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NONDESTRUCTIVE TESTING: TRENDS AND TECHNIQUES

Proceedings of the
Second Technology Status and Trends Symposium
Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

Few industrial functions have undergone so many significant technological changes in the last few years as has nondestructive testing. In addition to a large number of improvements in such traditional techniques as X-ray and ultrasonic testing, whole new approaches such as laminography have been proved out, and display systems have been substantially enhanced.

The activities of the National Aeronautics and Space Administration have led to a number of significant advances in nondestructive testing. Some of these advances were recently described in a symposium for industry at the NASA Marshall Space Flight Center. That symposium was an activity of the NASA Technology Utilization Program, which seeks to communicate rapidly to potential users the new knowledge generated by NASA research and development programs. Publication of the nine papers in this volume is an effort to communicate these technical advances to a broader audience.

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Nondestructive Testing Techniques for Multilayer Printed Wiring Boards

JAMES F. BLANCHE

One of the basic needs in the electronics field is for a high density interconnection technique that is compact, reliable, and will eliminate the possibility of human error in wiring. Point-to-point wiring of electronic assemblies introduces the possibility for human error with every wire connected, and the assembly often becomes a rat's nest of wires. Conventional single- and double-sided printed circuit cards will not allow compact interconnection of microelectronic circuits.

One obvious solution to the problem of high density interconnections is the multilayer printed circuit board. It allows very high interconnection density, and the interconnections are identical in all assemblies using any particular circuit; thus, much of the possibility of human error is eliminated. However, the reliability of this system is questionable because multilayer printed circuit boards are generally fabricated in such a way that the internal joints formed cannot be inspected. In the most widely used multilayer system a number of copper clad sheets bonded to an insulating material are etched with the appropriate circuit pattern. The layers are laminated, and holes are drilled through the laminated assembly at the points where interlayer connections are to be made, thus exposing the edge of the copper conductors at the appropriate level. The layers are then electrically connected by plating the wall of the hole with copper or by fusing an eyelet, tublet, or post into the hole. Optimum interconnection is achieved when 100 percent of the surface of the hole is covered with a prescribed minimum thickness of the conducting material and when the cylinder, thus formed, is interconnected with 100 percent of the intersecting area of the printed conductor at each layer. The problem of reliability arises in the inspection of the joints formed at the interface of the exposed edge of the printed conductors and the plated wall.

In the past, inspection has been made in several ways. One method has been to pass a high current through the joints on the theory that any poor joints will be burned out. However, this stress testing may create new marginal joints. Another technique has been to check continuity of the circuitry. This method will detect both open and short circuits but will tell little about the quality of the joints. Some manufacturers X-ray their multilayer circuit boards to determine how closely the layers are alined. The problem with this method, particularly on boards with dense circuitry, is that an internal layer tends to be masked by those layers above it.

A program was initiated to develop a nondestructive technique to inspect multilayer printed circuit boards. If possible, the technique was to be rapid and accurate and lend itself to mass testing. A number of techniques were examined for relative promise in fulfilling the requirements of this program. Some of them were:

Techniques Involving Heat.—Thermographic powder is applied to the surface of the board. Under ultraviolet light, the fluorescence of this powder decreases with increasing temperature and will, therefore, detect hot spots in the board. Detection of infrared or electromagnetic radiation in the millimeter range would also detect hot spots in the board. However, these techniques lose both sensitivity and resolution as the number of layers increases.

Eddy Current Technique.—Passing an ac current through a coil placed in a plated-through or eyelet hole will cause eddy current to flow in the metal on the sides of the hole. The fields of these eddy currents will in turn affect the electrical properties of the coil. By varying the frequency of the ac current and detecting the changes in the coil caused by the behavior of the eddy currents, it is possible to determine the characteristics of the joints. One of the detection systems used with the eddy current technique was selected for more detailed study.

Intermodulation Technique.—Currents of two different frequencies are passed through the printed wiring. Currents at intermodulation frequencies are then produced by any electrical nonlinearity. These intermodulation currents can easily be filtered out to detect even small nonlinearities. Attempts to detect a defect using an intermodulation technique were successful, but difficulties were encountered in reproducing test results and in pinpointing the defective connection.

E–Field Sensors.—Faults in printed wiring boards and plated-through holes may be found by the irregularities which they cause in the equipotential surfaces of the currents flowing through the wiring. Several probing techniques to detect irregularities were examined. Although they are theoretically workable, there are a number of practical difficulties that would limit their usefulness.

Radiography.—Neutron radiography was investigated, but resolution and contrast were of insufficient quality. Autoradiography might be used if the hole-plating material could be doped; however, the film would have to be inserted into the hole which is to be inspected. Electron microscopy is primarily limited to descriptions of surface characteristics. X-ray is basically limited by the masking effect of circuit layers above the layer being inspected. The most important result of these radiographic investigations was the discovery of a technique known as axial transverse laminography. Since it appeared to meet most of the nondestructive test requirements, this technique was chosen for detailed examination.

