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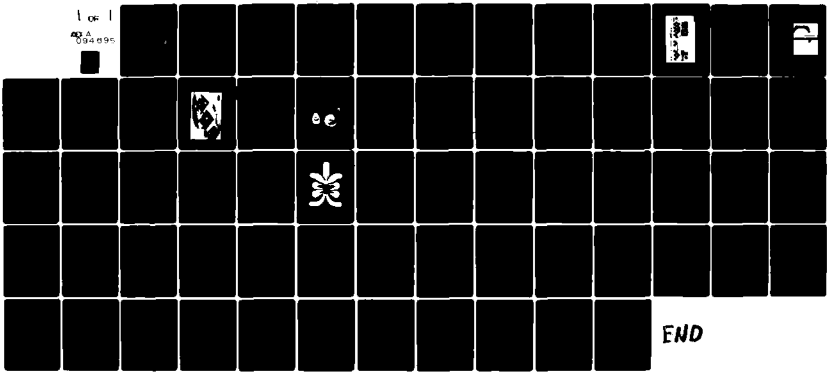

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Manufacturing Techniques For Producing High Quality Fluidic Laminates At Low Cost

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This report presents the results of a program conducted by AiResearch for the Naval Air Systems Command and monitored by Harry Diamond Laboratories. The precision stamping and fine blanking manufacturing processes were investigated as a means of producing high quality, low cost fluidic laminates.

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FOREWORD

In the past 20 years fluidic technology has advanced to the point where a few fluidic devices have reached production status. In this era of development and research, industry is finally recognizing the advantages of fluidics in many diverse applications. Fluidic technology is now on the brink of the advancement of fluidic components and systems into applications in large quantities requiring both high production rates and high quality.

In anticipation of the potential for rapid growth in the application of fluidics to large quantity production, AiResearch, in concert with the Naval Air Systems Command, has explored manufacturing processes which will satisfy these requirements. Precision stamping and fine blanking processes have been evaluated as means of producing fluidic amplifiers of high quality at high production rates. The electrical discharge machining (EDM) and laser manufacturing processes have also been evaluated to obtain very high performance amplifiers in limited quantities.

The program was authorized by the Naval Air Systems Command under Contract N00019-78-C-0365 and was conducted from June, 1978, to August, 1980. The program was monitored by the U.S. Army Harry Diamond Laboratories.

"Publication of this report does not constitute approval by the Naval Air Systems Command of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas."

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1. INTRODUCTION

Through concerted research and development efforts, fluidic technology has now grown to the point where a limited number of fluidic circuits are presently in production. In several areas, industry is on the brink of wide acceptance of fluidic technology; however, the manufacturing base to support the production required for this type of application has not kept pace with the advancement of fluidic applications. This paper describes the evaluation of various methods for manufacturing high quality, low cost fluidic laminates in large quantities at high production rates, for reduced cost.

A long range plan has been made and methods are being developed to fabricate fluidic laminates, and to plate, handle, assemble, and braze the fluidic circuits with as much automation as possible. The program phase discussed in this report addresses the preliminary steps in the evaluation process and the selection of a method whereby laminates can be produced with good quality in various quantities.

Fine blanking and precision stamping appeared to be the processes most likely to meet these requirements. The photochemical etching process, which is the method most commonly used at present to make fluidic laminates, was used as a basis for comparison.

The wire electrical discharge machining (EDM) process was used to fabricate the dies for use in precision stamping and fine blanking. Since the laminates manufactured from these dies should be no better than the laminates made by the EDM machine directly, the EDM process should establish the theoretical limit of laminate performance. Therefore, the laminates made by the EDM process were used to check the EDM computer program before the dies for the fine blanking and precision stamping were made. Using this technique for die manufacturing prompted further exploration of the EDM process for obtaining high quality laminates where cost and production rate are not the controlling criteria.

2. BACKGROUND

Over the years, many fabrication techniques have been used to make fluidic components and circuits. Much of the early research and development manufacturing was accomplished by machining, primarily since quantities were often limited to one or two units. As the technology advanced and limited-production quantities were required, other manufacturing techniques (such as etching) gained importance. The current emphasis, now that fluidic technology is maturing, is on high-quantity production methods.

The majority of fluidic circuits consist of thin metal plates or laminates of various configurations that are stacked together and bonded. Some of the types of fluidic laminates being manufactured are shown in Figure 1. These laminates may be made by shearing, eroding, melting the metal, molding, or by metal deposit. The following processes are some of the techniques which may be used to accomplish laminate fabrication

1. Photochemical etching
2. Injection molding
3. Electroforming
4. Hot wax process
5. Wire EDM
6. Laser cutting
7. Precision stamping
8. Fine blanking

Each of these processes is briefly discussed in the following paragraphs. The major purpose of the current study is to examine the last two processes in detail.

2.1 PHOTOCHEMICAL ETCHING (BASE LINE PROCESS)

In photochemical etching, the sprayed-on ferric chloride attacks the bare metal not protected by the photo-resist material to create the fluidic laminate.[1] Photochemical etching is the process used extensively in the electronic industry for printed circuit board manufacture. This process involves coating the surface of the material to be etched with a photo-sensitive film.

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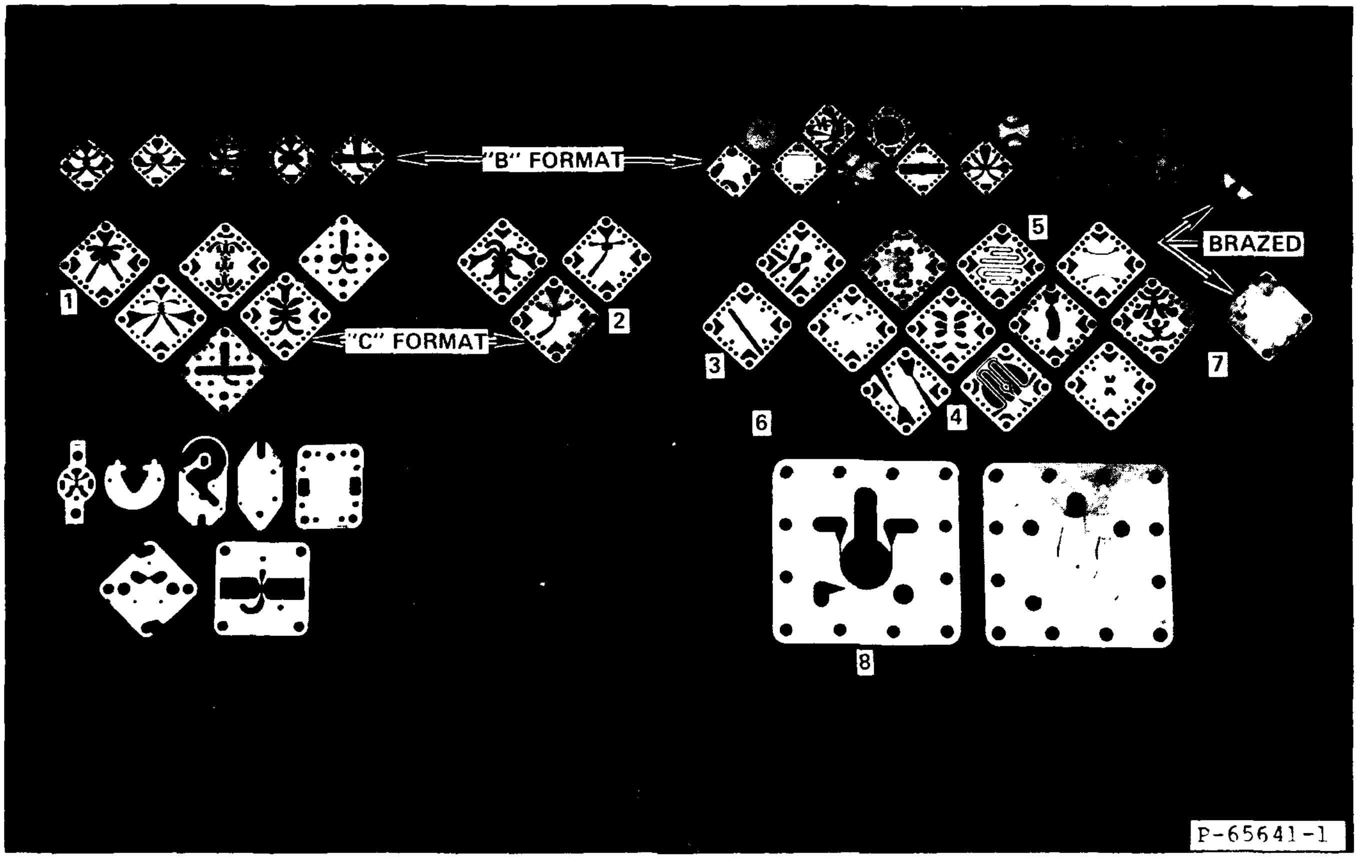
[1] T. G. Sutton and W. J. Anderson, "Aerospace Fluidics Applications and Circuit Manufacture," Harry Diamond Laboratories, Fluidic State-of-the-Art Symposium,Vol V, pp. 45-90, 30 Sep - 3 Oct 1974.

"B" FORMAT
1
"C" FORMAT
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The image of the part required is then contact-printed on both sides of the material. In this printing process, the film is polymerized such that the film is capable of being selectively dissolved in those areas to be removed by the subsequent etching. An etchant (commonly ferric chloride based) is then sprayed on both sides of the material and the exposed material not protected by the film is removed. Since the laminate is etched from both sides, a center ridge remains in the sidewall as a result of undercutting from the top and bottom of the laminate. Figure 2, a typical cross-sectional view of a chemically etched part shows the center ridge which adversely affects circuit performance. Since laminate thickness directly affects the sidewall shape, critical fluidic laminates are etched in thin sheets and then stacked together to obtain the desired thickness. Present critical fluidic laminates such as amplifiers may be fabricated by chemically etching metal thicknesses up to 0.25 mm (0.010 in.). Noncritical laminates may be etched to 1.0 mm (0.040 in.) thick. The etching rate of this process is about 0.5 mm (0.020 in.) per hour. Photochemical etching is currently the most common method used to manufacture fluidic laminates.

2.2 INJECTION MOLDING

In the injection die molding process, hot plastic material is pressed into a set of dies to mold an amplifier design. This method was successfully used to manufacture a number of older designs of turbulent-flow fluidic digital amplifiers for Harry Diamond Laboratories (HDL) and is also used for the manufacture of a number of commercially available fluidic components. A program is in progress at HDL to examine the use of this process to manufacture the laminar proportional amplifier (LPA).

2.3 ELECTROFORMING

In the electroforming process, a special tool is used to make a part, with material deposited in layers on the tool. Electroforming is best suited to making simple circuits that fit in a planar configuration. The process has been successfully used in the manufacture of a fluidic stability augmentation system for helicopters.[2] However, this process has severe limitations, not only with respect to packaging but also in the type of materials that may be used.

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[2] W. Posingies, "Production Suitability of an Electroform Conductive-Wax Process for the Manufacture of Fluidic Systems," Honeywell, Inc., USAAMRDL-TR-77-2, April 1977.

