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PHOTOTOOL FABRICATION METHODS

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PHOTOTOOL FABRICATION METHODS

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October 1975

Prepared by M. L. Wilson, D/821, under PDO 6984762

New photographic materials and fabrication techniques have been implemented in the production of phototools used for the manufacture of printed circuits. A bombsight punch was designed and built for accurately locating and punching tooling holes in the film. Phototool tolerance capabilities have been improved with a reduction in fabrication time and cost.

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SUMMARY

This project was initiated to develop new phototool designs and fabrication techniques for the manufacture of printed circuits and other photofabricated parts. The objectives were to optimize the tolerance capabilities of the tooling and to reduce the phototool fabrication time and cost.

A new film-tooling concept was established and implemented which consists of precision-plotting the photographic image on a film base and precision-punching tool-location holes in the film. A bombsight punch was designed and fabricated to accurately locate and punch the tooling holes in support of the new concept.

A new photographic film, Kodak Kodaline 2566, was evaluated for use as a base for film phototools. Its physical properties were found to provide significant process improvement over films previously used in tooling applications. Dimensional stability studies indicated that no dimensional tolerance problems would be encountered if the film were in equilibrium with the humidity- and temperature-controlled clean-room environment in which it is plotted, exposed, processed, and used. Kodak Supermatic developer, normally used with Kodaline 2566 film, does not require the critical process controls which were necessary with the developer that was previously used.

A new 0.0005-inch (12.7 μm) Mylar protective coverlay was found to be superior to the 0.002-inch (50.8 μm) coverlay that was previously used. Automatic equipment purchased for its application assures a uniform covering which improves the photographic resolution of the image.

A commercially available Laminar photographic-exposure support and transport tool was modified to make it compatible with the Bendix Kansas City standard loading system for the exposure of thin, flexible printed circuits. Path-width measurements and light-undercut studies proved the tool to be acceptable for the production of printed circuits. Large savings in both fabrication time and cost were realized through its implementation.

DISCUSSION

SCOPE AND PURPOSE

This project was initiated to develop new phototool designs and fabrication techniques for the manufacture of printed circuits and other photofabricated parts. The tooling which was in use at the start of this process development activity was expensive, difficult and time-consuming to fabricate, and fragile. Tolerance capabilities were often marginal because of variation in photographic-glass flatness, frame-to-glass flushness, protective overlays, tooling-hole insertion techniques, and the inherent limitations of photographic materials.

The goal of this project was to optimize tolerance capabilities of the tooling and to reduce phototool fabrication time and cost. The work consisted of the following activities:

- Evaluation of new photographic materials,
- Evaluation of phototool fabrication concepts, and
- Evaluation of the phototool support and transport systems.

ACTIVITY

Background

New types of photographic films and processing materials are continually being introduced to the market by the manufacturers. Films recently made available promised increased dimensional stability and improved resolution through the use of a synthetic emulsion binder. Thinner protective films also were offered, along with equipment with which to apply them, and the Dynachem Corporation introduced a tool and panel-support system for use with very thin, flexible circuits which promised to reduce part-loading times. An evaluation program therefore was initiated to determine the feasibility of applying these technological advancements to the Bendix process.

The phototools in use at the beginning of this development project consisted of photographic glass plate bonded into a steel frame with accurately positioned, jig-bored tooling holes and locating pins along one edge. Two to eight weeks were required for their fabrication. Approximately one-third of the tools produced were rejected for inaccurate tooling-hole location, scratches in the emulsion or glass, cracked glass, or irregularities in the glass

surface. These tools could be easily broken during the exposure operation, and the photographic materials used were only available in limited sizes and emulsion types.

Because the emulsion on the glass base could be easily scratched, the use of a 0.002-inch-thick (50.8 μ m) plastic overlay was required. This overlay permitted light to undercut the phototool image and caused subsequent feature-size control problems on the parts. New materials and tool concepts therefore were evaluated to develop a phototool having improved dimensional stability without the disadvantages of the glass plate. Polyester-based photographic film was investigated as a possible replacement for glass. The film was evaluated for temperature and humidity stability, tooling-hole insertion techniques, fabrication time, and durability.

Because the tolerance capability of a phototool can be no better than the original circuit master, work was initiated to optimize the use of the automatic plotting equipment with respect to tolerance capability and repeatability, and to determine the feasibility of using locating pins for positioning the film on the plotter table.

Past experience with the photographic exposure of thin, flexible circuit panels on a production basis had revealed several problem areas. Thin, unsupported panels tend to become curled or wrinkled during the exposure operation. Transparent Plexiglas plates corrected the problem but dispersed the collimated light, thus increasing the exposure time and the image undercut. The introduction of the Dynachem Laminar phototool system provided the potential for improving the support system for the exposure operation. Development activity therefore was conducted to determine the feasibility of adapting the Laminar phototool system to Bendix production use.