AXIAL TRANSVERSE LAMINOGRAPHY

Axial transverse laminography is a radiographic technique which permits examination of a thin section of a thick sample without physically sectioning the sample. The technique depends on smearing all unwanted images over a large area while the image of interest remains sharp throughout the exposure. This result is achieved by synchronously rotating the sample and the film during exposure. The system, which is shown schematically in figure 1, consists of a point X-ray source, a rotating test table which holds the sample to be inspected, and a rotating film table. The plane that will be inspected is geometrically defined by the system. This plane is located at the intersection of the main axis and rotary axis #1 and will be parallel to the film plane.

The laboratory setup is shown in figure 2. The low energy X-ray tube (25 keV silver K X-ray) is shown in the upper right-hand corner. The source diameter is approximately 0.03810 mm (0.0015 in.). The grid pattern shown on the film table is for vacuum hold-down of the film. The two tables are rim-driven by a single motor through rubber drive rings. Changing the compression of the rubber ring causes a variation in the driving ratio, allowing precise synchronism to be achieved.

The operation of the system is described in figure 3. Consider line C–B to be a through-connection in a multilayer sample at the initial point of exposure to X-ray. C–B will project $\bar{C}$–$\bar{B}$ onto the film. Now consider the same line C–B after it has rotated 180° about rotary axis #1. The line is now defined as

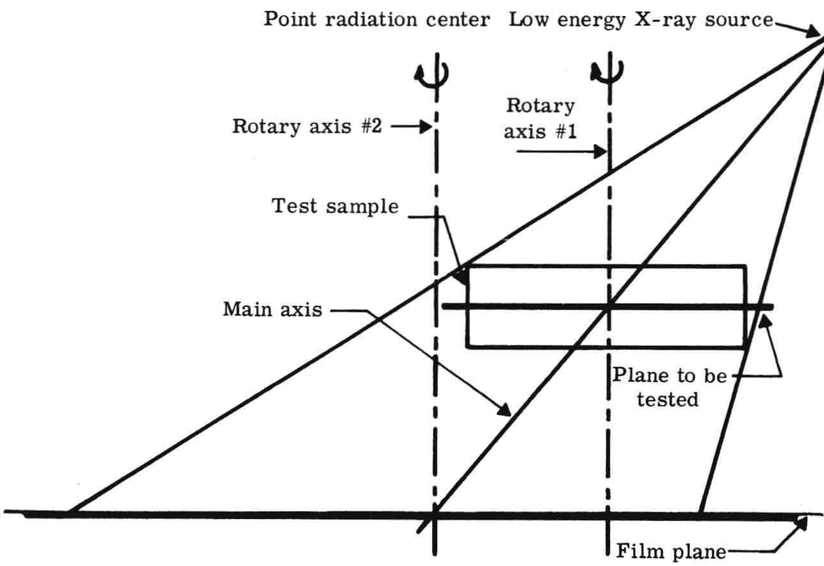


FIGURE 1.—Axial transverse laminography.

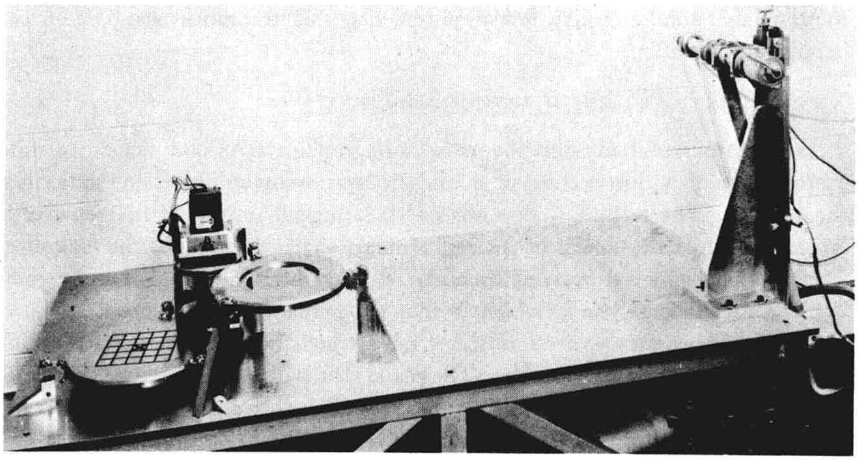


FIGURE 2.—Experimental laminograph.