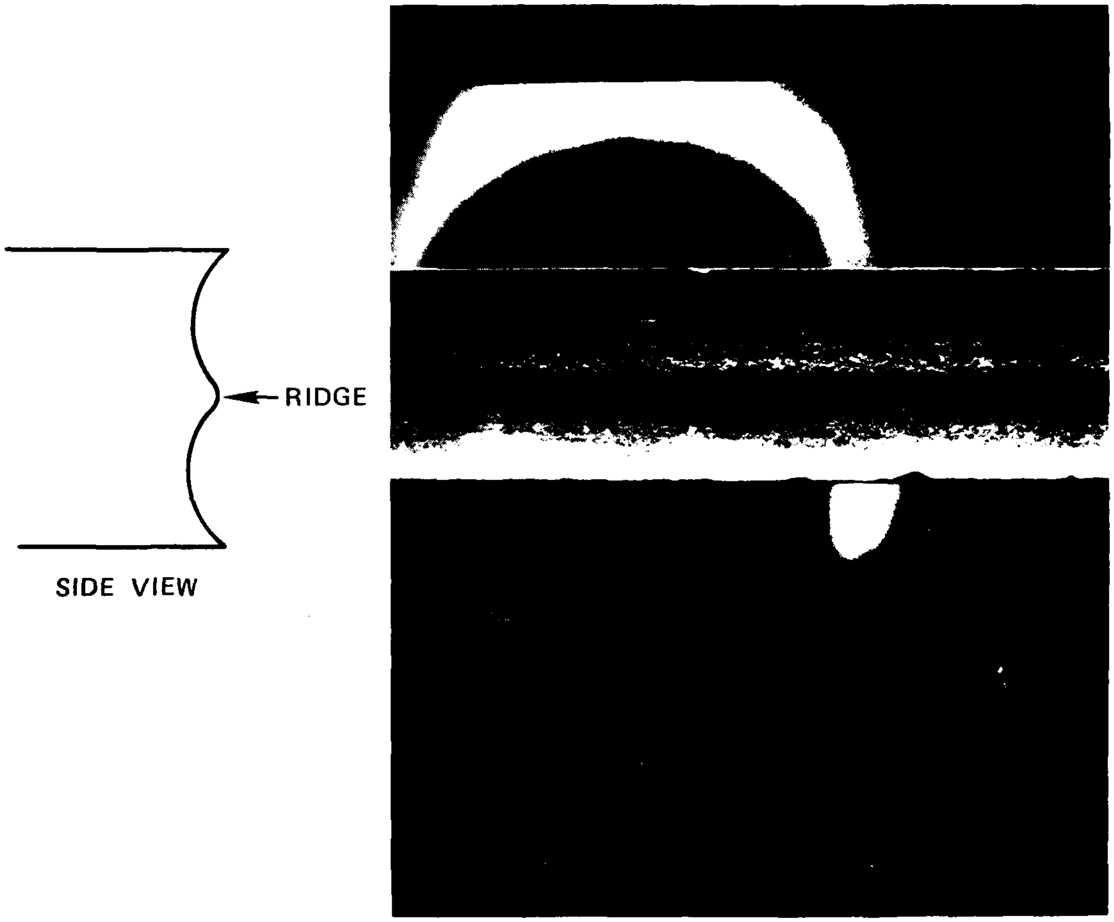


Figure 2. Sidewall profile of a photochemically etched laminate.

2.4 HOT WAX PROCESS

The hot wax process is a method by which not only fluidic laminates but the entire fluidic circuit can be made in one step. In this process, metal is deposited around a wax tool. After the part is formed, the wax is melted out. This process may have some potential for simple fluidic circuits; however, where very high quality laminar proportional amplifiers are required, the consistent repeatability of quality parts may not be possible.

2.5 LASER CUTTING

The process of laser-cutting of fluidic amplifiers was limited to a feasibility evaluation. Tests have been conducted using a pulsed laser beam to cut an amplifier profile. The material is melted by a high energy beam and then removed by 275-kPa (40-psig) shop air or an inert gas. Since the components made for tests to date have not been optimized with respect to average power, pulse width, pulse rate, focus, and cutting speed, the side walls produced have been scallop shaped. The time required to fabricate amplifier profiles in 0.76 mm (0.030 in.) thick materials averaged 30 seconds per part (two parts per minute).

2.6 WIRE EDM

In wire EDM and conventional EDM, an electrode melts the material in the controlled cutting process of a part. The wire EDM process uses a programmed set of coordinates to locate the wire position, while the wire is continuously unwinding. Arcs across a small gap are used to melt the material; the wire never physically contacts the material. A deionized water solution is passed over the spark area to provide the necessary electrical contact, to clean and remove melted material, and to maintain a fairly consistent material temperature. The wire size used for most fluidic amplifiers is about 0.20 mm (0.008 in.) diameter; however, for small radii and corners, a 0.10 mm (0.004 in.) diameter wire is required.

Burning rates vary depending on material thickness and wire diameter. For a 2.5 mm (0.100 in.) thick stack of laminates using a 0.20 mm (0.008 in.) diameter wire, about three hours are required for setup, cutting, and trimming a typical amplifier profile.

In programming the amplifier profile, the machine allows for the wire to be offset. The amplifier can then be cut undersize, and the wire is progressively offset to trim the profile to the proper dimensions.

2.7 PRECISION STAMPING

Precision stamping is refined conventional stamping in which punch and die clearances are minimum, and a spring-loaded counterpunch can be located in the die cavity. Figure 3 is a cross-sectional view of the precision stamping die showing how the material is sheared. Figure 4 identifies the die roll, shear and break edges, and the burr.

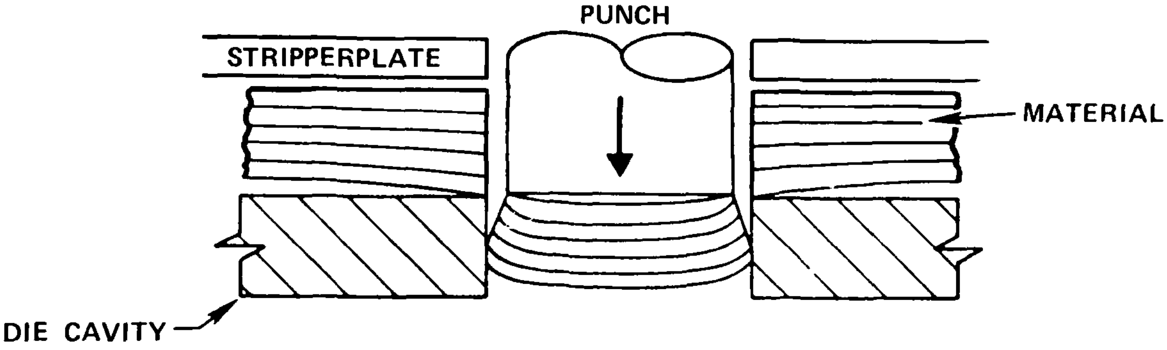


Figure 3. Cross-sectional view of precision stamping die.

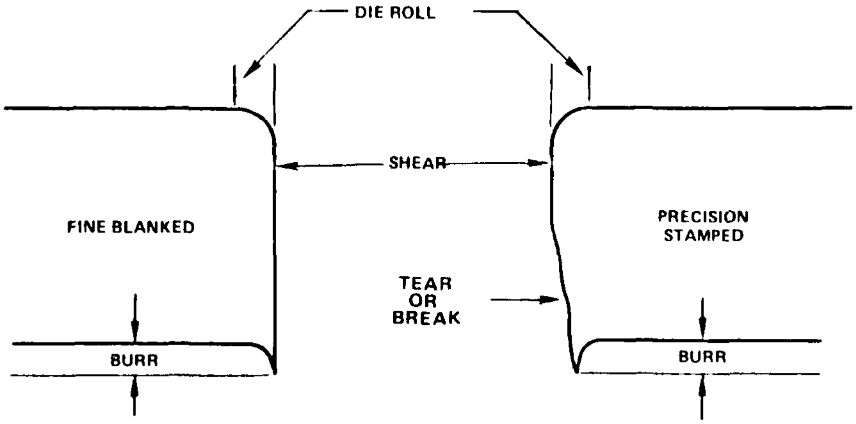
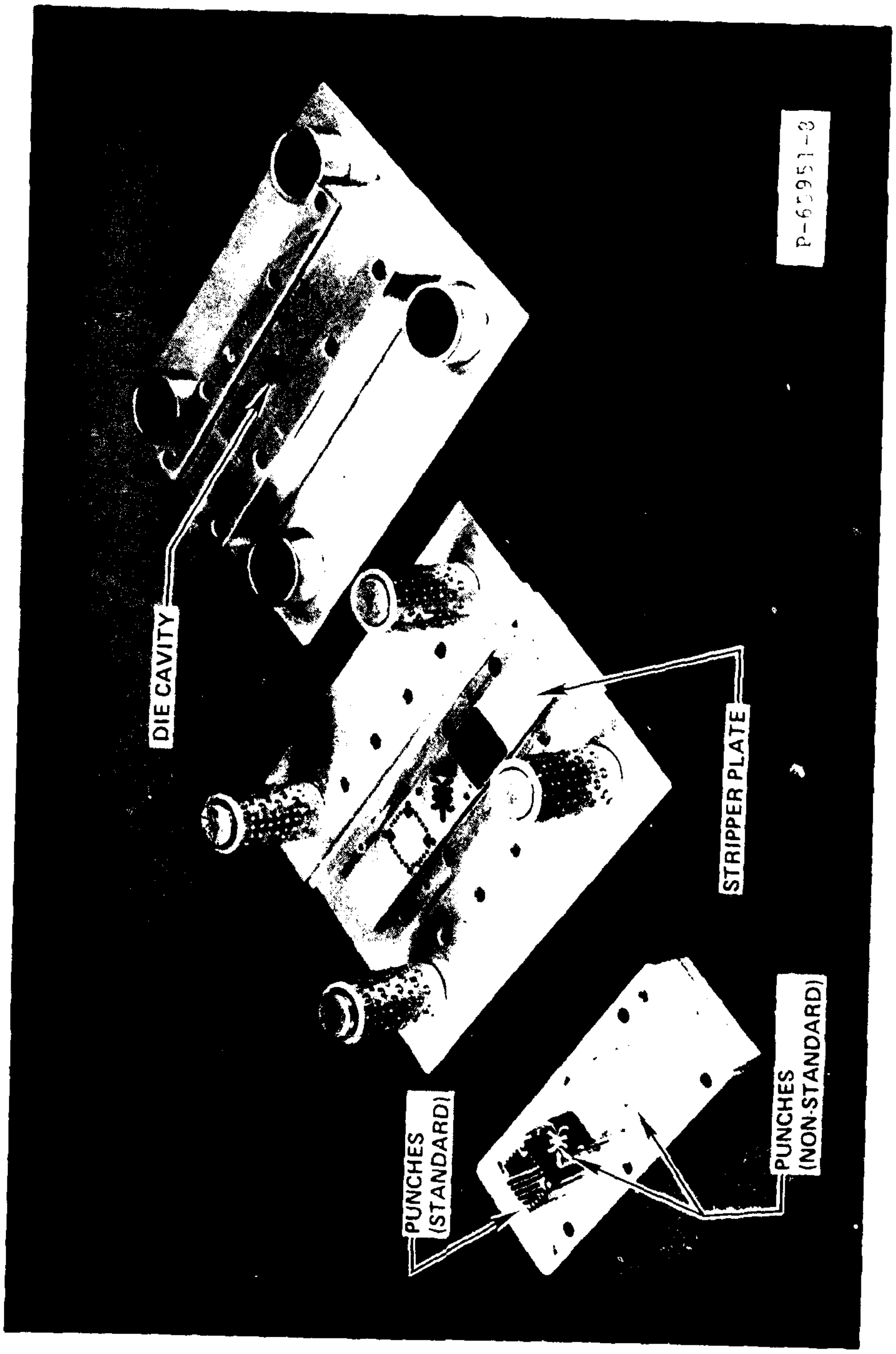


Figure 4. Cross-sectional view of a typical fine blanked and precision stamped part.

Figure 5 presents a typical precision stamping die showing the punches, die cavity, and multiple stations. The amplifier profile punch and other nonstandard punches are made on the wire EDM machine. Generally, the punch is cut first. The die cavity is then cut undersize and progressively increased in size until a proper fit is obtained between the punch and die cavity. The clearance between the punch and die are on the order of 0.013 mm (0.0005 in.) per side. The punch forces are supplied by a flywheel and cams, but the counterforce to the punch is a spring-loaded pad which creates what is called a compound station. This allows the material to be supported during cutting to obtain a flatter laminate with a good portion of the side wall sheared rather than torn. The one drawback to the spring-loaded compound station is that the pad pushes the slug back into the strip which tends to bend the laminate. The degree of bending is determined by the amount that the slug is pushed into the strip. The original die configuration had a compound station or pad for the amplifier profile and a square laminate profile for the last station. The amplifier pad was eliminated due to the detrimental effect of pushing the slug back into the strip. However, when the amplifier section was still a compound station, the last station pushed the amplifer even further into the strip, thus resulting in serious bending of the amplifier when the amplifier slug was finally removed from the laminar proportional amplifier (LPA) laminate. The square laminate profile pad was also removed; however, the laminates produced without a pad in this station were bent [0.051 mm (0.002 in) out of flat].

Since precision stamping dies are generally multiple stations, a different laminate can be fabricated by: (1) removing punches, or (2) substituting a new punch and die cavity. By removing punches, only gaskets and laminates with holes can generally be fabricated. When a new punch and die cavity replaces a certain portion of the old die, a completely new part can be made. This new die with the substituted punch, die cavity, and stripper plate is called an insert die. Insert dies use about one-half of the parts of the original die and also cost about one-half what a new die would cost.

The material to be stamped plays a large part in the design selection of the die. Smaller radii can be stamped from soft materials (i.e., aluminum and 347 stainless steel) than from tougher or harder materials. The material selected for the dies tested in this program was D-2 tool steel because of cost, quantity of laminates to be produced, and the shape of the thin narrow sections such as the splitter. A carbide tool may produce more laminates, although at a slightly higher initial tooling cost. The carbide die has a higher probability of chipping in the narrow splitter segment of the die cavity when the higher strength alloys are stamped.


