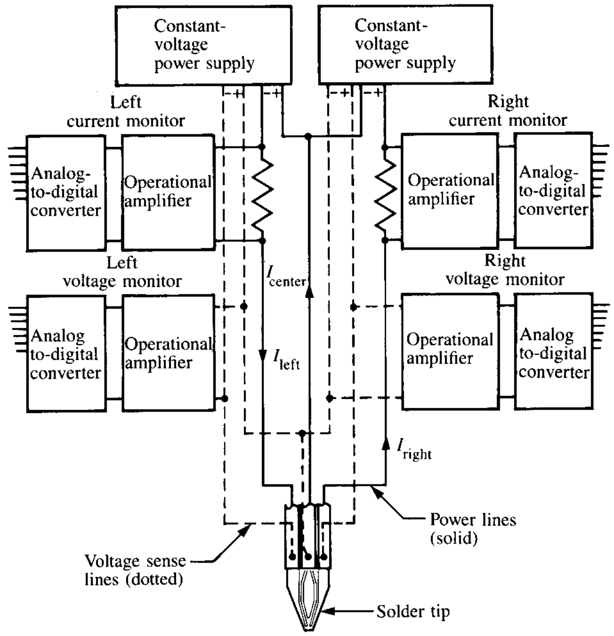

Figure 11 Solder tip circuit.

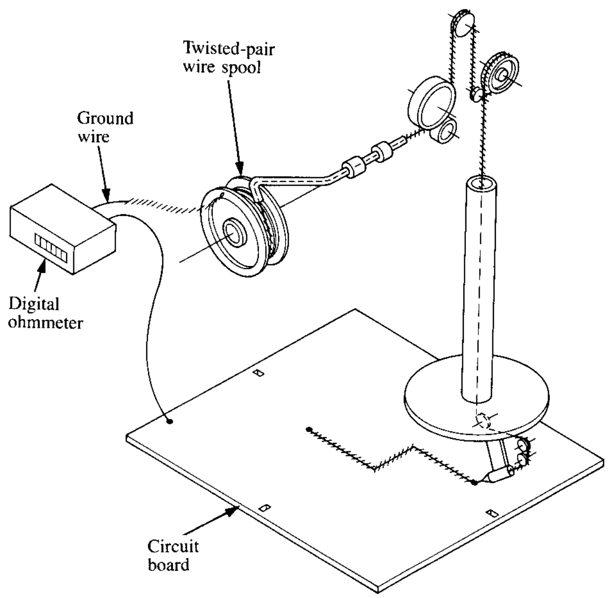

Figure 12 Ground bond check path.

The display station is an I/O device for the machine operator. For example, the operator can call in the control program for the machine and wiring data for a specific board by means of the keyboard on the display station. Messages and data for the operator are displayed and the printer is used if a hard copy of the displayed data is needed.

Data generation system

The primary function of the data generation system is to merge all the data for the different types of wires (overflow, engineering change, and repair) into one data set for a particular board. The data which come into the data generation system describe the endpoints and turning points for the routing of two-pin connections, overflow wires, and EC wires. These data also contain endpoints and turning points for routing discrete wires that are equivalent to every printed-circuit line in the board. The latter are used by the data generation program when a printed-circuit line is found to be defective and must be replaced with a discrete wire. Therefore, in order to do a merge, the data generation program must have information common to all boards of a particular EC level plus information unique to a particular board (test and analysis data).

The output of the data generation system is a set of "commands" for each wire that may be accessed automatically by the wire bond operator: initial bond, terminal bond, stitch bond, channel entry, channel move, and wire length. Essentially, a command is required for each leg of an orthogonally routed wire. That command specifies the desired x, y, and spindle positions, pad orientation, bond schedules (for bond commands), wire lengths, and whether or not the wire lengths are critical.

Conclusion

Although the manufacturing technology described in this paper is the most sophisticated known to the authors for installing twisted-pair wires on printed-circuit boards, many areas still need to be addressed to extend the technology and make full automation possible. Perhaps the most basic problem preventing full automation is the dimensional variation in the tips as they are manufactured and as they wear during processing. This results in variations in the bond temperature, which makes it necessary for the operator to view the bonds and to make heat adjustments after tips are changed and during processing.

Other areas which should be addressed in order to make the process more automatable are detection of maze-penetration failure and the control of wire twisting. A maze-penetration-failure detection scheme is needed to stop the machine if a failure occurs. More consistent wire twisting is needed to prevent erratic loop formation and "stabbing" failures.

Acknowledgments

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