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Large Multi-Layer Panel-Drilling System

This paper describes the mechanical, electrical, and control features of an advanced four-station, twelve-spindle, large printed-circuit panel-drilling system. The system was designed as a production tool to produce over 35 000 0.4-mm-diameter holes in a panel containing twenty layers of copper and nineteen layers of epoxy glass. Built around a precision four-station x-y positioning system with three motor-driven spindles over each work station, the system includes a minicomputer, a printer, a display station, and a controller/interface station. Drilling parameters, such as infeed, outfeed, top of stroke, bottom of stroke, and spindle revolution rates, are all computer-controlled.

Introduction

The mass-production of IBM's thermal conduction module (TCM) board [1] for use in the 3081 processor models required the development of a drilling system with orders-of-magnitude-improved accuracy and reliability. The TCM board is a large (610 mm × 710 mm), highly integrated multi-layered printed-circuit panel consisting of twenty layers of copper and nineteen layers of epoxy glass, that contains a large number of tightly spaced, high-aspect-ratio (panel thickness to hole diameter equals 11:1, see Fig. 1) holes for inter-layer circuit connections. The equipment had to be capable of drilling approximately 35 000 0.4-mm-diameter variable-stroke-length holes per panel and operating in a three-shifts-per-day manufacturing environment.

The control specification S_C for the location of a drilled hole is given by $|\overline{X}_F| + 3\sigma_F \leq S_C$, where $|\overline{X}|$ is the absolute value of the mean error for drilled holes measured on the top side of the panel and σ_F is the standard deviation for the location data for these same drilled holes. This specification can be met by following sound machine design principles. These include 1) the use of air bearings for support and guidance on rigid, lapped-granite surfaces; 2) the use of materials with similar temperature coefficients of expansion to minimize the influence of temperature; and 3) the reduction, to the extent possible, of all sources of heat [2].

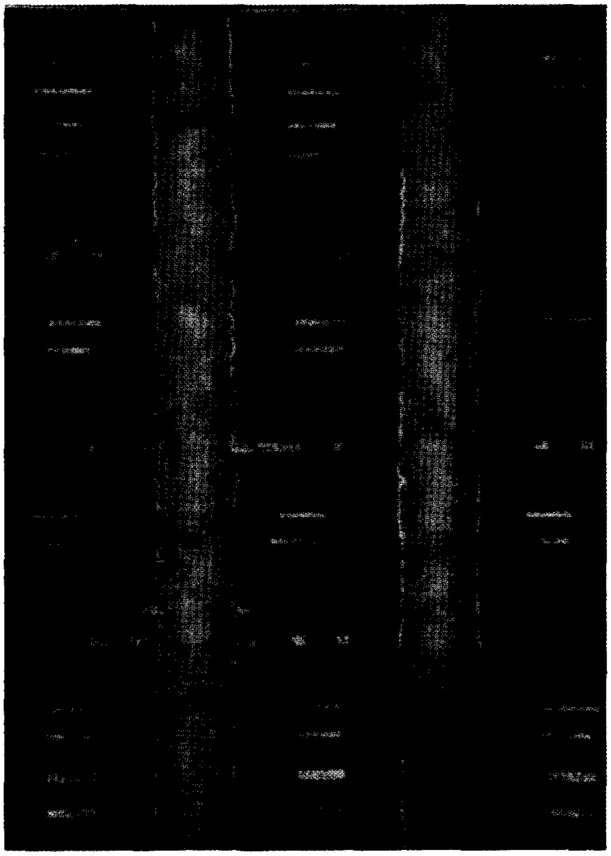

Figure 1 Cross section of drilled holes after plating, showing the high aspect ratio of panel thickness (hole depth) to hole diameter and the smoothness of the hole sidewalls.