DIE CAVITY
STRIPPER PLATE
PUNCHES (STANDARD)
PUNCHES (NON-STANDARD)
P-65951-3

The stamping rate is a function of the material thickness and the size of the part. For most fluidic laminates, the production rate will be between 70 to 120 parts per minute.

2.8 FINE BLANKING

Fine blanking is similar to precision stamping where all the blanking can be performed in one compound station.[3] In blanking, the counter force which supports the material during blanking is controlled by a cam action rather than the spring action used in the stamping process. The laminates are removed from the dies by ejectors which push the slugs and the laminates into the die cavity area for final removal either by an airblast or by hand. Production rates for fine blanking are 30 to 40 laminates per minute when the laminates are removed from the machine by air blasting. About four laminates per minute can be produced when laminates are removed from the machine by hand.

Blanking dies are made in approximately the same manner as precision stamping dies. A wire EDM machine is used with a minimum tolerance of 0.013 mm (0.0005 in.) maintained between the punches, die cavity, and ejectors. A typical fine blanking die used to fabricate 0.64 mm (0.025 in.) and thicker parts has a "Vee" groove around the punch to hold the material and prevent it from flowing around the small radius of the die cavity, thus minimizing burr formation. However, the "Vee" groove was eliminated because of the thinness of the fluidic laminates. The small radius on the die cavity was also eliminated to reduce the burr and thereby improve the flatness. However, elimination of this small radius was at the expense of tool life. Since the small radius means essentially additional tolerance between the punch and die, any decrease in punch and die clearance puts an extra strain on the punches and thus reduces the tool life. Figure 6 shows a cross section of a fine blanking die in the process of fabricating a part. A picture of the fine blanking die is shown in Figure 7.

As with precision stamping, the selection of material to be fine blanked will affect the design of the die. Softer materials with radii as small as 0.095 mm (0.00375 in.) can be fine blanked in limited quantities.

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[3] F. Bosch, Fine-Blanking, Practical Handbook, Feintool AG, LYSS, 1972

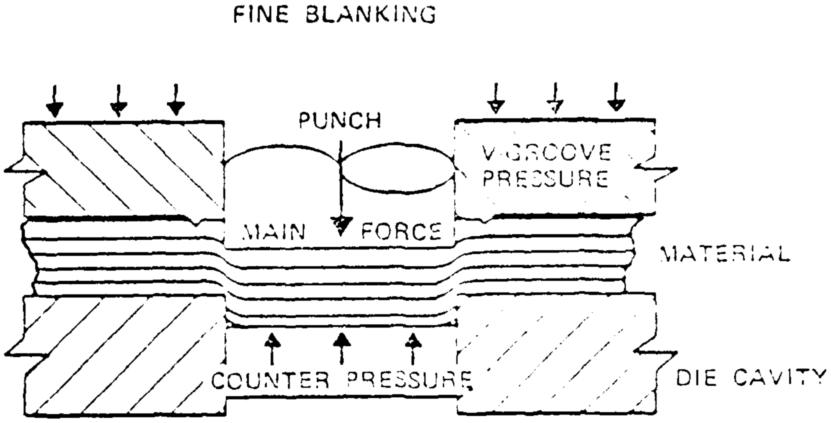

Figure 6. Cross-sectional view of a fine blanking die fabricating a part.

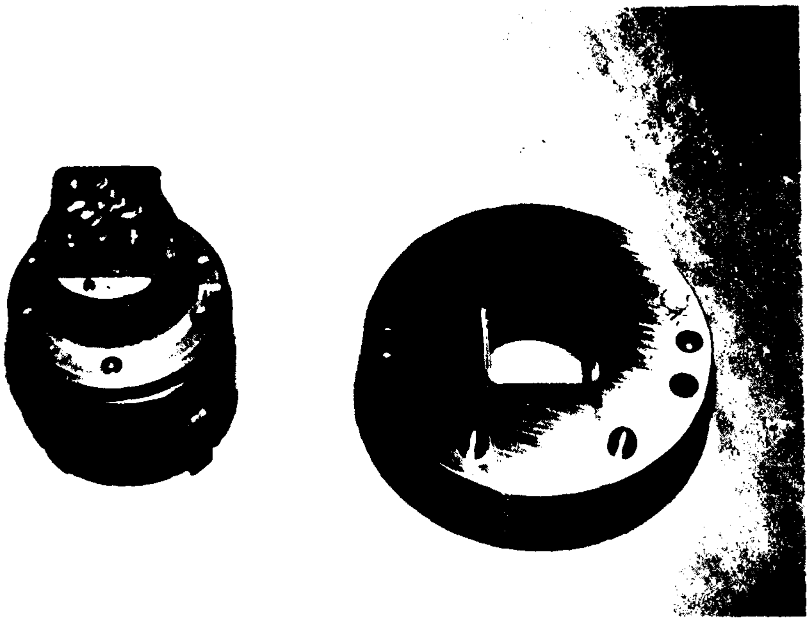

Figure 7. Typical single station fine blanking die.

A preliminary study of the fine blanking process for fabricating fluidic LPA laminates was performed by HDL.[4] The results were generally encouraging and provided a sound basis for the current program.

Of the eight processes discussed above, only precision stamping and fine blanking have the potential for high-quantity production of high-quality fluidic laminates. The chemical etching process may be adapted to high volume production for laminates not requiring high precision where the thickness is less than 0.25 mm (0.010 in.). For these reasons, the precision stamping and fine blanking processes were evaluated in depth and made the primary subject of this report.

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[4] R. M. Phillippi, "A Study of Fine Blanking for the Manufacture of Flueric Laminar Proportional Amplifiers," Harry Diamond Laboratories, HDL-TM-77-8, May 1977.

3. MANUFACTURING REQUIREMENTS

Each fluidic circuit contains some passive and active types of fluidic laminates. The passive elements are the exhausts, transfers, gaskets, etc. These laminates require a lesser degree of accuracy because the function they serve in the circuits is not as critical as the active types of laminates. The active laminates which require a high degree of performance and quality are the amplifiers, rate sensors, diodes, vortex valves, etc.

The quality requirement is therefore dependent on how the laminate is used. The criteria for maintaining and describing quality are listed below.

1. Laminate flatness is to be within 0.025 mm (0.001 in.) to minimize leakage of unbrazed circuits and to prevent leakage through joints when the circuits are bonded.

2. Sidewalls of flow paths are to be smooth and uniform throughout the laminate. The sidewall should be square with the top and bottom surface.

3. Repeatable performance of laminates is to be obtained without component modification or selective matching.

4. Amplifier control, supply, and receiver ports are to be symmetrical with respect to the centerline such that output in the laminar region has an offset of less than one percent, where offset is defined as the ratio of the block-loaded output differential pressure (with no control signal present) to the supply pressure, expressed in percent.

Most passive or noncritical laminates such as gaskets, transfers, etc., must meet only the first requirement; however, amplifiers generally must meet all four requirements.

4. DEVELOPMENT PROGRAM

The need for low cost methods of fabricating fluidic laminates depends on the application of the laminate as well as the quantity required. One application might require a very symmetrical and repeatable part, while another may require a less accurate part. Therefore, parts must be of high quality for one application, and not necessarily be of equal quality for another. Quantity also affects laminate cost since tooling must be amortized on a per piece basis. Therefore, in a limited quantity production, expensive tooling is difficult to justify for a low cost method. For this reason, various methods that may yield high quality fluidic laminates for a wide range of applications and in a variety of quantities were evaluated.

4.1 FLUIDIC LAMINATE DESIGN

The design of the laminates selected for evaluation was based on the following criteria:

1. It should be representative of the types of laminates in use and be of a usable configuration.
2. The design should have sufficient flexibility to permit evaluation of critical parameters (small radii and slot width) by small design modifications.

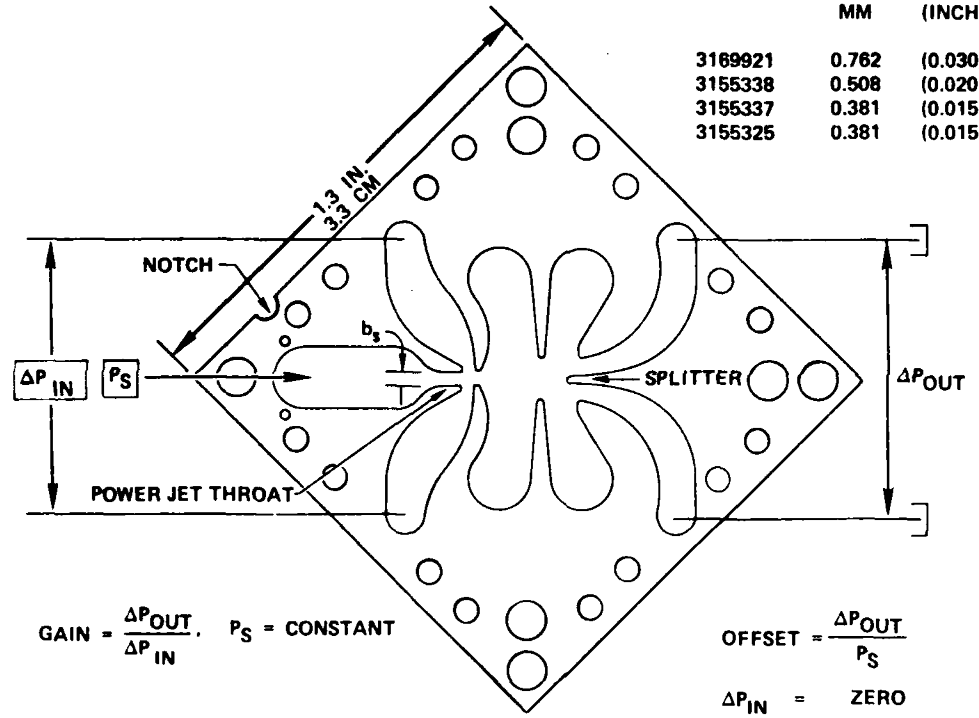
The fluidic laminate design chosen for this program was a standard AiResearch "C" format Laminar Proportional Amplifier (LPA). The amplifier was scaled from the basic design shown in Figure 8. The table on Figure 8 shows the three power jet widths used and the respective minimum radii on the amplifier splitters.

4.2 FABRICATION

A few parts were made as a feasibility study and as a comparison standard by photochemical etching, laser cutting, and wire EDM. Two fine blanking dies were made to fabricate two different size LPA's. Two precision stamping dies, one with interchangeable punches, were made to fabricate three different size LPA's. Table I is a summary of the die configurations used on this program. Dies 1 and 2 were designed to evaluate fabrication of the same amplifier by the stamping and blanking processes. Dies 3A and 3B were made to produce amplifier laminates with sharp corners on the exit of the power jet supply nozzle and control ports and to evaluate the ability to fabricate small radii splitters and narrow slot widths by stamping. Die 4 was the same as Die 3B except that it had round rather than sharp corners on the supply nozzle. Die 4 was designed to evaluate the ability to fabricate small radii and slot widths by fine blanking.

POWER JET WIDTHS AND SPLITTER RADII

AMPLIFIER NUMBER	POWER JET WIDTH (b_s)		MINIMUM SPLITTER RADIUS		DIE DESIGN
	MM	(INCH)	MM	(INCH)	
3169921	0.762	(0.030)	0.191	(0.00750)	1 AND 2
3155338	0.508	(0.020)	0.127	(0.00500)	3A
3155337	0.381	(0.015)	0.095	(0.00375)	3B
3155325	0.381	(0.015)	0.095	(0.00375)	4



$$\text{GAIN} = \frac{\Delta P_{OUT}}{\Delta P_{IN}}, \quad P_S = \text{CONSTANT}$$

$$\text{OFFSET} = \frac{\Delta P_{OUT}}{P_S}$$

$$\Delta P_{IN} = \text{ZERO}$$

Figure 8. AiResearch "C" format amplifiers.

TABLE I. DIE CONFIGURATIONS

Die No.	Die Type	Laminar Proportional Amplifier Power Jet Width (b_s)		Comments
		mm	in.	
1	Precision stamping	0.76	0.030	
2	Fine blanking	0.76	0.030	
3A	Precision Stamping	0.50	0.020	Sharp corners on exit of power nozzle and control ports
3B	Precision stamping	0.38	0.015	Sharp corners on exit of power nozzle and control ports
4	Fine blanking	0.38	0.015	

4.3 LAMINATE INSPECTION AND PERFORMANCE TESTING

The quality of a fluidic laminate is determined by an evaluation of both the physical and performance characteristics of the laminate. Physical evaluation consists of dimensionally inspecting the laminate for conformity to the applicable drawings. Performance evaluation consists of checking those active fluidic laminates such as amplifiers which have some basis for establishing an acceptance or rejection criteria.