Evaluation of New Photographic Materials

A new type of photographic film, Kodaline 2566, was made available to the printed circuit industry just prior to the start of this development activity. Kodaline film was developed by Kodak specifically for the generation of line transparencies on a photoplotter such as the one used at Bendix for circuit masters. Because of its synthetic emulsion, Kodaline 2566 was advertised as having improved physical characteristics and dimensional stability over the regular gelatin-emulsion films in use at that time.

The study of Kodak Kodaline film was initiated because of a change that was made in the emulsion of DuPont film. The change was made to favor graphic-arts reproduction by providing

exposure in a range of shades; however, it made the film unfavorable for phototool use since feature edges became shaded and not clearly distinguishable.

Kodak Kodaline film has low fog-level and high density characteristics which provide images that are either opaque or transparent, thus facilitating the identification of feature edges. Circuit images plotted on Kodaline film were comparable to those made on DuPont film prior to the emulsion change.

Kodak Supermatic developer, generally used to process Kodaline film, does not require the critical process control measures which are necessary with DuPont developer. Since the results obtained from the two systems were comparable, studies were initiated to implement the use of Kodaline film and Kodak Supermatic developer for all phototools.

Photographic Film Stability

A series of tests was conducted to determine the stability of Kodak Kodaline photographic film under changing temperature and humidity conditions. These tests were initiated as a result of dimensional instability observed during the inspection of a multi-image film phototool. Feature dimensions on the phototool decreased after overnight exposure to inspection-room atmosphere.

The initial test was designed to identify any dimensional changes which may occur from the time a tool is developed until it is ready for inspection. A special 10- by 20-inch (254 by 508 mm) test plot having target lands was checked periodically after developing until the plot became dimensionally stable in the atmosphere of the phototool-fabrication room. Obvious dimensional deviations which occurred may be seen in Table 1.

Table 1. In-Process Dimensional Stability Test Results

Time After Developing (Hours)	Deviation From Nominal	
	10 Inches (254 mm) From 0,0 (Inch) (mm)	20 Inches (508 mm) From 0,0 (Inch) (mm)
0	+0.0003 (+0.00762)	+0.0007 (+0.01778)
1.3	+0.0006 (+0.01524)	+0.0010 (+0.0254)
3.1	+0.0007 (+0.01778)	+0.0011 (+0.02794)
3.9	+0.0008 (+0.02032)	+0.0015 (+0.0381)
21.9	+0.0007 (+0.01778)	+0.0014 (+0.03556)
24.0	+0.0008 (+0.02032)	+0.0017 (+0.04318)
28.0	+0.0006 (+0.01524)	+0.0013 (+0.03302)

Data collected during a test in which the photographic film was first soaked in water and then dried in a film dryer show the effect of humidity on film stability. Great amounts of expansion and contraction occurred, as indicated in Table 2. The fact that the film did not return to the original dimension is due to dimensional change from processing. This can be controlled mainly by adjusting the developing parameters. Changes shown in Table 2 correspond closely to film-stability data published by Kodak.

Table 2. Effect of Humidity on Film Stability

Film Condition	Distance From Datum (Inches) (mm)	Deviation From Before-Soak Dimension (Inch) (mm)
Before Water Soak	10.0006 254.01524	
After 18 Hr. Water Soak	10.0062 254.15748	+0.0056 +0.14224
After Stabilization	10.0010 254.0254	+0.0004 +0.01016
After 20 Hrs. in Film Dryer	9.9949 253.87046	-0.0057 -0.01447
After Stabilization	10.0011	+0.0005 +0.01270

To determine whether the deviations indicated in Table 1 were caused by processing or by humidity instability of the film before plotting, a series of tests was performed on undeveloped film. These tests were conducted with film taken directly from a film stack and film which had been hung overnight in the atmosphere of the work area. Tooling-hole locations were measured immediately after the holes were punched in the film and again when the film had equilibrated with the humidity of the atmosphere. The film then was processed in the developer and again measured.

The data obtained during these tests, shown in Table 3, indicate that film taken directly from the storage stack may not be in equilibrium with the work-area atmosphere; thus, phototools produced with this film are susceptible to dimensional deviations caused by expansion of the film as it absorbs moisture from the atmosphere.

The film contracted after it was developed, but it did not return to its original dimension when it was again stabilized. This permanent change is caused by the developing process and will vary as the area humidity and drying temperature of the processor change.