Previous experience had shown that the heat generated by electric-motor-driven spindles was the most significant contributor to errors in the location of drilled holes, especially in

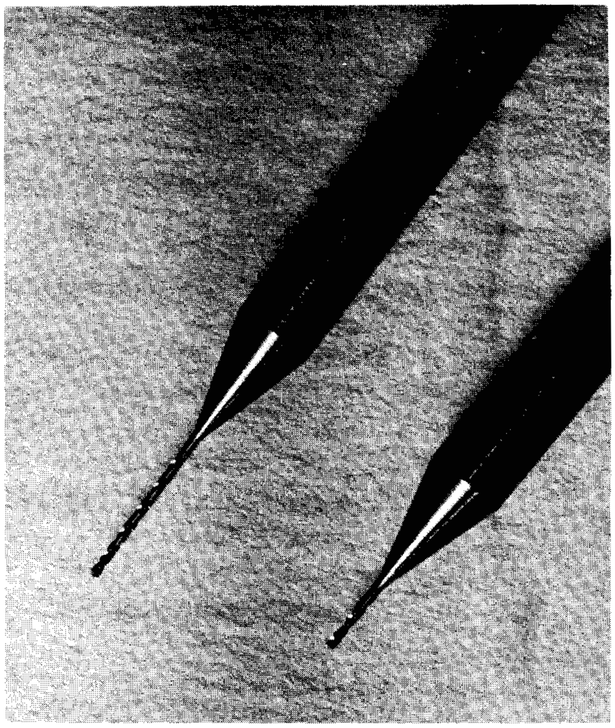

Figure 2 Sample drill bits for drilling 0.4-mm-diameter holes. The center drill (short flute) has a 0.381-mm diameter and is used to start the hole. The through-hole drill (longer flute) has a 0.406-mm diameter and is used to complete the drilling process.

multiple-spindle machines. Air-driven spindles can essentially eliminate thermally induced spindle movement; however, early experiments with suitable air-turbine spindles proved that it was not possible to maintain a constant bite when drilling high-aspect-ratio holes, especially at a variable hit rate. The bite is defined as the ratio of the spindle advance in centimeters per minute to the rotation speed of the spindle in revolutions per minute (rpm).

System design considerations

Three main considerations for the system design included drilling accuracy, system throughput, and system reliability. The specification for a drilled hole in the product S_P is

$$|\bar{X}_F| + 3[\sigma_F^2 + \sigma_W^2]^{1/2} \le S_P,$$

where σ_W is the standard deviation of the *drill wander*, as obtained by measuring the same holes on the back of the panel [3]. In order to meet the requirements for drill wander with an aspect ratio of 11:1, it is necessary to drill a panel in two steps. A drill with a short flute is used to start the hole and a drill with a longer flute is used to complete the drilling process [4]. Sample drill bits are shown in Fig. 2.

In order to optimize the product throughput, the number of drills in use must be maximized, while the machine cycle time must be minimized. The first requirement suggests that one place as many strategically located spindles on a machine as possible without compromising the machine accuracy. The second requirement is a little more involved. Machine cycle time is the sum of the z-axis infeed time, the z-axis dwell and withdrawal times, and the x-y move time. The z-axis infeed time is determined by the feed rate and spindle revolution rate that produce the highest-quality drilled hole. The quality of a drilled hole in a multi-layer panel is highest when there is no epoxy smear, no nail heading, no sidewall roughness, and no fracture of the glass fibers [5]. Thus, the z-axis infeed time is determined wholly by the process. The only alternative left open is to place emphasis on minimizing the remaining variables by using high-speed drive mechanisms in both the x and y axes while also providing for high-speed withdrawal in the z axis. The last not only saves machine cycle time but also reduces the amount of heat generated by the drill bit during the drilling process.

Another consideration for obtaining the maximum product throughput is to minimize fallout due to operator error. Historically, in multiple-product environments, adjustments were necessary to the feed rate, the spindle rotation rate, and in some cases, the position of the drilling heads, for the drill bits to clear both the product and the locating pins at the top-of-the-stroke position. These adjustments were made manually by each individual operator, thereby increasing the risk of improper adjustment and, as a result, possible panel damage or impairment of the quality of the drilled holes. The solution was to place all drill parameters under computer control and to track parts and processes with product-dependent part numbers.

There are several factors involved in system reliability. One is wear resistance of the materials used in the drive mechanisms. Another is mechanical or mechanically induced failure of the electronically controlled positioning systems. This must be virtually eliminated by careful selection of materials and components and through sound design practices. A third factor is the accuracy of communication between the controller and the machine. Drilling machines usually operate in a manufacturing area where power distribution lines are noisy. This can interfere with both machine performance and data transmission. A solution is to use computer-controlled in-process checks that can monitor important areas, such as the accuracy of axial positioning or the environmental conditions, and then to stop the machine and alert the operator if any operating limits are exceeded.