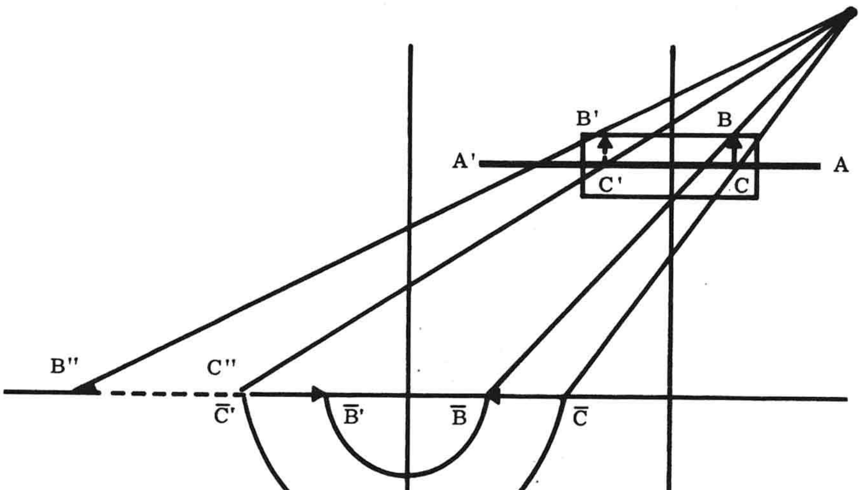


FIGURE 3.—Operating principles of the axial transverse laminography technique.

C′–B′. While C–B was rotating one-half revolution, the initial image $\bar{C}$–$\bar{B}$ was also rotating one-half revolution about rotary axis #2 to position $\bar{C}'$–$\bar{B}'$. C′–B′ now projects a new image C″–B″ onto the film. It will be noted that the only point at which the initial ($\bar{C}'$–$\bar{B}'$) and the new (C″–B″) image coincide or reinforce is at point C where the sample through-connection touches the geometric plane of inspection. This example considers only two positions of the line C–B. It must be recognized that C–B is in reality projecting an image onto the film continuously throughout at least one complete revolution of the sample and film tables. Thus, it will be seen that the projected image of any point in the sample plane A–A′ will reinforce itself continuously as long as the sample and film tables are rotating synchronously, while any point outside this plane will smear out or average over a larger area.

For any given vertical displacement of an object of fixed size from the plane of inspection in the sample, the area over which the object will smear is determined by the angle which the main axis makes with the horizontal plane. The angle used in the laboratory model was 20°; however, a geometric analysis was performed to determine the layering sensitivity for various angles and vertical displacements from the plane of inspection in the sample. The results are shown in figure 4. The curves assume a 76.2 cm (30 in.) horizontal displacement of the center of rotation of the sample from the X-ray source. Y is the vertical displacement above or below the plane of inspection of a spot 0.36 mm (0.014 in.) in diameter. The curve shows the ratio of the common area of projection of this spot to the projection of the same spot in the sample plane. It will be noted that for a vertical displacement of 0.10 mm (0.004 in.) and an angle of 20°, only 5 percent of the projected area of the spot is continuously reinforced or not smeared out.

One of the sample multilayer boards used in this program is shown in figure 5. It is a seven-layer board with four circuit patterns, each of which is a hole

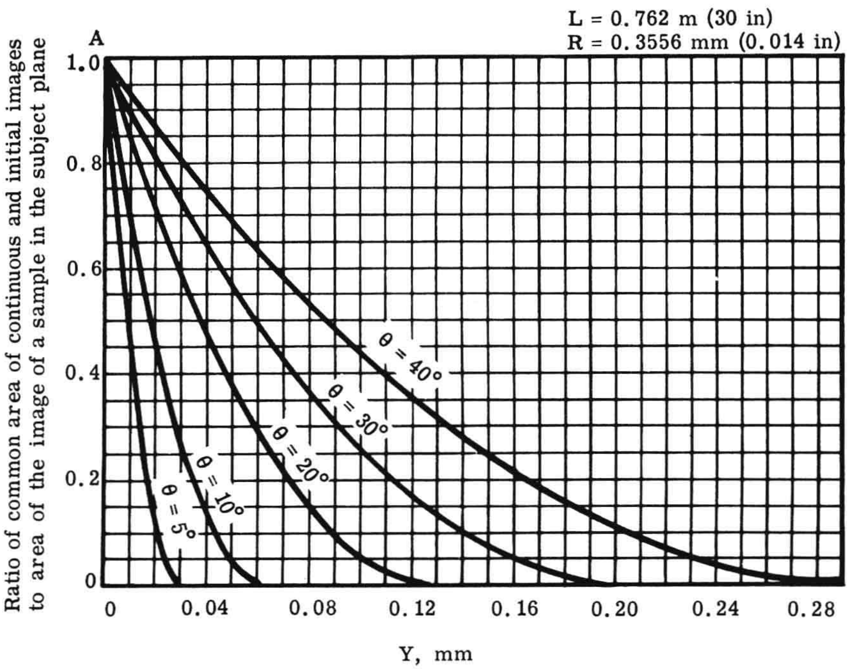


FIGURE 4.—Effect of main axis angular variations.