Table 3. Effect of Humidity Stabilization and Processing on Film Stability

Film Processing Status	Distance From Datum			
	Unstabilized Film Directly From Storage (Inch) (mm)	Dimensional Change (Inch) (mm)	Film Stabilized In Work Area Overnight (Inch) (mm)	Dimensional Change (Inch) (mm)
After Punching	10.0002 254.00508		10.0003 254.00762	
After Film Stabilization	10.0013 254.03302	+0.0011 +0.02794	10.0003 254.00762	0 0
After Developing	10.0007 254.01778	-0.0006 -0.01524	9.9997 253.99238	-0.0006 -0.01524
After Film Stabilization	10.0007 254.01778	0 0	10.0001 154.00254	+0.0004 +0.01016

The results of these tests indicate that film stability is affected by the humidity to which the film is exposed and by the processing by which it is developed. Dimensional deviations caused by minor changes in humidity are reversible; they should not prove detrimental if the phototool is produced and used in compatible environments, and if the humidity of the film is in equilibrium with that of the work-area atmosphere before plotting or contact printing is accomplished. Dimensional changes due to processing are not totally irreversible since they can be controlled, in part, by proper adjustment of the film-processing parameters. The significance of these deviations is dependent upon the distance between circuit features; as the size of the phototools increase, the probability of their rejection also increases.

At Bendix, the phototool fabrication, tool inspection, and production clean-room areas are designed to have the same atmospheric characteristics with respect to humidity and temperature. This should prevent any major dimensional instability which would have a deleterious effect on the products manufactured; however, since phototools must be exposed to the normal plant atmosphere while being transported from one clean room to another, they should be allowed to equilibrate with clean-room atmospheric conditions before they are inspected or used.

Protective Coverlay Film

A clean protective coverlay is normally applied over the emulsion side of printed circuit board phototools to protect the emulsion from scratches and other handling damage. The coverlay previously used consisted of a 0.001-inch-thick (25.4 μm) Mylar film with a pressure-sensitive adhesive. The total thickness of the coverlay, after application, was approximately 0.002 inch (50.8 μm). A new 0.0005-inch-thick (12.7 μm) Mylar coverlay made by Tapecon Inc. was investigated and found to be from 0.0010 to 0.0013 inches (25.4 to 33.02 μm) thick after application.

In the past, the coverlay had to be applied to the emulsion side of the phototool by hand. This resulted in air pockets, bubbles, and wrinkles between the phototool and the coverlay. A 24-inch (609.6 mm) Laminator, Model EPL-11, was acquired from Tapecon to overcome this problem. The laminator rolls the coverlay onto the phototool at a constant speed with continuous tension on the coverlay film, thus providing a smooth application without air bubbles or wrinkles.

The new coverlay film and laminator are now used for all printed circuit phototools. The incorporation of this system has improved the phototool resolution characteristics.

Phototool Fabrication

Film-Tooling Proposals

The phototools used prior to this development activity consisted of photographic glass plates bonded into a steel frame (Figure 1). Tooling holes and pins were used to maintain the proper part registration. The tooling holes were jig-bored into the steel frame to establish the necessary precision tolerances.

Figure 1. Glass/Steel Frame Phototool

The fabrication time for these glass/steel frame phototools was from two to eight weeks. Approximately 30 percent of the tools fabricated were rejected for mislocation of tooling holes, scratches in the emulsion or glass plate, cracked glass, and irregularities in the surface of the glass. The tools were easily broken during use, thus requiring frequent replacement. Furthermore, the

glass-based photographic materials were available only in limited sizes and emulsion types. Because of these disadvantages, three new phototool fabrication concepts were derived and investigated..

Proposal 1. The first proposal consisted of plotting the tooling-hole locations on the circuit master film at the same time the circuit image is plotted. A "bombsight" punch then would be employed to optically locate and punch the tooling holes. Original phototools and subsequent replacements could be contact-printed on prepunched films from the plotted circuit master.

Although troubles associated with the glass/steel frame phototools would be eliminated through the adoption of this proposal, the following problems would have to be considered.

- A bombsight punch, accurate to ± 0.00015 inch (± 3.81 μm), would have to be developed and fabricated.
- Tooling-hole locations would have to be consistently plotted to ± 0.00015 inch (± 3.81 μm). This total 0.0003-inch (7.62 μm) tolerance is considered adequate for all printed-wiring-board tooling now encountered at Bendix Kansas City. (Most phototools have a ± 0.0005 -inch (± 12.7 μm) tolerance on tooling-hole locations.)
- Only film tooling would benefit; steel-frame tooling would still require jig-boring of tooling holes.
- Process Engineering would be required to determine and submit the offset coordinates for the tooling holes before the final plot was made.
- Multi-image tooling would require that image step-and-repeat be performed on the N/C Plotter.

Proposal 2. The second proposal consisted of adding a precision-hole plate to the table of the N/C Plotter. The holes in the plate would be used to locate prepunched film tooling on the plotter table. The plotter film would be prepunched according to panel size and pinned to the plate for image plotting. Phototools could then be contact-printed on prepunched film from the plotted circuit master.

Again, while the adoption of this proposal would eliminate troubles associated with the glass/steel frame phototools, the following problems would have to be solved.