Design concepts for the drilling machine

One approach to the design of a machine that must drill over 35 000 holes in a 610-mm × 710-mm panel is to use a large number (perhaps 40 to 60) of individually programmable spindles on a single station. The mounting arrangement should offer the ability to fine-tune each spindle location in both the x and y directions (a difficult task, since data on the locations of the drilled holes do not always agree perfectly with measured data on the locations of the spindles). This approach offers the highest risk for error in the locations of the drilled holes because of the influence of heat generated by the spindle motors.

A second approach is to use clusters of, e.g., four, eight, or twelve spindles per station in a multiple-station design. A clustered-spindle arrangement offers an advantage in spindle utilization, provided the spindles can be packaged sufficiently close to allow simultaneous drilling in a module site where the density of holes is very high. Again, it is desirable to be able to adjust the location of the spindles for the reason mentioned earlier. The influence of heat on spindle-to-spindle dimensions still remains a concern; however, it should be more manageable because of the shorter distances between the spindles within a station.

A third possibility is to use a number of individual spindles spaced at intervals equal to the distance between module sites on a panel in a multiple-station design. One major advantage of this design is that spindles can be precisely located within a station. Thermally induced movement can be minimized by cooling each spindle assembly to prevent the heat generated by a spindle motor from penetrating the surface on which the spindles are mounted. A second advantage is that a z-axis drive that is controlled by a servomotor can be used with individual spindles. This type of drive appears to be the most versatile for drilling a panel with module sites densely populated with holes. This is because it can be made completely programmable for handling stroke-length differences between the center and through-hole drilling operations, and for varying the infeed rates as required for the diverse product mix.

System configuration

A combination of computer and microprocessor control was chosen to obtain optimal performance, with three or more drilling machines operated by a single computer. The configuration of the drilling system, shown in Fig. 3, consists of an IBM Series/1 (S/1) computer, a controller interface, and the drilling machine. Communication with a host IBM System/370 is through a sensor-based communications adapter (SBCA). A display terminal is used to select the product-dependent part numbers, to display operator-requested information, e.g., parameter checks, and to facilitate the use of special maintenance routines used to debug and calibrate various portions of the drilling machine. By entering a part number, the file of hole-location data is sent from the host to the S/1 diskette for storage and drilling use. The printer is used to record data related to x- and y-axis machine performance.

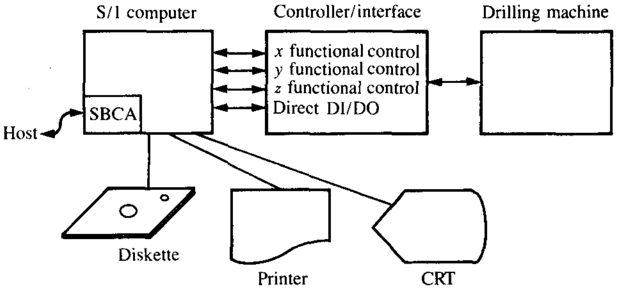

Figure 3 *Drilling system configuration.* The host computer supplies x-y hole-positioning data through the SBCA (sensor-based communications adapter) to the S/1 (IBM Series/1 computer) on the request of an operator entry at the display keyboard. The S/1 saves the data on its own disk and controls the drilling machine operation through the controlled/interface logic. (Note: DI = digital input, DO = digital output.)

Table 1 Main functions of the x- and y-axis and the z-axis functional controllers.

x- and y-axis	*z-axis*
Home position	Perform normal drill cycle
Perform move	Move up to park from top of stroke
Verify move	Move down to top of stroke from park
Start slew jog	
Stop slew jog	
Transfer axis-oscillation error	

The controller/interface contains the functional controllers of the x, y, and z axes, and handles direct digital input and output (DI/DO) information from the operator control panel, the drilling machine, and the S/1 computer. Direct DI/DO includes control switches, non-hardwired indicators, x-, y-, and z-axis limit switches, and x- and y-axis display feedback. The computer manages the functional controllers, handles interrupts, and communicates with peripheral equipment attached to the system. The main functions of the three functional controllers are listed in Table 1; the x-axis and y-axis functional controllers have similar functions and are therefore combined in one column. A photograph of the entire drilling system is shown in Fig. 4.

Throughput design

The drilling machine design consists of a four-station split-axis x-y positioning system with three spindles at each station. Individual, rather than clustered, spindles were chosen so that they could be precisely located over individual module sites on the TCM panel to achieve the maximum accuracy in the location of the drilled hole and reasonably high spindle utilization. Each spindle housing has a cooling labyrinth to minimize thermally induced spindle movement.