Standard inspection tools were used to perform physical inspection for conformity to applicable drawings and to determine the amount of die roll, break, and burr. The die roll and break are essentially determined by the die tolerances and the laminate material. Although both parameters are easily measured, few simple changes other than sharpening the die cavity and punches will significantly affect the die roll or break. On the other hand, the burr is directly related to the punch profile and sharpening the punch will decrease the burr. A comparator chart, shown in Figure 9, provides a rough comparison of a template

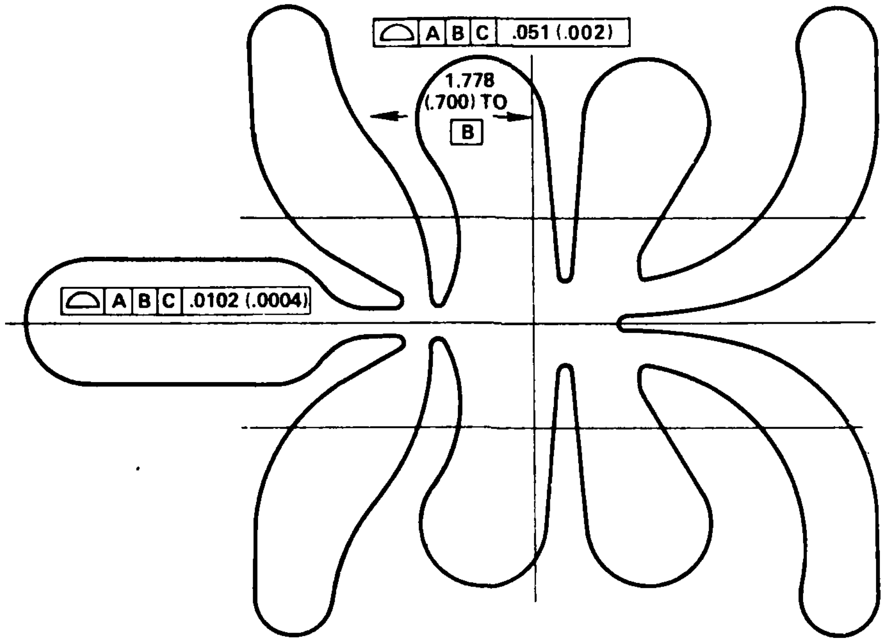


Figure 9. Comparator template.

limit to the laminate shadow. However, the lack of a definite reference line limits the usefulness of a simple comparator or template. More sophisticated comparators, such as a numerically optical comparator, are capable of inspecting the amplifier design. These devices are very expensive and are also somewhat limited in actual usefulness since the actual criteria for amplifier acceptance is based on performance rather than on dimensional tolerances.

Performance evaluation offers a meaningful method of accepting or rejecting amplifier laminates by measuring gain and offset. Gain is defined as $\Delta P_{OUT}/\Delta P_{IN}$ and offset is defined as $\Delta P_{OUT}/P_S$, where ΔP_{OUT} vs P_S is shown in Figure 8. The test procedures are detailed in Appendix A. Gain tests verify that the gain of the amplifier is within a reasonable limit. The offset test reveals more about amplifier symmetry than any of the other tests and is used to define the repeatability of the manufacturing process. The objective of the evaluation was to show that if a specific process can produce fluidic laminates within reasonable offset variation limits, then lot sampling becomes a viable inspection technique.

5. PROCESS ANALYSIS

In the current program, the major emphasis has been on evaluating two processes that are capable of high-quantity production of fluidic laminates while minimizing cost. These two processes are precision stamping and fine blanking. In addition, two other processes (wire EDM and laser cutting) were briefly examined as potential low-quantity processes where high quality is the prime consideration. Evaluation of these processes for high-quality laminates was spurred by the hypothesis that if the dies for precision stamping and fine blanking were made by the EDM process, then the quality of these laminates could be no better than if they were made by the EDM process directly. The continuous beam laser machining process is also a computer-controlled process that uses a laser beam rather than a continuous wire as in the EDM process. Therefore, a basic assumption was made that the laser beam process also could be used to achieve the same high quality as the EDM process.

Various aspects of the above processes, along with a discussion of chemical etching for comparison purposes, are presented in the section that follows.

5.1 PRECISION STAMPING PROCESS

Evaluation of this process has shown that a wide range of materials (either plated or unplated) can be used to blank out fluidic laminates in thicknesses now in common use in fluidic circuits. The quality of the laminate can be controlled by the precision used in the fabrication and rework of the die. This process has the flexibility of fabrication in multiple stations. This permits some refinement of the sharpness of corners being cut in a laminate and also permits the fabrication of a variety of laminate configurations by removing die stations or parts of the punch. Additional laminate configurations can be achieved at a much reduced cost by replacing punch configurations in appropriate stations.

This manufacturing technique shows good overall potential for achieving the desired objective outlined for this program. The technique for removing the laminate from the machine needs to be improved to prevent the possibility of damage. Presently, the laminate falls out of the die by gravity through a slide which is machined into the die. This facilitates extraction of the laminate from the die, after which the laminate drops into a box. Laminates handled in this fashion are exposed to damage. As an alternative, the laminates can be removed by hand one at a time; however, this seriously slows down the production rate (e.g., 3 to 4 parts per min). Even though the laminates are carefully extracted by hand, there is no guarantee that they will not be damaged in cleaning, storage, or assembly. Therefore, continued evaluation is necessary to develop techniques for laminate extraction, cleaning, handling, storage, and assembly to prevent damage of the laminates and to facilitate automation of fluidic circuit manufacture.

5.1.1 Insert Punch

Laminates are fabricated by precision stamping using multiple stations. The porting holes around the periphery are stamped in one station. The center section is then stamped in another and finally the exterior of the laminate is stamped out of the strip in another station.

Additional stations may be added which will permit stamping the amplifier, or other laminate configurations, in sections. In this program, the amplifier control porting was cut separately in a fourth station to facilitate achieving square corners at the power jet and control port output in the interaction region.

The use of multiple stations in the die provides flexibility which permits replacement of the punches in the die with insert punches and new stripper plates. These inserts offer flexibility for making multiple precision laminates from one die. Amortization of die cost is thus spread over the production of a larger number of laminates which reduces the cost of using the process.

A variation of the process of inserting punches to increase the number of laminate configurations which may be made from a single die is the simple removal of punches. When the center (amplifier) punch is removed, gaskets can be fabricated with the die. In addition, removal of the peripheral punches will permit fabrication of cover plates. Removal of discrete peripheral punches permits a large range of gasket configurations to be made. Also, if the die is designed with another station for transfer lines, vents, or exhausts, then approximately 50 different laminates could be made by one tool, thereby reducing tooling cost.

5.1.2 Die Modification

After the precision stamping die was fabricated, a representative sampling of laminates was made and tested for performance. The performance data initially showed excessive null offset (7.5 percent) in the LPA's produced from this die. Consequently, the pierce punch was then modified by hand rework to improve the resultant performance of subsequent laminates. The steps in the procedure for modifying the die are:

1. Establishing which receiving port is at the higher pressure.

2. Removing a small amount of the pierce punch sidewall at the powerjet throat on the same side of the LPA receiver port having the higher pressure recovery

3. Blanking approximately 20 LPA's

4. Retesting as described in Step 1 above.

5. Repeating as necessary.

The process specification, Appendix B, Section 3, contains additional die calibration procedures. A diamond grit compound was used to remove 0.002 to 0.005 mm (0.0001 to 0.0002 in.) of material in steps until the desired performance was achieved. The performance change from die modification is illustrated in Figure 10.

5.1.3 Laminate Design Adjustment

Modification to improve laminate performance can also be accomplished by adjusting the position or location of the centerline of the receiver ports relative to the centerline of the supply pressure power jet. The computer design data defining the laminate (amplifier in this case) is changed in small increments until the die is recut (by wire EDM machine) in the receiver port area sufficiently to produce an LPA laminate which will give the desired performance. This is an excellent alternative to the technique of modification of the power jet of the die described previously. However, the change in performance is more sensitive to modification of the power jet.

5.2 FINE BLANKING MANUFACTURING PROCESS

In many respects, the fine blanking process is similar to the precision stamping process. Therefore, this process will be described in terms of how it differs from the precision stamping process. The fine blanking die is generally built in a single station; thus, the laminate is fabricated in one blanking movement instead of the three or four strokes which are required in a multiple station stamping die. In the fine blanking process, pressure is exerted from below the material being blanked as well as from above; therefore, the laminate is well-supported in all segments of the amplifier.

The fine blanking die can be modified or its design can be adjusted to improve LPA laminate performance in a manner similar to that of the precision stamping die. Dies built for small changes in performance of laminates with small slots or radii are difficult to modify because it is difficult to insert the proper tooling into the area around the small throat section of the power jet. Redesign of the

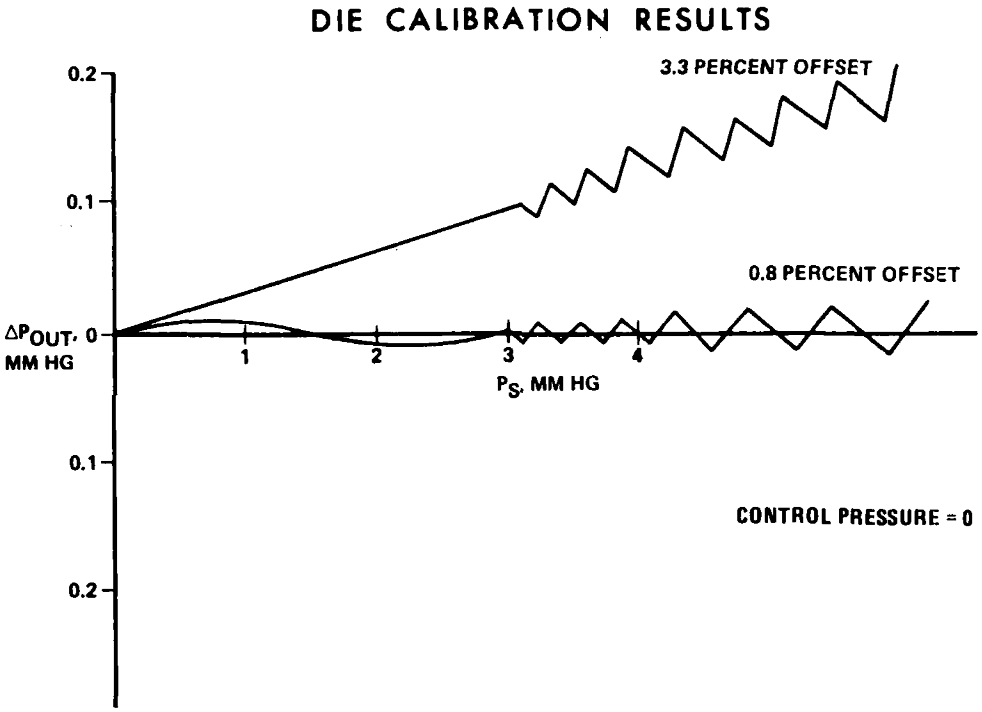


Figure 10. Offset performance before and after die calibration.

receiver section to achieve performance improvement of amplifiers is also very difficult for small flow channels and radii because of the large changes in performance that occur with very small changes in or minor modifications of the receiver ports. However, the problem with small dimensions exists for both the precision stamping as well as the fine blanking processes. There is some possibility that the critical areas of amplifiers can be stamped or blanked in separate stations so as to facilitate die modification.

Insert punches and multiple station dies can, like precision stamping, be made for fine blanking. This enhances the flexibility of this process by reducing the tool cost per laminate.

5.3 SHORT RUN STAMPING

Low cost stamping dies can be made which can produce noncritical laminates at low cost in limited quantities at fairly high rates. Tooling cost are estimated to be approximately $500 per tool. Quality of noncritical laminates is not a significant factor as long as the sidewalls are reasonably smooth and the laminates do not leak when bonded. To achieve this, the size of the burrs must be no greater than those obtained by fine blanking or precision stamping. Initially, this approach appeared to be a good process for this category of laminates. However, this process should be evaluated to determine if it is cost effective when compared with the multiple-die precision stamping process described in paragraph 5.1.1.