- A precision-hole plate would have to be fabricated and mounted on the N/C Plotter table. Attachment and alignment would be difficult because of the rough surface of the table.

- Offset dimensions from the holes in the plate might prove difficult to determine and maintain.
- Process Engineering would be required to determine and submit the offset dimensions to the plotter programmer before the final plot was made.
- Multi-image tooling would require that image step-and-repeat be performed on the N/C Plotter.

Proposal 3. The third proposal consisted of purchasing and installing in the circuit-master-preparation area a jig borer capable of optically locating image target datums for setup, and then boring the tooling holes at specified locations. The jig borer would be interfaced with a small computer so that the image target datums would not have to be aligned with the axes of the machine; instead, the computer would calculate the coordinates for the tooling holes from the image datums.

The adoption of this proposal would involve the following problems.

- The cost of a computer-controlled jig borer would be approximately \$30,000.
- The equipment would have to be installed in a humidity- and temperature-controlled environment.
- All of the disadvantages of the glass/steel frame would be retained.

Cost estimates of the three proposals were prepared and each proposal was reviewed to determine which would be the most effective method of phototool fabrication. The review included an investigation into the feasibility of performing multi-image plotting on the N/C Plotter, a comparison study of multi-image-plotted tools versus step-and-repeat tools, and a determination of the feasibility of adding a tooling-hole plate to the N/C Plotter table. The following list shows the estimated cost of implementing each of the proposals.

Proposal 1 (Bombsight Punched-Film Tool):	\$2,500
Proposal 2 (Plotter Locating Plate):	\$2,000
Proposal 3 (Jig-Borer Procurement):	\$30,000

Feasibility of Multi-Image Plots

A multi-image plot of a Sandia/Bendix capability study board was made for the subsequent production of a phototool. To accomplish

this, a card deck from the single-image plotter tape was made and the Side 1 and Side 2 comment sections (information pertinent to the tabulation of N/C data) were isolated. These sections, along with image-offset coordinates, were reassembled in such a manner that the two sides would be plotted in multi-image form before the tape recycled.

Inspection results from the first plot indicated that positional locations deviated a maximum of ± 0.0005 inch ($\pm 12.7 \mu\text{m}$) from the datum location in Image 1 of the plot. Because inaccuracies of this magnitude can be expected from the plotting of a circuit image, the results indicate that a multi-image plotter tape may be constructed from a single-image tape without incurring inaccuracies other than those which are inherent to the normal plotting operation.

Multi-Image Versus Step-And-Repeat Plots

Further studies were conducted to compare plotted multi-image phototools with tools produced on the step-and-repeat machine. For this purpose, two multi-image phototools were made on the step-and-repeat unit.

Inspection results from the first phototool indicated dimensional deviations ranging from $+0.0003$ to -0.0005 inch ($+7.62$ to $-12.7 \mu\text{m}$). This is comparable to the ± 0.0005 -inch results obtained by plotting a multi-image phototool. The second tool did not compare as well, since deviations ranged from $+0.0004$ to -0.0010 inch ($+10.16$ to $-25.4 \mu\text{m}$) with 58 percent of the feature positions falling within ± 0.0005 inch.

From these results, the conclusion was reached that phototools could be multi-image plotted with improved accuracy over the step-and-repeat method.

N/C Plotter Table Modification

An investigation was conducted to determine the feasibility of adding a precision-hole plate to the N/C Plotter table. This modification would allow prepunched unexposed film to be pinned to the table and the required circuitry could be plotted with reference to the tooling holes. The photomaster then could be contact-printed directly from the plot.

The results of the investigation indicated that the modification necessary for this type of operation could be successfully made.

Proposal Selection

Careful consideration of the three proposals led to the conclusion that Proposal 1, utilizing a bombsight punch, would be the most practical approach to the development of a new phototool concept.

The following factors especially favored the selection of Proposal 1.

- Tooling cost would be significantly reduced from approximately \$300 per tool copy to approximately \$50.
- The flow time for tool fabrication would be reduced from approximately six weeks to less than one week.
- Glass/steel-frame-related problems such as fragility, fabrication difficulties, and high rejection rate would be eliminated.
- Storage space required in the production area would be significantly reduced.
- The ease with which additional copies could be made would provide increased exposure-operation efficiency.
- Repeatability would be increased for providing replacement copies.

All problems associated with the adoption of Proposal 1 were resolved, with the exception of the design and fabrication of a bombsight punch. Work toward the design and fabrication of a bombsight punch therefore was initiated.

Bombsight Punch

The design concept for the bombsight punch necessitates plotting two lands at predetermined locations with reference to the fiducial points of the circuit master. These lands are individually "sighted in" with a microscope which is an integral part of the punch. The film then is clamped in place and a hole is punched at the sighted-in position.