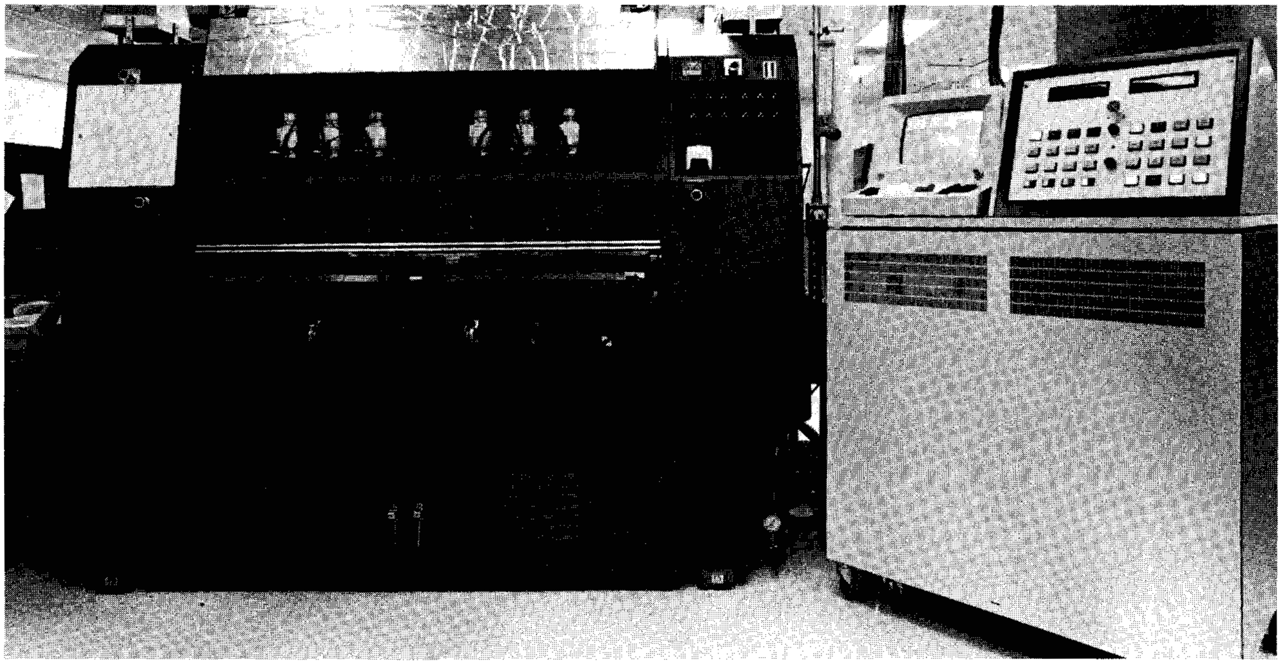

Figure 4 Photograph of the entire production drilling system.

The number of spindles in a station and the number of stations were chosen to meet the base capacity (BC) requirements for throughput,

$$BC = \frac{N_d}{N_c}\left(\frac{1}{t_m}\right),$$

where N_d is the number of drills drilling, N_c is the number of drilling cycles per panel, and t_m is the machine cycle time; N_d is just the product of the spindle utilization, the number of spindles in a station, and the number of stations in the machine, and t_m is equal to the sum of the x- and y-axis move times and the actual drill cycle time, which includes the z-axis infeed, dwell, and outfeed times.

Positioning mechanism

The influence of N_d and t_m on the base capacity for one type of TCM panel is shown in Fig. 5. The machine is constructed from commercially available precision components. Four TCM panels are held by vacuum chucks mounted on a table that moves in the y direction. The table is supported and guided on a granite base that weighs approximately 600 kg. The base also supports, on steel box castings, a granite beam on which a slide moves orthogonally to the direction of table travel. The twelve spindle housings are mounted on the slide, which is guided along the beam. Both the slide and the table are driven by a lead screw, the force of which is directed at the center of gravity of the moving mass. Each axis has a closed-loop positioning system that uses a dc drive motor with an integral dc tachometer-generator and a glass scale with 125 lines per millimeter for feedback. The output of each scale encoder is electronically subdivided to provide a resolution of 1.0 μm. The x-axis beam and y-axis guiding rail were made substantially wide. Large air bearings were used to obtain the dynamic stability necessary for a machine in which two complete move-and-drill cycles must occur in one second.