5.4 WIRE EDM PROCESS

The LPA laminates produced by the wire EDM machine are cut relatively slowly by a carefully controlled process, thereby resulting in good repeatability. Null offsets for EDM-produced LPA's are usually less then two percent.

A brief experimental study was initiated to further optimize the EDM process to obtain reduced null offset. To improve performance, the LPA computer program for the EDM process was modified to move the splitter or entire output receiver area to compensate for whatever null offset was initially measured. Results of this study are summarized in Figure 11. In general, moving only the splitter provided better null offset reduction than moving the receiver land area. However, the sample sizes involved were insufficient to draw any firm conclusion. Although it appears that such modifications can be used to improve null offset to produce a high-quality LPA, exact procedures for so doing cannot be defined at this time.

5.5 LASER CUTTING PROCESS

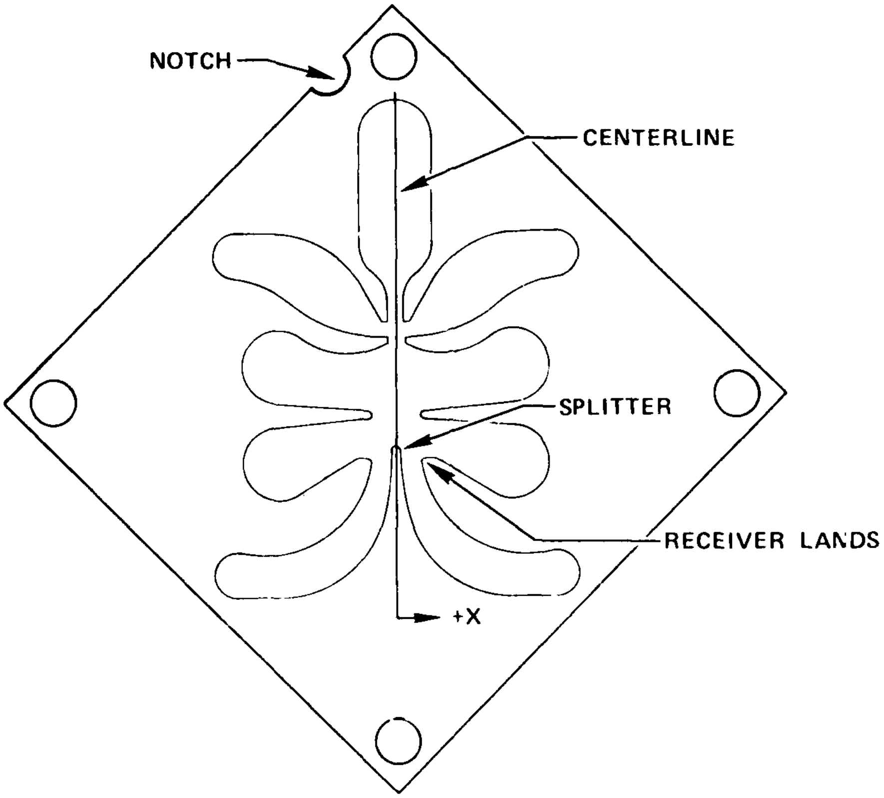
Laser cutting was investigated as a possible method to fabricate high quality laminates. Figure 12 is a comparator view of a laser-cut amplifier. The scalloped sidewall condition resulting from the pulsed laser beam and the cleaning gas adversely affects amplifier performance. Inspection after laser cutting revealed a hard burr where the melted metal adhered to the underside of the laminate.

The burr was brittle and some of the sidewall of the laminate was removed when the burr was chipped away. The effects of the burr could be minimized by cutting a stack of laminates and using a thin laminate on the underside to provide a surface on which the melted material may adhere.

The jagged edge and sharp corners may be eliminated or reduced substantially by a continuous beam laser, provided that the heat generated by this process does not adversely affect the laminate. Although this process was considered as being no better than wire EDM in terms of potential quality that could be realized, it can produce LPA's at a faster rate (2 parts per minute as compared with about 0.03 parts per minute).

5.6 PHOTOCHEMICAL ETCHING PROCESS

The photochemical etching process has been used over the past 20 years to produce fluidic laminates. This process is particularly good for fabricating low cost, noncritical laminates in small quantities. The quality of the laminates produced by this process is not suitable for amplifiers, rate sensor laminates, and similar type laminates where good repeatable accuracy is required for circuits in production. However, for engineering development work where engineers and laboratory technicians work closely with each laminate, this process is quite satisfactory. When selected at random, the performance of amplifiers which have been photochemically etched will unpredictably vary in performance with an offset up to ±10 percent. To assure good repeatable and no greater than ±1.0 percent. This is the reason that this process is not suitable for fabricating production quantities of amplifier laminates.



AMPLIFIER	REGION OFFSET SPLITTER INCH	 RECEIVER LANDS INCH	OFFSET PERFORMANCE PERCENT
3169921 1	0.0	0.0	1.8
3169921-2	+0.0001	0.0	1.2
3169921-3	+0.0003	0.0	0.7
3169921-4	0.0001	-0.0001	1.2
3169921-5	0.0003	-0.0003	1.8
3169921-6	+0.0004	+0.0001	2.4
3169921-7	+0.0006	+0.0003	3.2

Figure 11. Receiver offset calibration and performance variation.

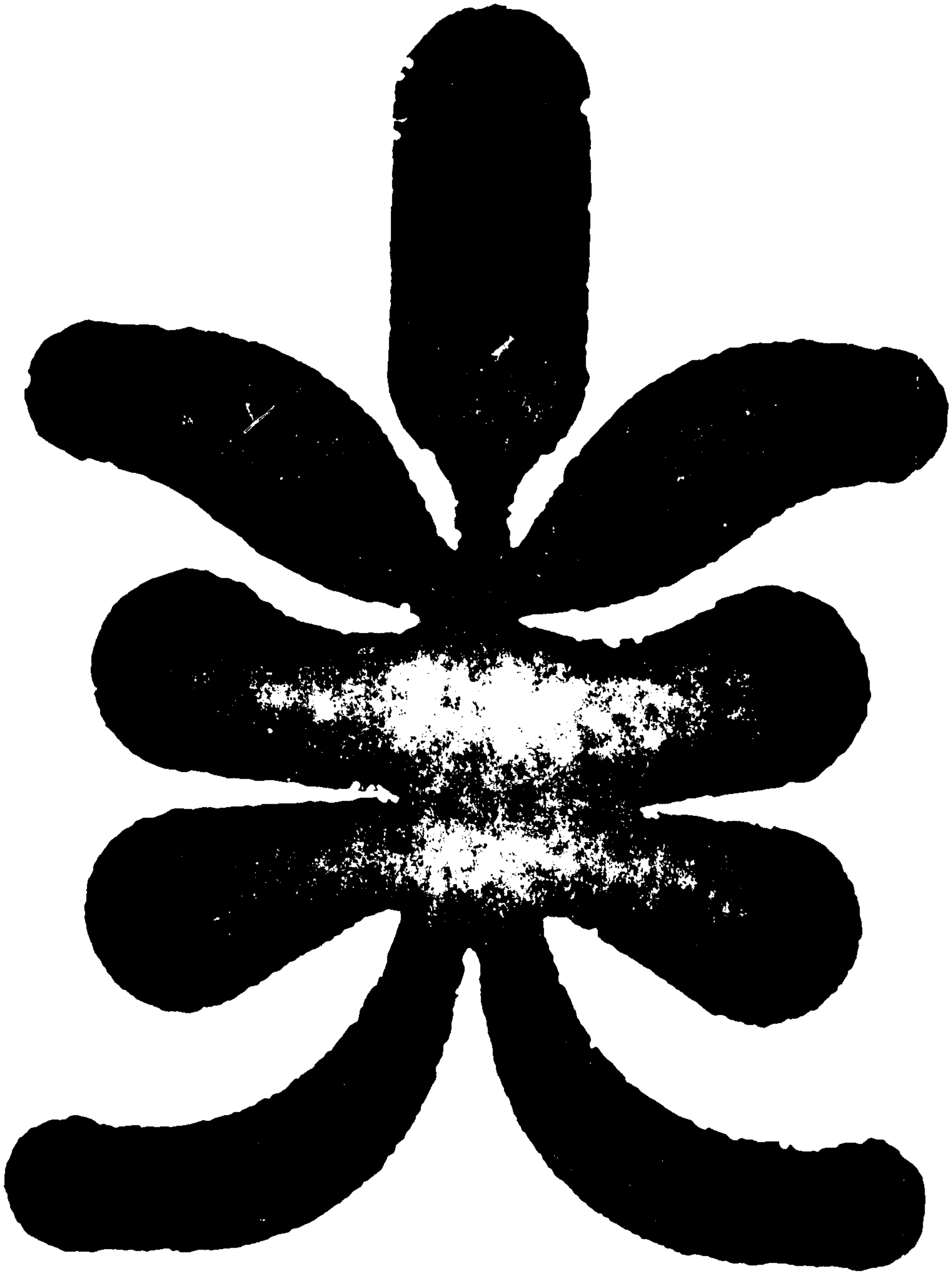


Figure 12. Comparator view of a laser-cut amplifier.

6. TEST RESULTS OF STAMPED AND BLANKED LPA LAMINATES

Four dies were made to evaluate the precision stamping and fine blanking processess for making fluidic laminates. The amplifier shown in Figure 8 was fabricated by these four dies to evaluate the feasibility of these processess to make the amplifiers in the sizes shown in Table I. Optimum LPA performance is generally obtained when the aspect ratio (laminate thickness divided by the width of the power jet throat, b_s), is one. Therefore, the objective was to blank a laminate that was as thick as the power jet is wide.

The offset performance, as described in paragraph 4.3 was repeated about 25 times each for three different amplifiers to establish test method repeatability. Although each LPA laminate had a different average offset, the standard deviation(s) for test method repeatability was 0.075. From this test, it is shown that the effects of the test method on performance is negligible.

6.1 DIE NO. 1

This die was made for precision stamping and produced amplifiers with offsets in output pressure ranging from 1.8 to 3.3 percent. The results of random sampling of lots from 2500 laminates made from SAE 347 stainless steel, shown on Figure 13, indicates a significant improvement in performance resulting from die modification. The average offset was variable as a function of the sequence of laminate fabrication. The average increased from 1.32 to 2.13 percent in the last 500 laminates. After sharpening, the die laminates were made from 17-7 stainless steel. The average offset was 1.86 percent for a sampling of 26 laminates. This is 0.14 percent greater than the average offset of a sampling of 44 laminates of the first 2500 made from 347 stainless steel. An analysis of the effects of increased thickness of materials from 0.5 to 0.762 mm (0.020 to 0.030 in.) resulted in an increase in offset from 1.72 to 3.1 percent. The most significant improvement after die modification was obtained during stamping of nickel gold-plated 347 stainless steel. The offset was reduced from 1.72 to 0.92 percent. Attempts to precision stamp very thin laminates (0.127mm or 0.005 in.) were unsuccessful. The amplifier profile was distorted and did not meet inspection requirements. Amplifiers fabricated from material 0.254mm (0.010 in.) and greater in thickness met inspection and performance requirements.