A punch subsequently was built to this design (Figure 2), but preliminary results indicated that the following alterations were needed before the required tolerances could be obtained.

- Excessive clearance between the punch bushing and the assembly frame, detected during an inspection of the punch assembly, adversely affected the critical alignment of the punch. Rework of the bushing was necessary.
- The original concept involved the use of a two-color microscope to locate a target land prior to punching the tooling holes. To insure accurate location of the land, the scope had to be positioned so that its center line was coincident with the center line of the sighting hole in the punch. Although this positioning was possible, realignment was necessary after each tooling hole was punched.

Figure 2. Bombsight Punch

A conventional microscope was mounted temporarily on the equipment, and the sighting hole was reworked to facilitate the location of the target land with direct reference to the diameter of the hole. To evaluate the new method, a 0.050-inch-diameter (1.27 mm) target land was used as a reference to the 0.0502-inch-diameter (1.27508 mm) sighting hole. This change in alignment criterion eliminated the accumulation of error which might occur when two alignments were performed, and it also simplified the land location procedure.

Inspection results obtained after the modifications were completed are shown in Table 4. Holes for these tests were punched by five different persons so that discrepancies attributable to individual operator techniques could be detected.

The bombsight punch later was equipped with a permanently mounted conventional microscope and a punch having a 0.040-inch-diameter (1.016 mm) sighting hole to facilitate the use of the 0.040-inch

Table 4. Test Results After
Modification of
Bombsight Punch

Deviation From True Position (Inch) (μm)	Number of Holes
0.0000 0.00	1
0.0001 2.54	4
0.0002 5.08	3
0.0004 10.16	1

diameter target land that is commonly used for a datum; this eliminated the need for an aperture change during plotting.

Data collected during prove-in indicate that the punch is accurate within 0.0006 inch (15.24 μm) TP diameter with respect to the 0.040-inch (1.016 mm) plotted land (the land used for punch alignment). Observations made during phototool production indicate that the punch is accurate within ± 0.0003 inch (7.62 μm) from the circuit datum to the punched tooling holes. These accuracies are comparable to those formerly obtained when the tooling holes were drilled on the jig borer.

To facilitate the use of the bombsight punch, two 0.040-inch-diameter (1.016 mm) lands may be plotted in the proposed tooling-hole location. This will provide a reference point for aligning the punch and for the subsequent punching of a tooling hole.

Special instructions were prepared to insure the proper location of the reference land. These instructions specify the maximum rectangular dimensions of a printed wiring board that can be associated with the standard tooling spacings now being used.

An alternate technique for use of the bombsight punch has been developed and implemented at Bendix to permit the punching of photomasters which have been plotted without the 0.040-inch-diameter datum lands. An Optometric Coordinate Measuring Machine fitted with a PDP-8 computer is used to optically locate datum features on the photomaster and to compute offset dimensions for the datum lands. Pressure-sensitive datum lands are then placed at these locations for use in locating the tooling holes.

Because the tooling holes can be punched in the controlled environment of the circuit-master preparation area, the possibility of tooling holes being out of tolerance because of varying environmental conditions is eliminated. This problem was most prevalent

on the larger photomasters. The time necessary to schedule and perform a jig-boring operation in the Tool Room also has been eliminated. As a result, a high-quality phototool can be made available to production personnel with minimum cost and effort sooner than has been possible in the past.

The combination of precision plotting, bombsight punching of tooling holes, and the quick dimensional-check capability offered by an Optometric measuring machine has eliminated the necessity for inspecting phototools before they are used in production. Phototools need be inspected only when tolerances tax the capability of the equipment used.

Comparison Between Punched and Jig-Bored Tooling Holes

Inspection of jig-bored and punched tooling holes produced the results shown in Table 5. Approximately 20 phototools or photomasters were inspected for each indicated situation. The ± 0.0005 -inch (12.7 μm) range was used because it is the allowable tolerance for tooling-hole location.

Table 5. Comparison Between Punched and Jig-Bored Tooling Holes

Distance Between Holes (Inches) (mm)	Jig-Bored Holes Within ± 0.0005 Inch (12.7 μm) (Percent)	Punched Holes Within ± 0.0005 Inch (12.7 μm) (Percent)
2.000 50.8	90.0	84.0
4.000 101.6	81.5	76.0
5.000 127.9	75.0	71.5
8.000 203.2	61.5	71.5

Completion and prove-in of the bombsight punch accomplished the primary objective of this project by establishing an inexpensive, short-lead-time phototool-fabrication capability at Bendix Kansas City.

Laminar Phototool System Evaluation

Experience with the production of thin, flexible circuit panels revealed the following problems in photographic exposure.

- Thin panels tended to become curled or wrinkled during exposure unless they were supported by transparent plates. However, the transparent Plexiglas plates dispersed the collimated light and increased the image undercut.