The measured performance of the machine indicates that each axis will accelerate to >5 m/min and will stop within a distance as short as 3 μm in 0.15 s. The high-speed performance of the positioning system is achieved through the use of hollow-rotor, low-inertia dc servomotors and a stop algorithm tailored to the physical characteristics of each axis. The algorithm is a programmed deceleration or list of voltage levels that is supplied to each amplifier for the servomotor as a function of the *to*-position distance. Maximum drive voltage is applied to the motor at the start of a move and is reduced to different optimum levels, starting at 2 mm from the desired stop position. The purpose of the programmed deceleration is to minimize the time required to make an accurate stop.

Drilling mechanism

Each drilling head consists of an air-bearing spindle capable of 90 000 rpm and a dc servomotor-driven lead screw

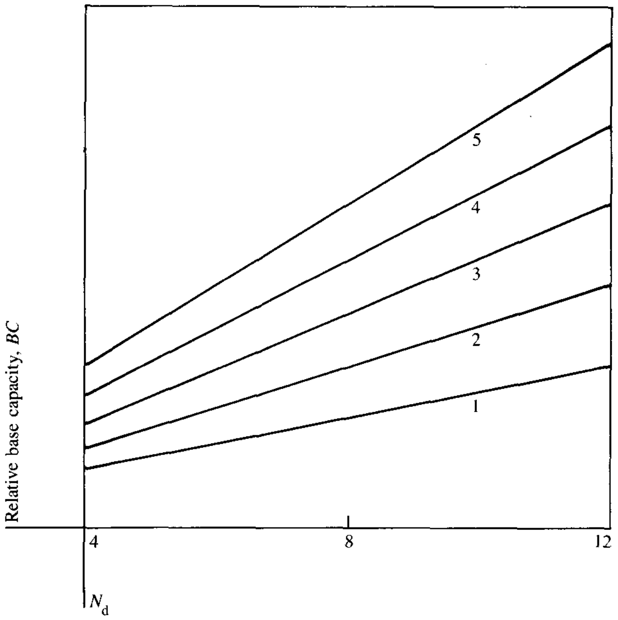

Figure 5 Relative base capacity BC plotted against N_d, the number of drills used for a series of machine cycle times t_m. Curves 1–5 represent increasing cycle times from 1 to 3 drilling cycles per second (cps) in 0.5-cps increments.

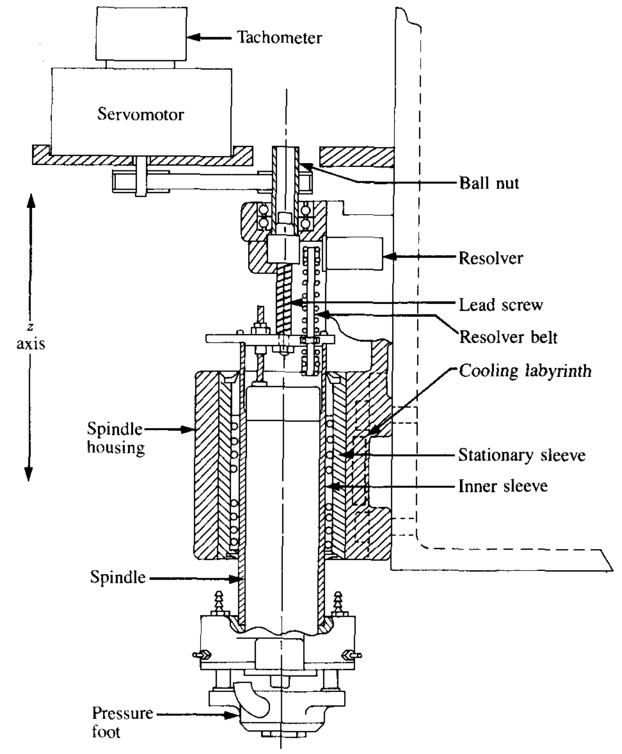

Figure 6 Illustration of a single spindle housing assembly.

arrangement that is completely programmable in the z direction. Drilling parameters such as infeed rate, dwell time, outfeed rate, top-of-stroke and bottom-of-stroke positions, and spindle speed are all controlled by the computer, and are selected via a product-dependent part number. The spindle is held in a sleeve that is guided inside a second stationary sleeve by a ball cage (see Fig. 6). The dual sleeve assembly is contained in a spindle housing that is secured to a mounting plate located on the x-axis slide. One end of a small lead screw is attached to the inner sleeve containing the spindle. During a drilling cycle, vertical motion of the spindle results when the servomotor rotates the lead screw ball nut. Depth control of the drill is provided by feedback from a resolver coupled to the spindle.