6.2 DIE NO. 2

This die was made for fine blanking the same size amplifier as Die No. 1. The performance of amplifiers made from this die is shown in Figure 14. The original Die No. 2 produced amplifiers with an average offset of 2.9 percent. After modification

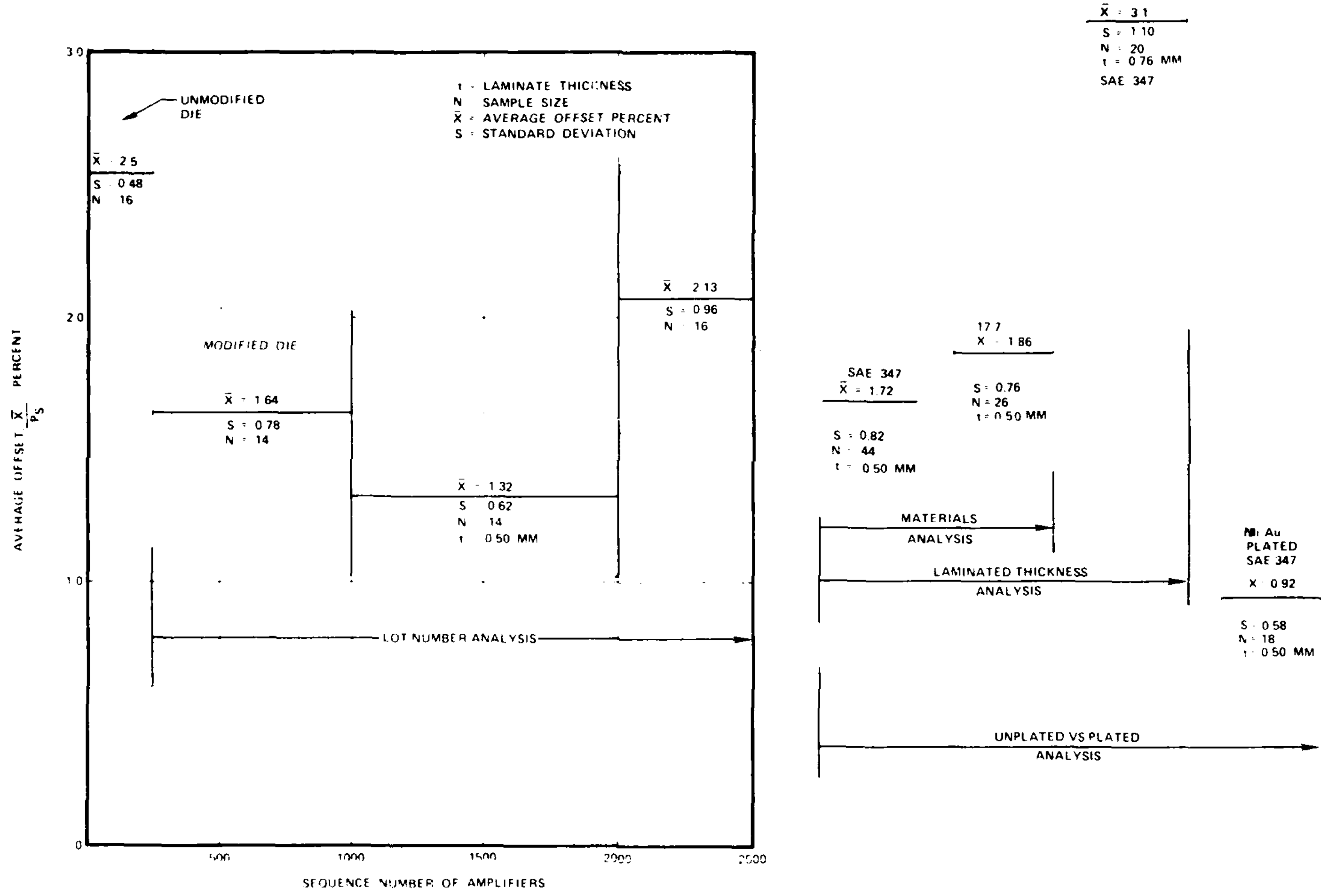


Figure 13. Offset performance analysis of amplifiers from Die No. 1.

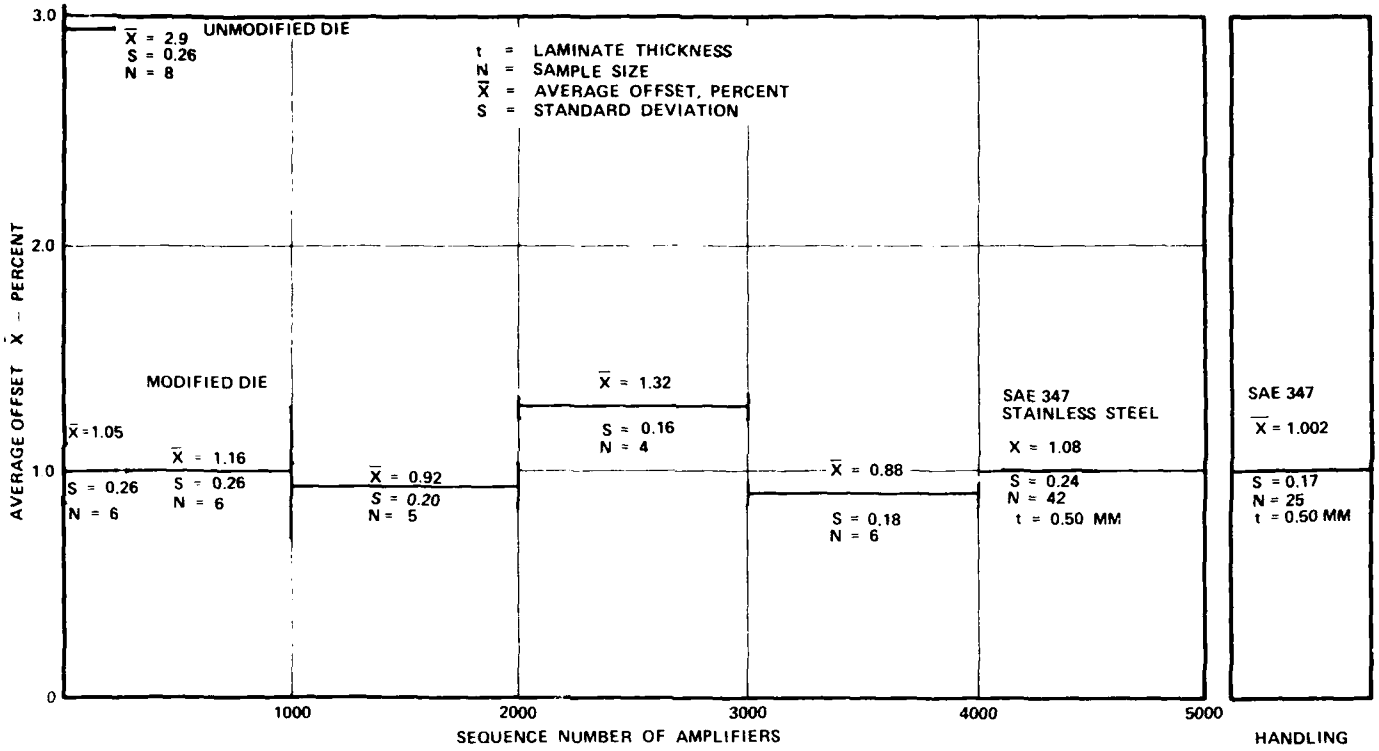


Figure 14. Offset performance analysis of amplifiers from Die No. 2.

of the power jet, the offset was reduced to 1.08 percent for 5000 laminates before a small burr appeared on the tip of the splitter. After sharpening the punches, the offset on subsequent laminates was about one percent.

The gain of LPA's from this die ranged from 8 to 9, which is comparable to the gain of similar amplifiers fabricated by other processes.

Amplifier laminates made from aluminum and 347 stainless steel up to 0.76 mm (0.030 in.) thick and from Waspaloy, H.S. 188, and Inconel 617 up to 0.50 mm (0.020 in.) thick were successfully fine blanked. Titanium was also fine blanked; however, resulting parts exhibited a step in the sidewall, indicating that the upper limit of the die capability was being approached using titanium.

The two methods used for laminate removal from the dies were hand picking and air blasting. When the laminates were carefully hand picked, the blanking rate was about three to four hits per minute. The data presented in Figure 14 is mainly from laminates that were hand picked from the dies. The air blast method blows the laminate from the dies into a box. Laminates 0.50 mm (0.020 in.) and thicker could withstand the air blast without much bending. The performance tests on Figure 14 show the offset results of 1.002 percent on 25 randomly sampled LPA laminates which were air blown out of the dies into a box and then shipped by truck while still loose in the box. This should represent the maximum amount of damage by handling that a laminate would expect to be subjected to. Laminates thinner than 0.508 mm (0.020 in.) showed considerable damage, especially those that were 0.254 mm (0.010 in.) thick. To prevent damage to laminates resulting from removal and handling, a better process for removing laminates from the machine needs to be evaluated.

6.3 DIE NO. 3A

This die was made for precision stamping amplifiers in four stations, with a power jet throat dimension of b_s = 0.5 mm (0.020 in.), and with sharp corners at the supply and control port exits in the interaction region. To make the sharp corners, a fourth punch was made which would stamp the control ports separate from the rest of the amplifier. When the control port was stamped, insufficient material remained to properly support the laminate when the remainder of the amplifier profile was stamped. This resulted in a twisting or bending of the thin section between the control and supply ports, which affected laminate offset performance. To create more pressure on these thin sections, the stripper plate was relieved about 0.002 mm (0.0008 in.) except at the amplifier profile area. Also, a hard rubber shim was placed behind the stripper which gave additional support to the amplifier. Although these two items minimized the twisting on this section between the control and supply ports, they did not completely eliminate the problem. The degree to which the twisting action adversely affected the offset is indicated by the large standard deviation (approximately one) as shown in the test results of Figure 15.

The punch and die clearance for the amplifier was about 0.020 to 0.025 mm (0.0008 to 0.001 in.) which is about twice the clearance of the other dies. In attempting to blank 0.508 mm (0.020 in.) thick 347 stainless steel, the splitter on the die cavity chipped. Therefore, most of the parts evaluated for this die were 0.025 mm (0.020 in.) thick 347 stainless steel.

6.4 DIE NO. 3B

This die was also made for the fabrication of amplifiers in four stations as with Die No. 3A. However, it was made to prove out the concept of replacing a punch to make an amplifier with an 0.38 mm (0.015 in.) power jet. The concept worked very well; however, the same twisting of the section between the control and the supply ports was experienced as with Die No. 3A. This die proved the concept of stamping small power jet sections with a small radius splitter. The tolerance between the punch and die for Die No. 3B was approximately 0.008 to 0.013 mm (0.0003 to 0.0005 in). This allowed for 0.381 mm (0.015 in.) thick material to be stamped without chipping the die caivity. However, due to the limited amount of 0.381 mm (0.015 in.) thick 347 stainless steel, most of the laminates blanked were 0.254 mm (0.010 in.) thick. The test data is shown in Figure 16.

Performance results of amplifiers made from both Die No. 3A and Die No. 3B were affected by the twisting of the section between the control and supply ports; otherwise, the offset results confirmed the results of Die No. 1.

6.5 DIE NO. 4

Die No. 4 was used to fine blank the LPA's with b_s = 0.38 mm (0.015 in.) that had a minimum splitter radius of 0.095 mm (0.00375 in.). Only aluminum and 347 stainless steel up to 0.38 mm (0.015 in.) thick, and 17-7 up to 0.25 mm (0.010 in.) thick were attempted with this die. The die modification procedure was used to reduce the amplifier offset. This die was more difficult to modify due to the smaller size of the amplifier. In addition, the offset was more random for this size amplifier. Unlike the amplifiers produced from Dies 3A and 3B, no noticeable twisting occurred in the small segment between the control and supply channels because this segment was not subjected to any twisting action during the fine blanking process.

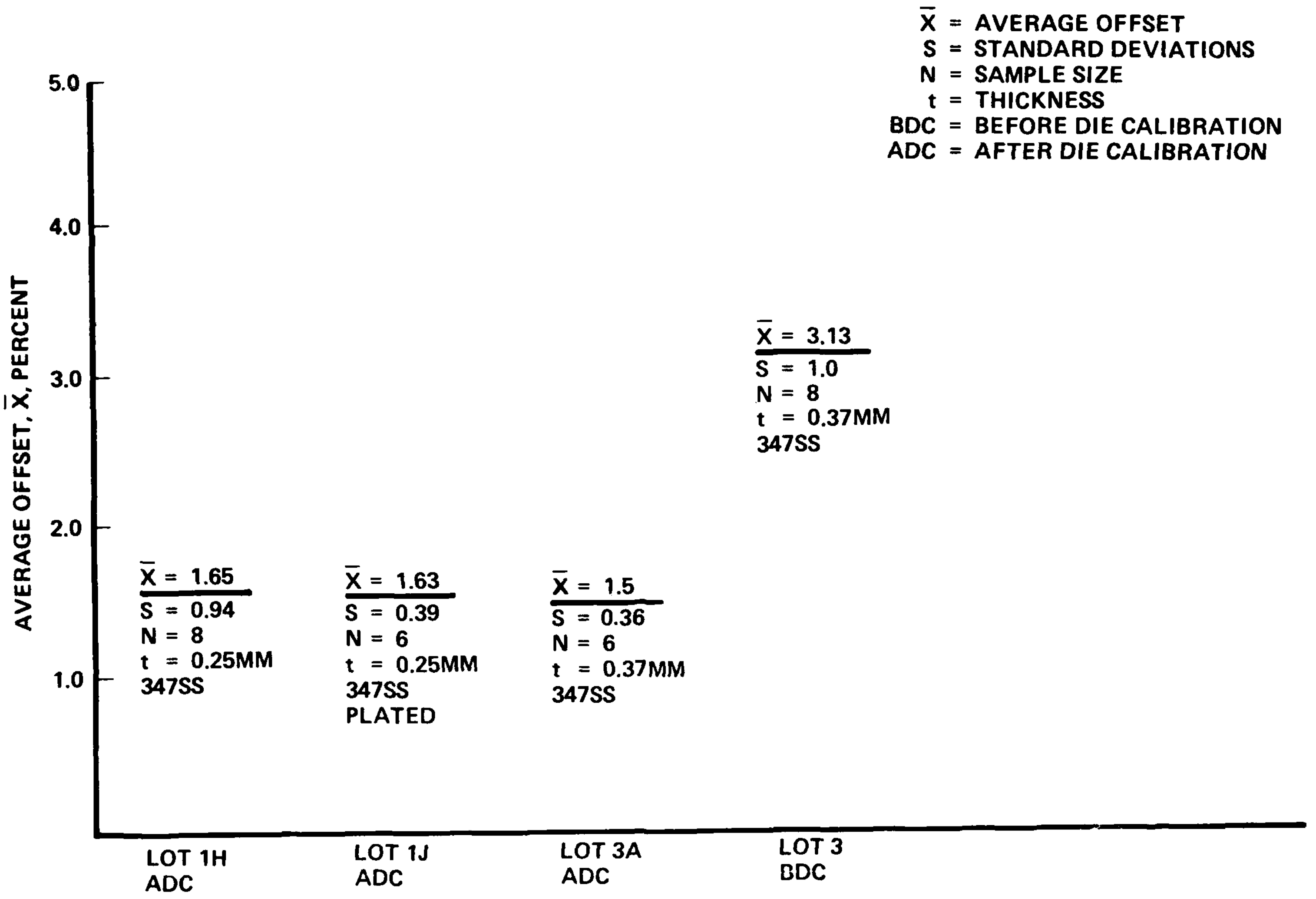


Figure 15. Offset performance analysis of LPA's from various lots produced from Die No. 3A.