- The thinness of the flexible circuit (from 0.002 to 0.010 inch, or 50.8 to 254 μm) and the film master (0.007 inch, or 177.8 μm) prevented the two components from being held in accurate registration without slippage or separation during exposure. Plexiglas plates having precision-bored tooling holes were used to support the part panels and insure intimate contact between the master and the part, but again, the refractive properties of the Plexiglas increased the undercut, loading time, and running time.

The introduction of the Dynachem Laminar phototool system provided the potential for an improved support and transport system for the exposure of thin, flexible circuits.

Laminar Phototool Configuration

The Laminar phototool system, as purchased, consists of two leaves of Type G-UVA II Plexiglas joined along one edge with a steel piano-type hinge (Figure 3). The Plexiglas leaves are coated with a proprietary material which increases light-transmission in a manner similar to that attained using coated optics. The increase is advertised to be 94 percent.

Figure 3. Laminar Phototool, As Purchased

The edges of the leaves opposite the hinge have a step and recessed lip to allow for the thickness of the part panel and the photomaster film. The hinge is recess-mounted the same amount. Several thickness ranges are available, depending upon the thickness of the part and the photomaster to be used.

Two 0.125-inch-diameter (3.175 mm) tooling pins are supplied with the Laminar phototool. The pins are pointed to provide for the piercing of dry-film photoresist. Dynachem recommends that allowance be made in the diameter of the part tooling holes for the photoresist which would be pushed into the hole.

Laminar Phototool Modification

The Laminar phototool system, as purchased, is not compatible with the photofabrication process used at Bendix in the following respects.

- The tooling-pin size and location are different.
- The dry-film hole-piercing feature prevents accurate location of the part and photomaster.
- The space provided for the part and photomaster is too liberal for precision photofabrication.

The Laminar system, as purchased, therefore required modification to make it compatible with the Bendix process.

The tooling pins supplied with the Laminar phototool were discarded in favor of a specially designed pin which provides the size and close tolerance necessary for use with the Bendix system. The specially designed tooling pins are $0.2497 +0.0000 -0.0002$ inch ($6.34238 +0.0000 -0.00508$ mm) in diameter by 0.300 inch (7.62 mm) long with a bullet radius on the top end and a rectangular support plate (1.000 by 0.500 by 0.005 inch, or 25.4 by 12.7 by 0.127 mm) spot-welded to the opposite end (Figure 4). The bullet radius on the tooling pin provides a means of centering the pin in the hole without damaging the hole. The ability to pierce through the dry-film photoresist is not needed with the Bendix system, since the tooling holes are not covered with resist.

The tooling-hole location for the Laminar system also was revised. Dynachem recommends the use of two in-line, 1/8-inch-diameter holes parallel to and midway between the hinged edge and the opposite edge. The modified system uses a row of $0.250 +0.0002 -0.0000$ -inch-diameter ($6.350 +0.00508 -0.0000$ mm) holes on 1.000-inch (25.4 mm) centers located 1.000 inch from and parallel to the edge opposite the hinge, on the bottom plate. This arrangement accommodates all of the even-inch-centered tooling-hole patterns of the Bendix system. The tooling holes in the top-plate row were

Figure 4. Tooling Pin for Modified Laminar Phototool

bored oversize to a diameter of 0.280 inch (7.112 mm) to provide clearance for closing the leaves (Figure 5).

The spacing between the leaves is controlled by the protrusion of the hinge and the height of the lip along the edge opposite the hinge. Each Laminar phototool, as purchased, accommodates a range of photomaster-part thicknesses. (A typical range is from 0.003 to 0.020 inch, or 76.2 to 508 μm .) To improve the contact between the photomaster and the part, the steps of each tool were machined to accommodate a specific photomaster-part thickness.

Photomaster Loading Method

The photomaster is the heart of the photographic exposure operation. To assure high-quality parts, the master must be aligned to the hole pattern of the part, and the front image of the master must be accurately registered with respect to the back image. Normally, this is accomplished by inserting tooling pins through accurately located tooling holes in the master and the part.

The modified Laminar phototool system uses the same principle, except that the photomaster is registered to the pins and taped

Figure 5. Modified Laminar Phototool Plates

to the leaves of the phototool to eliminate handling. This procedure requires that the photomaster be 2 inches (50.8 mm) larger than the part to allow space for the thickness of the tape. The master is loaded onto the phototool by placing pressure-sensitive tape along the edges of the film master. Thus, when the master is pinned to the phototool and the phototool is closed, the master is bonded in place on the two leaves. The tooling pins are left in the baseplate of the phototool to accommodate the loading of the part panels and to insure proper registration of the photomaster (Figure 6). Once loaded onto the phototool, the master remains in place until all parts are completed or until it is replaced by a new master. The entire master-loading sequence requires less than 5 minutes.