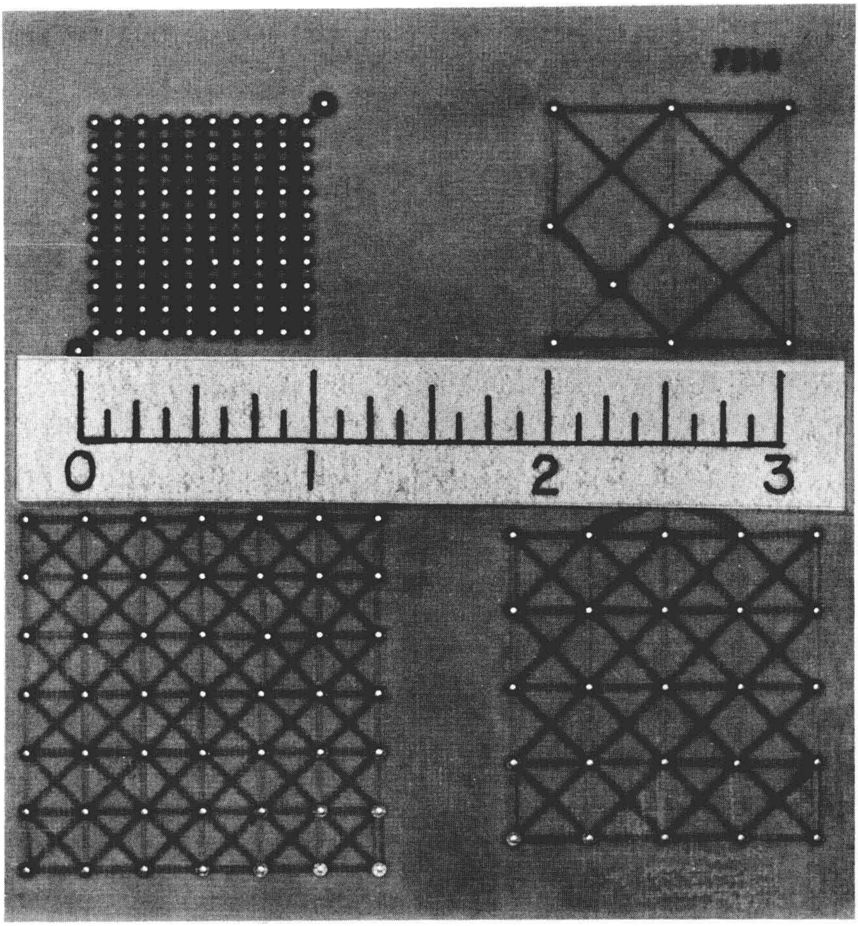


FIGURE 5.—Sample multilayer board.

matrix with defects built into the circuit. The patterns range from widely spaced to densely spaced holes. The most dense matrix has 100 holes or 700 joints per 6.54 cm^2 (1 $in.^2$). The optimum interconnection has been defined as that point at which the plated cylinder makes contact with 360° of the land to which it is joined. Some geometric deviations were introduced into the board, such as intentionally misregistering the land areas for one hole in each matrix and creating open circuits by hairline fractures. The through-connections are made by plating the holes with approximately 0.004 cm (0.0015 in.) of copper.

Figures 6 and 7 are laminographs of layers 3 and 4, respectively. The two layers are separated by 0.01 cm (0.004 in.). The cuts on the diagonal line in the upper right-hand pattern of layer 4 range from 0.06 to 0.15 mm wide. These laminographs have proven that the concept of axial transverse laminography is