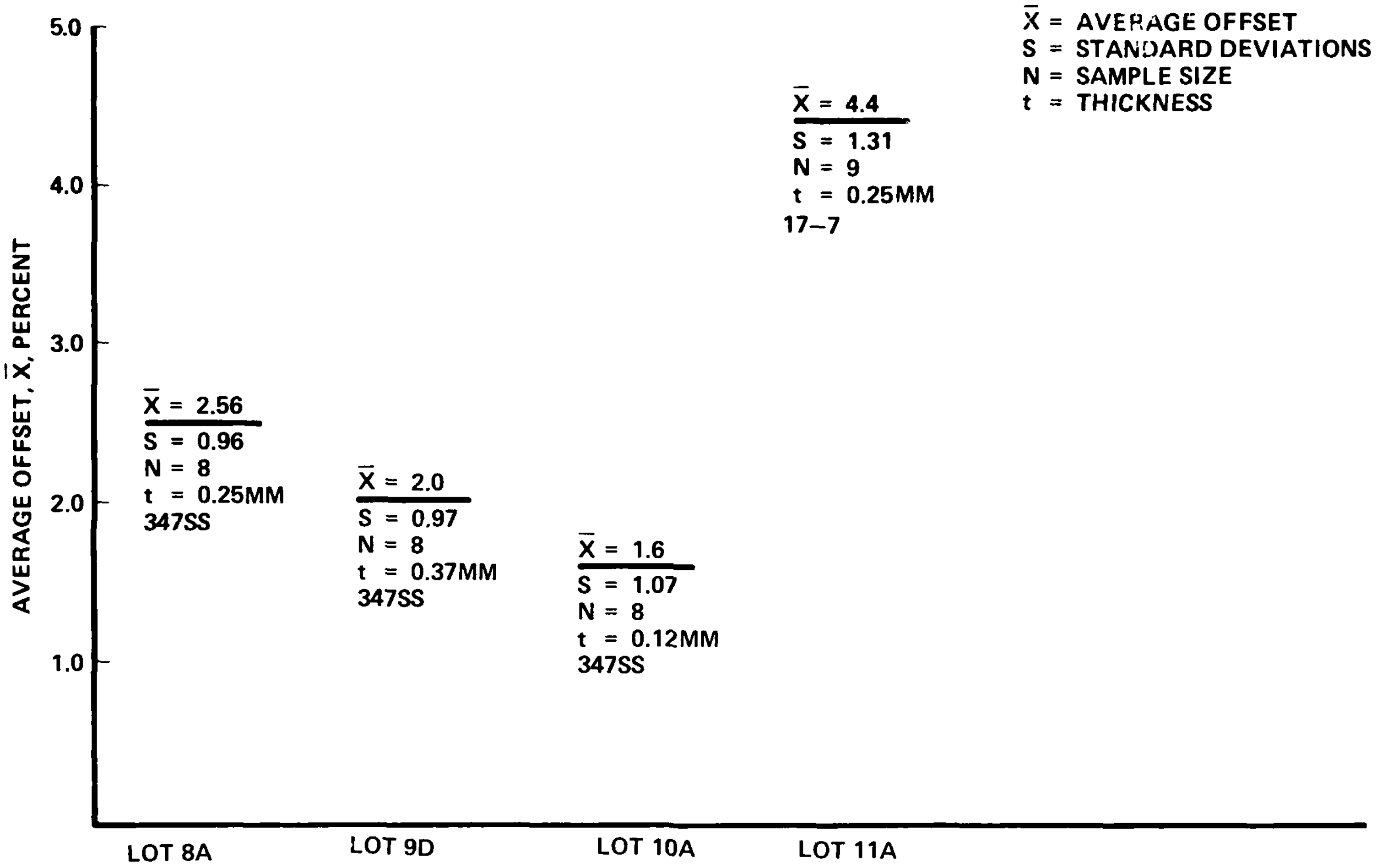


Figure 16. Offset performance analysis of LPA's from various lots produced from Die No. 3B after die calibration.

Also, the splitter in the die cavity is strengthened by the counter punches which support the material during the fine blanking process. This design, coupled with the slow extruding process of fabricating the laminates, allows for slightly thicker materials to be fine blanked than can be stamped using a similar stamping design. Figure 17 indicates that the offset continues to decrease for the first 2000 laminates, after which the offset begins to increase considerably. This indicates that after about 2000 to 2500 laminates, the die should be sharpened.

6.6 BRAZING

Brazing metal laminates together to obtain a homogenous stack is accomplished by applying a thin layer of low melting point plating to the laminate material. Upon heating the plating on the mating surfaces, it melts and the laminates are thereby joined or brazed together. Factors which effect the brazing process are:

a. The flatness of the material (burrs or bending)

b. The thickness of plating material (too thin causes poor braze and leaks; too thick causes plugging of passages)

c. The temperature of and the length of time in braze

d. The pressure on the circuit used during brazing

e. Cleanliness of the surfaces

The plating process used for this program was consistent with the process presently employed in production and the thickness of the plating was controlled in accordance with proven procedures. The laminates were tested for the effects of:

1. Plating the material strip prior to blanking
2. Plating the laminate after blanking
3. Burr on bonding
4. Normal prebraze and preplate cleaning process

In the limited brazing analysis that was made, a consistent braze joint was obtained both by plating prior to and after the blanking operation. Burrs affect the quality of the braze joint. The burr separates the laminates and prevents a good surface-to-surface contact which is necessary for a good diffusion bond. A burr which is 0.025 mm (0.001 in.) high or greater is sufficient to prevent a good bond of the laminate flat surface; however, the

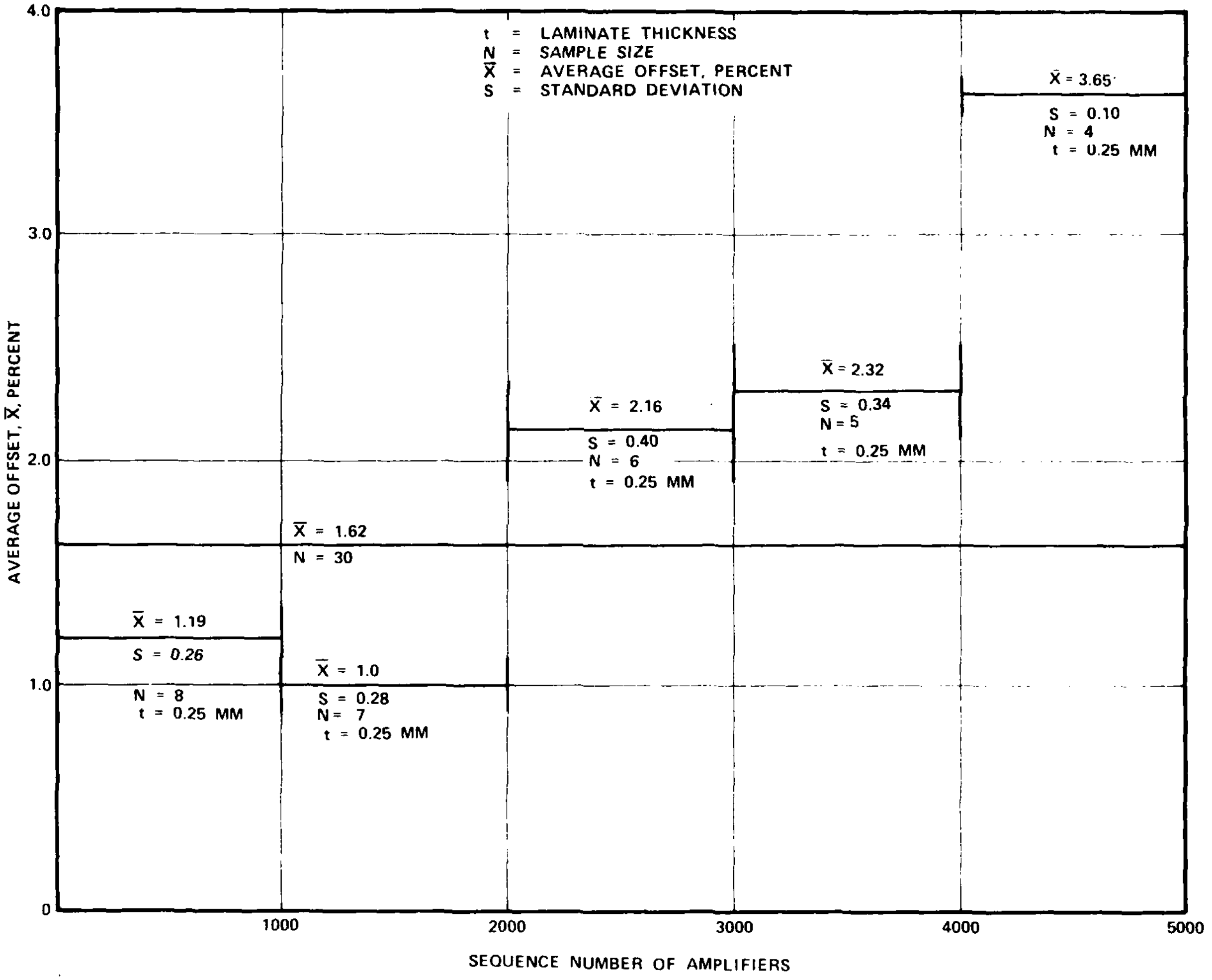


Figure 17. Offset performance analysis of amplifier from Die No. 4.

burr itself bonds very well and for some applications is satisfactory. More study is necessary for incorporating a process for deburring the laminates or improving the bonding method. The ability to clean the oils used in the stamping and fine blanking operation was considered a potential problem; however, the cleaning technique using a degreaser, an alkaline acid bath, and rinsing with water afterward appeared to clean the preplated laminates sufficiently to obtain a good bond.

Plating thickness is an important factor in obtaining a good bond joint. Excessive plating will result in blockage of fluidic flow passages. Too little plating will result in leakage and a poor joint. The plating process used in this program has been proven optimum. In the stamping and fine blanking process of preplated laminates, the sidewalls are clean of plating. Thus, the potential for residual plating remaining in the flow path is reduced. Conceivably the plating thickness could be increased without the danger of blockage of passages. This is another area that should be investigated further.

6.7 TOOL LIFE

Tool life is measured in terms of the number of usable laminates which can be produced with a die. Factors which affect tool life and tool design are:

a. The anticipated production run

b. Type of material to be used in fabrication (hardness and toughness) and material thickness

c. Punch sharpening interval

d. Production rate required

e. Required laminate quality

Using these factors, the die material and punch height may be selected and the rate of production established.

The die material and punch height selected for this program were based on the fact that the D-2 steel used in the die is lower in cost than carbide steel and is less susceptible to chipping in the small segments of the die when punching hard or tough material. The program was not designed to a specific production run or production rate but rather to evaluate the factors which affect die life so as to be able to establish a production process to achieve a given production run or rate. The choice of D-2 steel was adequate to achieve these objectives; however, it would be advisable to further evaluate the advantage of carbide steel to achieve a longer tool life.