Part Loading

Once the photomaster is bonded to the leaves of the phototool, any quantity of parts can be exposed simply by opening the leaves, placing a part panel on the tooling pins, closing the leaves, making the exposure, opening the leaves, and lifting the part from the pins. This procedure completely eliminates the extensive master-loading time formerly required in handling the individual masters, inserting and removing the tooling pins, and placing and removing protective washers. Also, damage to the photomaster

Figure 6. Modified Laminar Phototool With Photomaster and Tooling Pins

is significantly reduced by the Laminar system since the master is never handled during the entire part loading and unloading sequence.

Loading times for two-sided photomasters and parts without use of the Laminar system require 70 seconds per part; by use of the Laminar system, the part-loading time was reduced to 10 seconds. This is a reduction in time of 86 percent.

Exposure Light Loss

The effective transfer of the image from the master to the photo-sensitive resist on the part is dependent upon the time and intensity of the light which passes through the phototool and the photomaster. In the production process, the exposure is controlled by the amount of time the part is under a constant-intensity light source. Since the equipment used includes a conveyORIZED part-transport system, the exposure is controlled by the speed of the conveyor.

Observation of the exposure operation indicated that light was being reflected from the surface of the Laminar support plates. A test therefore was conducted to determine the effect of the light reflection upon the exposure operation.

A group of panels was exposed with only the photomaster between the light source and the photosensitive emulsion (without use of the Laminar phototool). A conveyor-speed setting of 12 (1.2 in./sec, or 30.48 mm/s) was required to obtain an exposure reading of 7 on a Stouffer 21-step density tablet.

A second group of panels was exposed at the same conveyor-speed setting of 12, but with the panels and master inside the plates of the Laminar phototool. This time, the exposure step-tablet reading was 8, thus indicating a reduction factor of $\sqrt{2}$, or 1.414, in the amount of light which reached the emulsion.

On subsequent test panels, using the Laminar phototool, the conveyor speed was reduced until an optimum exposure reading of 7 was obtained on the Stouffer density tablet. The conveyor-speed setting required for the optimum exposure was 7 (0.96 in./sec, or 24.38 mm/s).

Light Dispersion and Undercut

Ideally, the light passing through the phototool and the photomaster will be collimated to assure accurate duplication of the master image on the photographic emulsion. Collimation features were added to the exposure equipment to reduce the light undercut of the image.

Subsequent observation of the glow of light which was being emitted from the edges of the acrylic sheets indicated that considerable light reflection and refraction were present when the Laminar phototools were used. A study therefore was conducted to determine the amount of light undercut introduced by the use of the Laminar phototool plates as compared to the amount present when a cover plate was not used.

The test run consisted of 22 panels of G-10 printed circuit laminate clad on both sides with 2-ounce (2 oz/ft², or 0.61 kg/m²) copper. The panels were cleaned and resist-coated to the standard printed circuit process.* The exposure was made according to the standard process, except that Panels 6 through 22 were exposed using the Dynachem Laminar phototool plates with the conveyor speed reduced to give an equal light exposure to the resist. The image master consisted of a standard test pattern (S7466-004) with a Stouffer 21-step density tablet added for exposure control (Figure 7). All panels were developed according to the standard process.

*Process Engineering Specification P-1150047, Issue AC, Bendix Kansas City.

Figure 7. Standard Test Pattern S7466-004

Panels 1 through 5 were exposed at a conveyor-speed setting of 12 to yield a solid step-tablet reading of 7. The tooling arrangement consisted of the front and rear photomaster films pinned to the panel through two 0.250-inch-diameter (6.35 mm) tooling holes. This arrangement, normally used, provides the most intimate contact between the photoresist and the master, with the least possible amount of material between the light source and the resist.

Panels 6 through 22 were exposed at a conveyor-speed setting of 7 to yield a solid step-tablet reading of 7. The tooling arrangement was the same as that used for Panels 1 through 5, except that the panel and film master were sandwiched inside and pinned to the Laminar phototool plates.

An inspection of the panel images was made to determine the widths of three different-sized paths. The measurements obtained are shown in Table 6. Figures 8, 9, and 10 provide graphic displays of the data points and a comparison of process averages.

In Figure 8, a comparison of the median path width of Control Panels 1 through 5 (0.00294 inch, or 74.67 μm) with the median path width of Panels 6 through 8 and 11 through 22 (0.0030 inch, or 76.20 μm) indicates a 2-percent increase of 0.00006 inch (1.524 μm) with the use of the Laminar phototool.

Text continued on page 31.