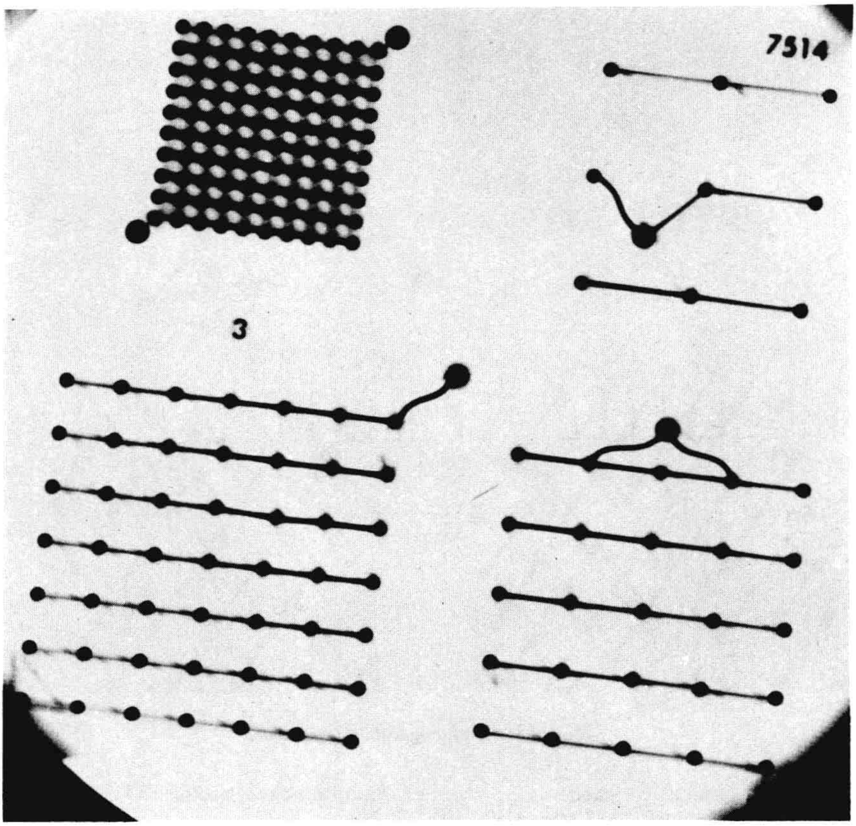


FIGURE 6.—Laminograph of layer three.

a sound one. It can separate layers which are as close together as 0.01 cm (0.004 in.) and can easily detect flaws as small as 0.03 mm (0.0007 in.).

A practical limitation is presented by the use of film. Much time is added to the inspection procedure by having to take a picture of each layer and then developing and examining the film. If the internal layers of the sample are not plane, several pictures of each layer may be required for complete inspection. To alleviate this problem, a different approach is being taken in the laminograph now being developed. The system is shown in schematic form in figure 8. The film plate has been replaced with a fluorescent screen. The visual image from the screen is focused through a lens onto a derotation prism rotating at one-half the screen speed and in the opposite direction. The stationary image from the prism is projected into a closed-circuit television system. The fluorescent screen will have the capability for vertical movement to change the plane of inspection in the sample. This design allows the operator to be at a remote station, thus permitting safe use of higher energy, higher intensity X-ray for better resolution.

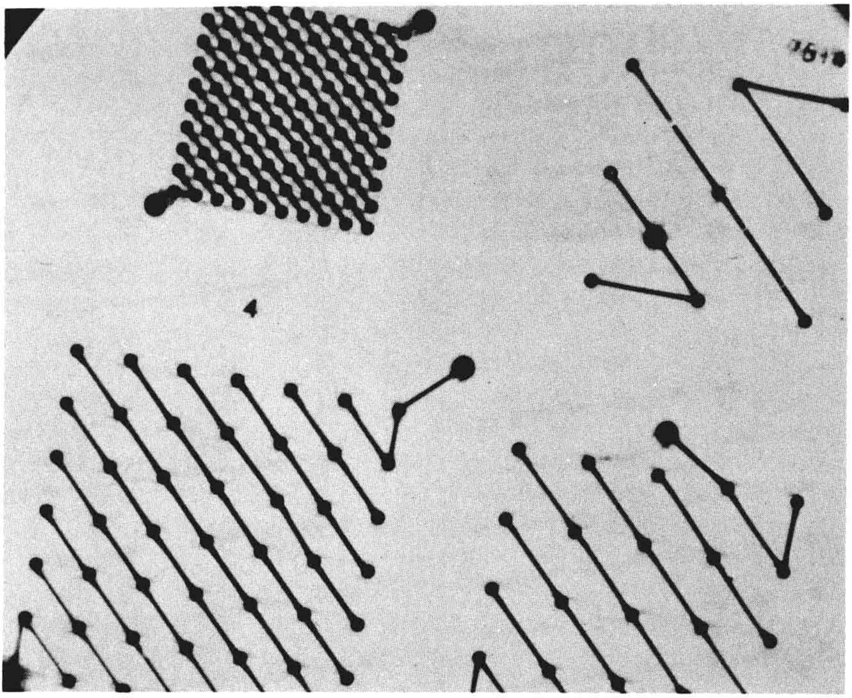


FIGURE 7.—Laminograph of layer four.