Operation

Machine alignment is accomplished by first ascertaining that the x- and y-axis positioning systems are within specification by using a laser interferometer for measurement. The spindles can now be adjusted by using the position feedback counters on the controller/interface, together with an electronic indicator capable of 1-μm resolution. After a warm-up cycle, the spindles are adjusted in the y direction by using precision spacers to achieve the desired location accuracy within a station. Measurements are made with the electronic gauge head placed on a precision pin that is held in the nose of each spindle.

Next, a spindle that has been selected for reference in each station is adjusted in the x direction to a fixed position with respect to the x-axis home position. The other two spindles are adjusted to the proper spacing by using the x-axis jog control, position counter, and electronic indicator. Corrections are made by loosening the bolts that secure the spindle housing to the station mounting plate and carefully moving the spindle assembly to the left or right to achieve the desired location accuracy within a station. All adjustments are made with the spindles lowered on precision blocks to maintain spindle-to-table perpendicularity. Panel locating pins are secured by keepers mounted directly on the table. Mounting holes for the keepers are drilled by the reference spindle at each station by selecting a part number from the keyboard and manually stepping through the program. After the vacuum chucks are installed, engineering boards are drilled and measured, and data on the drilled hole location are evaluated statistically to verify that the system is ready for a production-run start-up.

Drilling system performance

Systematic errors in the locations of drilled holes are related to machine accuracy, spindle location, and tooling (i.e., precise TCM board mounting on moving y-table) location. Random errors are due to drill-bit starting errors, repeatability errors of the positioning system, and the influence of glass

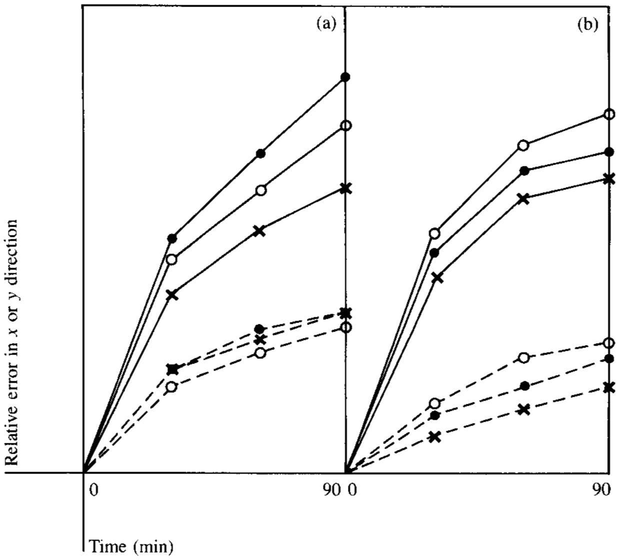

Figure 7 Relative drilled-hole location errors in the (a) x and (b) y directions, with (---) and without (—) air supplied to the labyrinth. Data are for spindles 1 (●), 2 (○), and 3 (×), where each data point represents the average of twenty drilled holes.

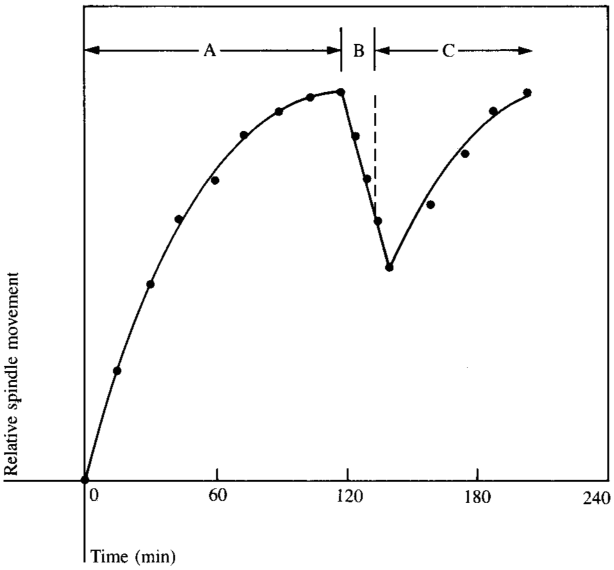

Figure 8 Relative spindle movement in the y direction as a function of time. The spindle speed was 85 000 revolutions per minute. For the intervals A and C indicated, the spindle was on; for interval B, the spindle was off.

fibers on the path of the drill bit as it travels through the panel. Spindle movement due to heat will result in a change in both the $\overline{X}$ and σ values for the drilled-hole location data if drilling occurs during a machine warm-up cycle.