Table 6. Path-Width and Undercut Inspection Results

Panel Number	Path 1		Path 2		Path 3	
	Width (Inch)*	Undercut (Inch)*	Width (Inch)*	Undercut (Inch)*	Width (Inch)*	Undercut (Inch)*
1C	0.0031	0.0015	0.0070	0.0025	0.0220	0.0025
2C	0.0028	0.0017	0.0075	0.0020	0.0229	0.0016
3C	0.0030	0.0015	0.0074	0.0021	0.0227	0.0018
4C	0.0030	0.0015	0.0077	0.0018	0.0231	0.0014
5C	0.0028	0.0017	0.0072	0.0023	0.0226	0.0019
Average Undercut		0.00158		0.00214		0.00184
6	0.0027	0.0018	0.0080	0.0015	0.0227	0.0018
7	0.0031	0.0014	0.0074	0.0021	0.0225	0.0020
8	0.0029	0.0016	0.0076	0.0019	0.0225	0.0020
9			0.0075	0.0020	0.0220	0.0025
10			0.0079	0.0016	0.0224	0.0021
11	0.0029	0.0016	0.0076	0.0019	0.0223	0.0022
12	0.0028	0.0017	0.0069	0.0026	0.0222	0.0023
13	0.0029	0.0016	0.0073	0.0022	0.0225	0.0020
14	0.0030	0.0015	0.0070	0.0025	0.0222	0.0023
15	0.0032	0.0013	0.0075	0.0020	0.0228	0.0017
16	0.0033	0.0012	0.0078	0.0017	0.0224	0.0021
17	0.0031	0.0014	0.0075	0.0020	0.0227	0.0018
18	0.0027	0.0018	0.0077	0.0018	0.0229	0.0016
19	0.0029	0.0016	0.0077	0.0018	0.0221	0.0024
20	0.0029	0.0016	0.0076	0.0019	0.0227	0.0018
21	0.0033	0.0012	0.0076	0.0019	0.0227	0.0018
22	0.0033	0.0012	0.0078	0.0017	0.0230	0.0015
Average Undercut		0.00150		0.00195		0.00199
Δ Average		+0.00008		+0.00019		-0.00015
*0.0001 inch = 2.54 μm.

Figure 8. Measured Widths of Nominal 0.005-Inch (127 μm) Exposed Paths

Figure 9. Measured Widths of Nominal 0.010-Inch (254 μm) Exposed Paths

Figure 10. Measured Widths of Nominal 0.025-Inch (635 μm) Exposed Paths

The Figure 9 comparison of the median path width of Control Panels 1 through 5 (0.00736 inch, or 186.944 μm) with the median path width of Panels 6 through 22 (0.00758 inch, or 192.532 μm) indicates a 3-percent increase of 0.00022 inch (5.58 μm) with the use of the Laminar phototool.

In Figure 10, a comparison of the median path width of Control Panels 1 through 5 (0.02266 inch, or 575.56 μm) with the median path width of Panels 6 through 22 (0.02249 inch, or 571.24 μm) indicates a 7-percent decrease of 0.00017 inch (4.318 μm) with the use of the Laminar phototool.

A precision inspection was made of the circuit-master path widths as a comparison of undercut for both the standard exposure process and the Laminar phototool exposure process. The same three paths were measured on all of the parts and on the circuit master. Results of the circuit-master inspection are shown in Table 7.

Table 7. Photomaster Path-Width Inspection Results

Path Number	Nominal Path Width (Inch) (μm)	Measured Path Width (Inch) (μm)
1	0.005 (127.0)	0.0045 (114.3)
2	0.010 (254.0)	0.0095 (241.3)
3	0.025 (635.0)	0.0245 (622.3)

An analysis of the light-undercut test data shows an undercut increase of 0.00008 inch (2.032 μm) on the 0.005-inch (127 μm) path, an increase of 0.00019 inch (4.826 μm) on the 0.010-inch (254 μm) path, and a decrease of 0.00015 inch (3.81 μm) on the 0.025-inch (635 μm) path. In all cases, the change in undercut caused by the use of the Laminar phototool was less than 3 percent.

ACCOMPLISHMENTS

A new photographic film, Kodak Kodaline 2566, was evaluated for use as a base for film phototools. Its physical properties and dimensional stability were found to provide significant improvement over films previously used in tooling applications.

A quantity of 0.0005-inch (12.7 μm) Mylar protective coverlay and automatic equipment for its application were procured and evaluated. The automatic equipment produced a more uniform application with greater ease than was possible with the hand-applied 0.002-inch

(50.8 μ m) coverlay that was previously used. The new coverlay also proved to be superior in function.

A new photographic tooling concept was established and implemented to improve the function of the phototool and, at the same time, to significantly reduce the fabrication flow time and cost. A bomb-sight punch was designed and built to punch the tooling holes in support of the new concept.

A commercially available Laminar photographic-exposure support and transport tool was modified to make it compatible with the Bendix Kansas City standard loading system for the exposure of thin, flexible printed circuits. Evaluation proved that implementation of the modified Laminar system would reduce the time and cost involved in the production and use of printed circuit phototools.

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