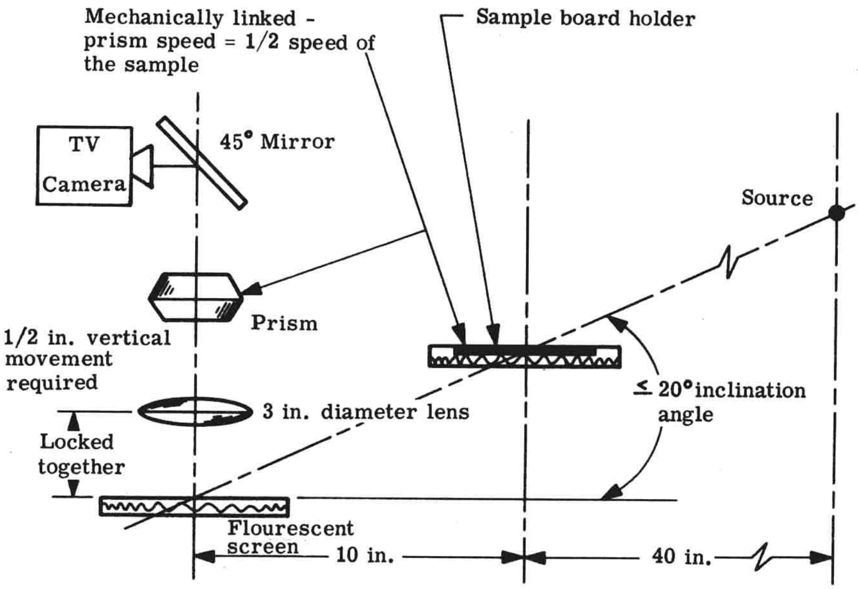


FIGURE 8.—Laminograph schematic.

The conversion to an immediate visual image of the sample produces a continuous scanning device, thereby allowing the operator to scan through the complete board. A zoom attachment on the camera allows a questionable area of the sample to be magnified for more detailed inspection. Photographs of the image may be made at any time for a permanent record.

MUTUAL COUPLING

Although laminography will provide the capability to rapidly inspect multilayer printed circuit boards, the expected detail resolution of approximately 0.03 mm (0.0007 in.) may not show one serious type of defect which is an order of magnitude smaller than this. This defect is epoxy smear over the exposed surface of the internal land areas which is caused by improper drilling. The epoxy masks the internal conductors during the hole-plating process and results in either an open circuit or a joint which may have far less than the desired interconnection of 360°. To inspect for this condition, the technique of mutual coupling, which uses the presence of the gap or high resistance area of the connection to develop an output signal, has been developed.

The application of this technique is shown in figure 9. Two coils wound in the form of a figure **8** are magnetically shielded from each other and are formed into a single probe which is inserted into the through-hole. A signal generator is connected to the excitation coil. The pickup coil is shielded from the direct field of the excitation coil. When there is no gap between the plated hole and the pad, the currents that are induced in the pad circulate in the region of the pad near the excitation coil; hence, little voltage is induced in the pickup coil. However, when the probe is brought near a gap between the plated hole and the printed conductor, the magnetic field from the excitation coil induces a current in the loop formed by the edge of the gap. The magnetic field from this current which circulates around the gap induces a voltage in the pickup coil. The pickup coil is connected to a tuned voltmeter which indicates the presence of the induced voltage.

Initially a large, 1.36-cm (0.85-in.) diameter probe was constructed to verify the concept (fig. 10). A second probe one-tenth the diameter of the initial probe was then constructed to determine the effect of miniaturization on the experimental results. When this proved successful, a further reduction of 4 : 1 was made to produce a probe with a diameter of 0.51 mm (0.020 in.). The comparative sizes of the probes are shown in figure 11. The results of the test run are tabulated in table I. In one test, a bare copper wire was wrapped around a conducting cylinder. By varying the tension on the wire, a connection having low resistance but mechanically unstable characteristics was formed. The mutual coupling probe could adequately detect this type of connection.

Tests were also conducted to determine the minimum practical gap angle that could be detected. It was found that for a reasonable ratio (5:1) of peak gap voltage to cylinder wall voltage, the minimum gap angle is approximately