An extensive set of experiments was used to determine 1) the amount of thermally induced spindle movement with and without air supplied to the cooling labyrinth in the spindle housing, and 2) the times required for the machine to reach thermal equilibrium, to explore methods for improvement, and to evaluate corrective action.

In one experiment, a test pattern was drilled under computer control immediately after powering the spindles on and at three subsequent half-hour intervals. The solid curves in Fig. 7 illustrate the relative errors in the hole location and the spindle-on time when no air was supplied to the cooling labyrinth. Heat transferred from the spindle motor through the spindle casting to the mounting plate results in spindle-to-spindle movement in the x direction. The smallest change in the x direction occurs in the spindle closest to the x-axis encoder. The largest change occurs in the spindle located farthest from the encoder, in a symmetrical pattern at all four stations. Movement in the y direction results from expansion of the various materials in the spindle assembly, including the steel sleeves and aluminum casting.

The dashed curves in Fig. 7 show the results of the same experiment when air is supplied to the cooling labyrinth in each spindle casting. The cooling labyrinth reduced the thermally induced spindle movement to one-half of the top-side drilled-hole accuracy and repeatability specification; however, two additional steps were taken to ensure performance well within the process window. Final spindle-location adjustments were completed by using actual drilled-hole location data and a spindle warm-up time was made part of the process specification.

Another important aspect of the thermal problem is related to spindle movement during the time in which the spindles are powered off for changing the drills, particularly since drills are changed many times during the center and through-hole drilling operations on a panel. Figure 8 illustrates how rapidly movement occurs in the y direction when the spindles are powered off. The curve shows that movement continues *after* the spindle is powered back on. Note also that the spindle must be operated four times longer than the power-off time before it again reaches thermal equilibrium. Spindle movement is negligible during the first five minutes the spindle is off. This presents no problem since the time required to change all twelve drill bits is approximately two minutes.

System reliability is very high due to the use of air bearings, the wear resistance of the lead screws, and the computer-controlled process parameters. Once the panels are loaded, the drills inserted in the spindles, and the part number entered from the keyboard, the only human intervention is for drill inspection and replacement. The machine stops after a predetermined number of cycles and a message appears on the display station instructing the operator to change the drills. In addition, the operator stops the machine and checks for broken drills every fifteen minutes. A broken drill is replaced and the operator continues with the drilling operation after recording the x-y address where the broken drill was found. Holes missed are drilled in a separate operation after the broken drill is removed from the panel.

The availability of the drilling system is approximately 90%. Down time for periodic maintenance or diagnostics is minimized with the aid of programmed utilities. A list of routines is displayed at the terminal on request, and the maintenance technician can select the desired routine by typing the routine number. The routines include x- or y-axis moves for calibration of the velocity, positioning time, and positioning accuracy, and z-axis moves for calibration of the drill stroke.

Summary

A mechanical drilling system for large printed circuit board panels which met the design objectives for drilled-hole accuracy, throughput, and reliability has been described. The advantages over previous large-panel drilling systems include improved accuracy in the location of drilled holes, computer control of the process parameters with product-dependent part-number control, automatic in-process checks, and programmed utilities for maintenance diagnostics. The system can efficiently drill a wide variety of part numbers because of the programmable servo-controlled z axis and the 1-μm resolution for positioning in both the x and y axes.

Acknowledgments

The author thanks his colleagues, in particular E. Bernardo and P. Gursky, for their competent technical assistance; T. Helfand and R. Memis for the design of software; H. Lin for the design and construction of the controller/interface; R. Austenfeld for his technical advice, cooperation, and data base management; and W. Lozier for his active and helpful participation during the early planning of the manufacturing system.

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Received January 7, 1981; revised December 20, 1982

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