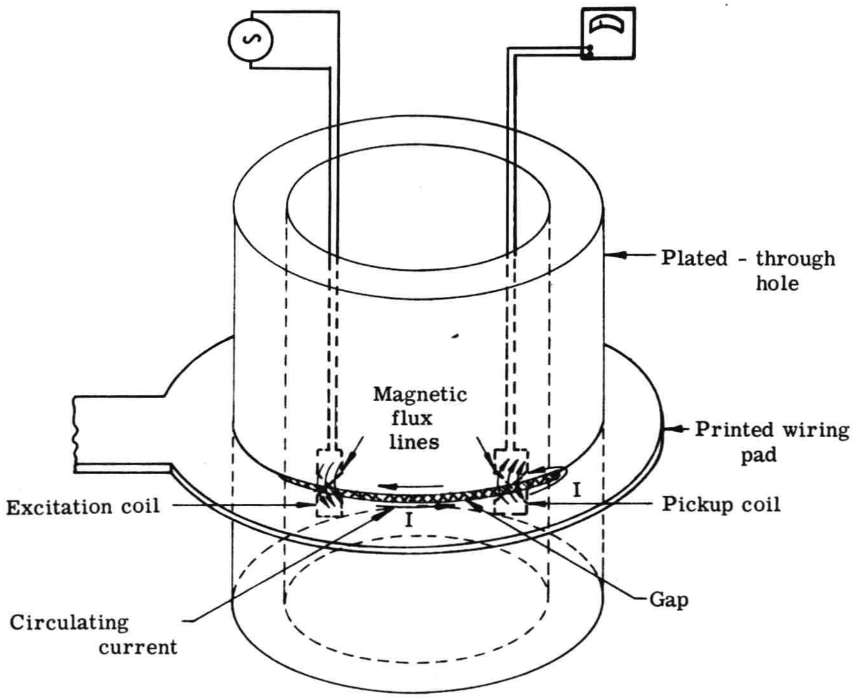


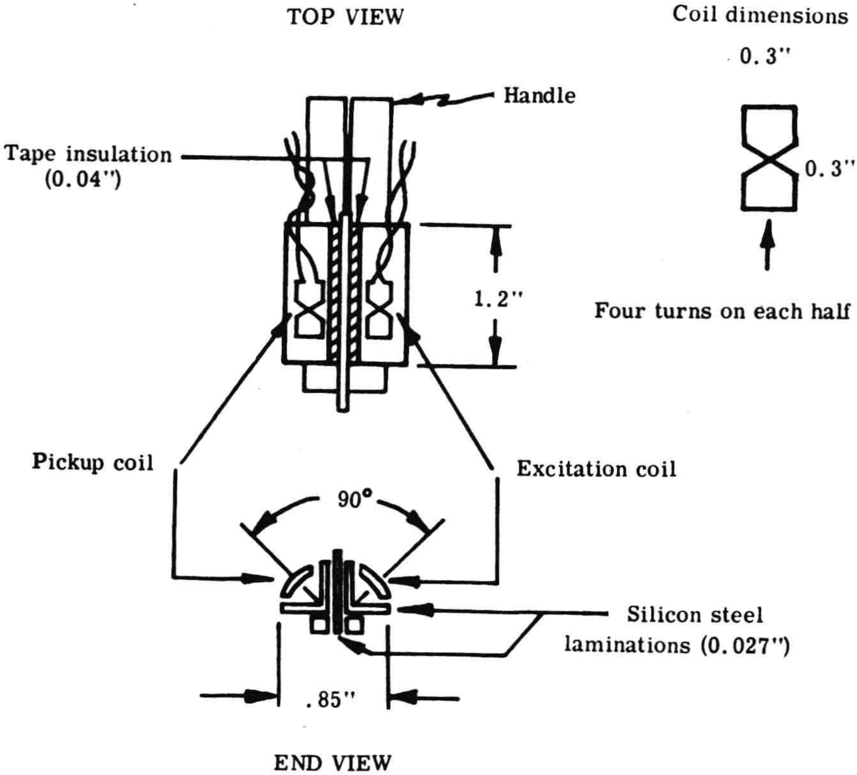
FIGURE 9.—Mutual coupling concept.

60°. This necessitates rotational as well as axial motion of the probe. The probe as designed for laboratory verification of the testing technique is very delicate and thus unsatisfactory for practical application.

A development program on the probe is presently underway. The probe will be a single piece of electrical steel with flats on it. A layer of electrical insulation will be grown on the probe, and single-turn figure **8** coils will be deposited on the flats. A number of coils will be deposited upon a single probe so that rotation within the hole will not be required for a complete profile. The same control tapes used in the automatic tape control drill to make the board could be used to program the probing of the plated-through holes.

CONCLUSIONS AND RECOMMENDATIONS

Laboratory experiments have verified the feasibility of both axial transverse laminography and mutual coupling as nondestructive testing techniques for the inspection of multilayer printed circuit boards. Laminography is well-suited for mass inspection of such boards. It will detect flaws as small as 0.03 mm (0.0007 in.) and can distinguish conductor layers separated from adjacent layers by 0.10 mm (0.004 in.). It can be used for screening the boards and for detecting gross internal defects.



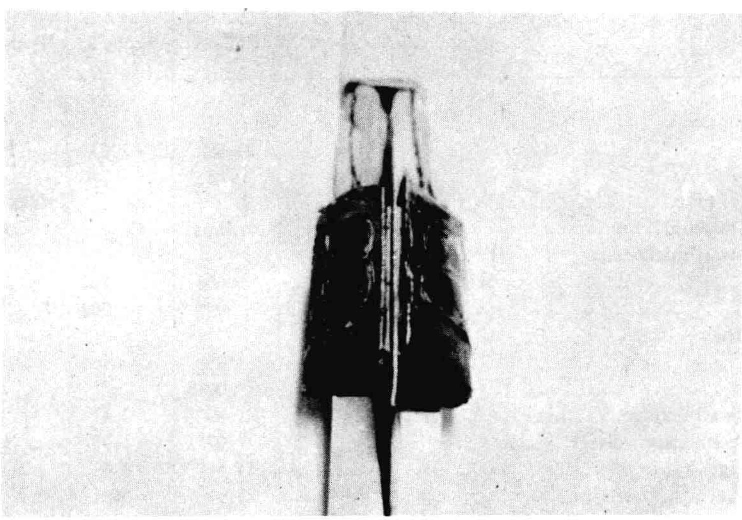


FIGURE 10.—Schematic and photograph of a large diameter probe.

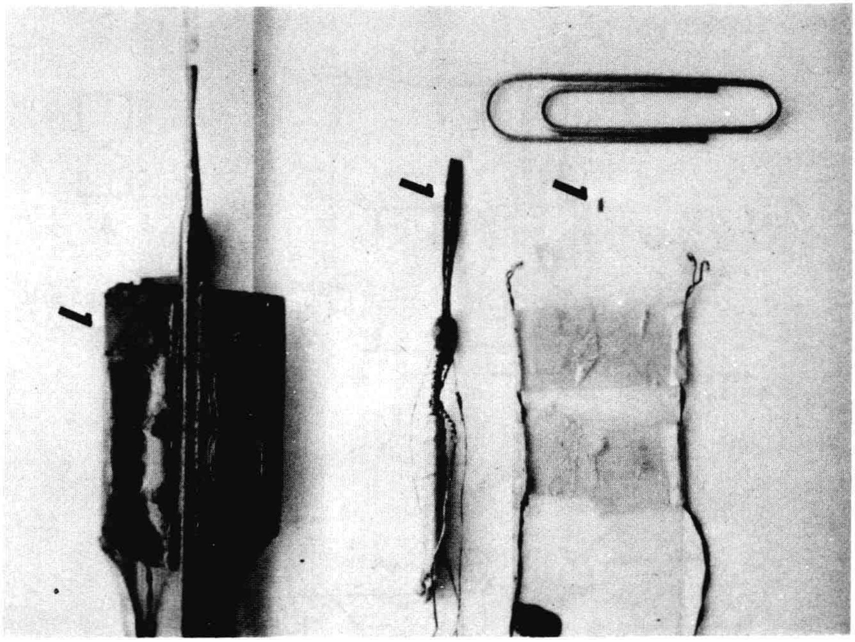


FIGURE 11.—Three mutual coupling probes with diameters of 1.36 cm (left), 2.03 mm (center), and 0.51 mm (right).

TABLE I.—*Pickup Coil Voltages for Three Mutual Coupling Probes (Excitation current—100 mA)*

	Probe 1	Probe 2	Probe 3
Probe diameter,			
mm	21.59	2.03	.51
in	.85	.080	.0015
Frequency, kHz	50	500	2000
Cylinder material	Brass	Copper	Copper
Cylinder wall thickness,			
mm	.686	.102	.038
in	.027	.004	.0015
Gap width,			
mm	.038	varied	$<$.0025
in	.0015		$<$.0001
Cylinder wall voltage, V_{cw}, μv	.39	.41	.12
Soldered connection voltage, V_{sc}, μv	.57	.78	....
Gap voltage, V_g, μv	15.6	4.6	1.0
Ratio, V_g/V_{sc}	27.4	5.9	8.3*

*V_g/V_{cw}.

Work is presently underway to transform the laboratory model of the laminograph into a piece of practical hardware. The new system will make use of optical and closed-circuit television techniques in conjunction with a fluorescent screen to produce a continuous scanning laminograph with the capability to make any permanent records desired.

The application of laminography is not limited to the inspection of multilayer printed wiring boards; however, it should become a powerful nondestructive testing tool for detailed examination of the interior of solid homogeneous or nonhomogeneous bodies.

Mutual coupling can be used as an adjunct to laminography in the detection of extremely small gaps in the through-connections, but it is more limited in application because it requires probing of each through-connection to be inspected. The laboratory model of the 0.51-mm (0.020-in.) diameter probe was difficult to fabricate and too fragile to be practical. Work is being done to deposit four to six coils on a single probe in order to simplify the probing operation, to improve the geometry of the probe, and to reduce the minimum gap angle that can be detected. While these two complementary techniques will not answer all the questions concerning the quality of multilayer wiring boards, they will go a long way toward answering the question concerning the reliability of the interconnections.