Factors that contribute directly to die life are punch height and the interval and the amount of material removed per sharpening. The punch height available for sharpening varied between 3.81 mm to 7.62 mm (0.150 in. to 0.300 in.) The sharpening intervals for the D-2 tool steel die was determined by when: (1) a burr became greater then 0.038 mm (0.0015 in.) on the splitter, and/or (2) the measured offset became more than one percent. Based on the performance results, a die sharpening interval as shown in the tabulation below was established:

Power Jet Width b_s = in.	Sharpening Interval Number of Laminates
0.030	5000
0.015	1800

Using this information, the tool life, TL, was established by the following equation:

$$TL = (8.5 \times 10^5 R - 1400) \frac{P}{S} \qquad (1)$$

where

R = minimum radius of the punch

P = usable punch height

S = average punch height removed per sharpening

The term $(8.5 \times 10^5 R - 1400)$ relates to the number of producible laminates in each sharpening interval.

Either 0.1016 mm or 0.2032 mm (0.004 in. or 0.008 in.)of material is removed from the fine blanking punch each time it is sharpened. The die is designed so that standard shim stock is used behind the punch after each sharpening. The sharpening intervals could be increased, provided special smaller shims were made. A total of 0.1016 mm (0.004 in.) of punch material is removed at each sharpening interval of the precision stamping punch.

Therefore, a die made of D-2 tool steel will produce approximately 300,000 to 400,000 LPA laminates with a b_s of 0.762 mm (0.030 in.) before the punch would be too short to sharpen. A new punch can be made easily at minimum cost to produce an equal number of laminates.

Tool life can be increased by going to a carbide die and redesigning the thin segment sections such as the splitter. The carbide die should permit manufacture of approximately 100,000 laminates between die sharpening intervals. This extended sharpening interval is based on the die being designed for only one material thickness. Die wear increases significantly when thicker laminate material is blanked than that for which the die was designed. Thinner laminate material does not adversely affect die wear; however, the tear on the laminate will be increased since the punch and die cavity clearance is increased. Designing amplifiers to provide as much support as possible around thin wall segments can have a significant impact on extending die life. The present splitter design, together with a proposed design which can extend die life, is shown in Figure 18.

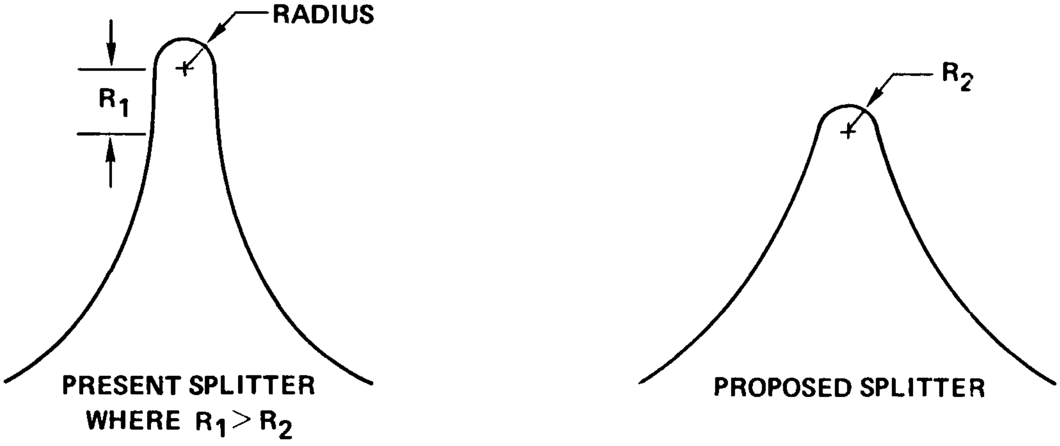


Figure 18. Present and proposed splitter design.

The benefits of the proposed splitter are as follows:

1. The die support area around the splitter is increased to decrease the risk of chipping the splitter section in the die cavity.
2. A smaller radius on the splitter is allowed without the potential of double cutting both sides of the punch when wire EDM cutting the punch profile.
3. The LPA laminate is strenghtened so the splitter is not as susceptible to bending when handling.

6.8 GENERAL OBSERVATIONS

6.8.1 Burr Effects

The slight burr, die roll, and side wall conditions resulting from precision stamping and fine blanking have no significant effect on offset performance. As would be expected, the burr height increases as a function of the increase in laminate thickness. The maximum burr experienced with 0.254 mm (0.010 in.) thick laminates was 0.0127 mm (0.0005 in.), whereas the 0.762 mm (0.030 in.) thick laminate produced a burr as high as 0.0508 mm (0.0020 in.). Generally, the higher strength materials produced a slightly higher burr. The burr on titanium was equivalent to the burr on SAE 347 stainless steel. The burr generated on thicker laminates 0.762 mm (0.030 in.) using the fine blanking process produced slightly smaller burrs than were produced by the precision stamping process. The maximum burr height produced from 347 stainless steel material using fine blanking was 0.030 mm (0.0012 in.).

6.8.2 Small Radii

Small radius amplifiers (with radii of 0.095 mm (0.00375 in.) can be fabricated by either the precision stamping or fine blanking processes. However, the material thickness is critical to the minimum radius which may be fabricated. The maximum thickness tested at this small radius was 0.38 mm (0.015 in.) using SAE 347 stainless steel.

6.8.3 Tear Effects

The amount of tear on the sidewall resulting from stamping or blanking varies as a function of the laminate thickness, the type of material used, and die tolerance. The stamping process produces a greater percentage of tear than fine blanking; however, die calibration can negate the effects of the tear on performance. Tear does have an effect on performance, but can be overcome by die calibration.

6.8.4 Plating Factors

Plating before fabrication removes all plating material from the laminate sidewalls which permits better dimensional control. The soft plated surface also acts as a lubricant which results in improved accuracy of the part. From a cost standpoint, it is also less expensive to plate a sheet or strip before stamping or fine blanking than to plate each laminate after fabrication.

6.8.5 Flow Test

Flow tests were made to compare the amount of flow through the amplifier as defined in Appendix A. The LPA's from Die No. 1 and No. 2 were tested to determine capacity flow. Typical laminate thicknesses vary ±10 percent. Since the flow area is proportional to the thickness, flow variation of ±10 percent is attributed to the laminate thickness. The flow for most 0.508 mm (0.020 in.) thick LPA's tested was within four percent of the average flow which is well within the flow variation due to thickness. The titanium LPA's had a slightly higher flow consumption than the other laminates. Since the tests did not reveal anything new about the LPA's, flow tests were not performed for the other laminates.

7. CONCLUSIONS

The objective of the program presented in this report was to develop a manufacturing process for making high quality fluidic laminates at low cost. The precision stamping and fine blanking processes were found to be good techniques for achieving high quality critical laminates with flexibility for producing non-critical laminates. By slightly modifying the dimensions of a critical performance laminate, a highly accurate and repeatable laminate may be fabricated. These processes are adaptable to high production in large quantities. The use of insert punches with these dies permits a high degree of flexibility for producing laminates of a multitude of configurations at a minimum cost. Since many types of laminates can be made from a single die (thereby allowing the die cost to be amortized over a larger number of laminates), the cost per laminate is significantly reduced.

The material used to make the laminates may be plated prior to fabrication. This in itself provides added flexibility in the overall laminate manufacturing process and also tends toward a further reduction of the cost per laminate. A large variety of materials can be used with this process with no change in the machine setup. Radii less than 0.127 mm (0.005 in.) are difficult to manufacture by this process. Laminates were made successfully out of 347 stainless steel with an amplifier splitter radius of 0.095 mm (0.00375 in.); however, amplifiers should be designed with wider and shorter support sections in the area of these small radii.

The fine blanking process tends to be somewhat more expensive (see Table II). It is possible, however, to make laminates with 0.095 mm (0.00375 in.) radii in limited quantities because the dies provide better support around the periphery of the amplifier section. Fine blanking can also successfully produce parts down to 0.13 mm (0.005 in.) thick, whereas quality laminates for thicknesses below 0.127 mm (0.005 in.) cannot be made by precision stamping when the dies are designed to blank 0.50 mm (0.020 in.) thick materials.

TABLE II. COSTS FOR 0.5-MM (0.020-INCH) THICK 347 STAINLESS STEEL AMPLIFIER

	Material	Production Cost	Amortize Tooling (100,000 Parts)
	$/amplifier	$/amplifier	$/amplifier
Chemical Etch*	0.06	0.80	0.004
Fine Blanking Hand Picked	0.017	0.125	0.100
Fine Blanking Blown Out	0.017	0.014	0.100
Precision Stamp	0.017	0.007	0.100
Precision Stamp Insert Punch	0.017	0.007	0.050

* The photochemical etching process is restricted to maximum material thicknesses of 0.25 mm (0.010 in.); therefore, two laminates are required to make a 0.5 mm (0.020 in.) thick amplifier.

NOTE: To these basic costs, a cost for bonding material must be added (ranging from 30 cents to three dollars per amplifier, depending upon the plating material used).

The photochemical etching process will always be a good fabrication process for making low cost, noncritical laminates. It will also be a useful process for the development engineer to use for making engineering development circuits where a small quantity of laminates of a special design are required.

The EDM process is particularly good when a small quantity of high quality laminates is required. This process becomes more cost effective in these circumstances than precision stamping because the cost to make the die must be amortized over a large number of laminates before it can be cost effective.

On the basis of a preliminary evaluation, the pulsed laser will require additional development efforts to refine the process for fabricating critical fluidic laminates. HDL is presently reviewing laser cut LPA's produced from a pulsed laser beam. Other continuous beam lasers have not been evaluated.

8. RECOMMENDATIONS

The precision stamping and fine blanking processes can be modified to enhance the capability of fabricating high quality fluidic laminates in large quantities. The following are suggestions for future work to further improve the total process of producing fluidic laminates and components.

1. Investigate burr removal in more detail. The limited amount of bonding accomplished in this program indicated that burrs which separate the laminates enough to create a void between laminated prevent obtaining a good bond joint. A method capable of removing the burrs that leaves the laminate capable of being used in subsequent operations without any additional rework should be reviewed. Such methods might include glass bead peening, electro-chemical burr removal, etc.

2. Handling and storage of laminates to prevent bending or deformation should be investigated. The handling of the laminate from the time of fabrication to the time of assembly is being investigated under Contract N0001980-C-0365 with NAVAIR. Also, laminate retrieval from the fine blanking press by a simple robot will reduce the damage to the laminate, as well as improve the production rate.

3. Build additional dies to evaluate other critical fluidic laminates. Additional critical laminates that could be fabricated using dies are the worm track capillary laminates, vortex resistors, and rate sensors. Presently, fine blanking dies to fabricate a dropping resistor, vent plate, and a 0.020 in. wide powerjet (b_s) LPA are being manufactured under MM and T 6803901 sponsored by HDL.

4. An evaluation of die materials should be made to maximize tool life for the fine blanking and precision stamping processes. Tool steel (D-2) was used to establish these processes under this program and it proved to be highly successful; however, carbide dies should be evaluated to determine its potential for extending tool life. The carbide die has a potential for chipping in the thin wall areas of the splitter and vents of amplifiers; however, these dies might prove to be more cost effective for less complex and critical type laminate configurations (gaskets, transfers, etc.)

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APPENDIX A.--PERFORMANCE TEST SETUP

1. INTRODUCTION

Tests were conducted to compare the performance of laminates made by the fine blanking and precision stamping process with photochemically etched laminar proportional amplifiers (LPA's). The gain, offset, and flow characteristic for a constant pressure were compared from statistical analysis of a representative sampling of LPA's from each process.

2. GAIN

The gain was determined by applying a push-pull signal at the inputs of the LPA while holding the supply pressure, P_S, constant. The differential output pressure, ΔP_{OUT}, was recorded as a function of differential input pressure, ΔP_{IN}. The slope of this curve, $\Delta P_{OUT}/\Delta P_{IN}$, is defined as the gain.

2.1 Test Conditions

1. All amplifiers in this test and subsequent tests were LPA laminates.
2. The fluidic signal generator (Figure A-1) consisted of an electrofluidic transducer (E/F) driven by an electronic signal generator.
3. The resistance load (blocked output) was infinite.
4. The aspect ratio of the LPA's varied. However, unless otherwise noted, only one laminate was tested at a time.
5. The control bias pressure was maintained at 10 to 20 percent of the supply pressure.

3. SUPPLY AND CONTROL FLOW AT A CONSTANT PRESSURE

The standard deviation of supply and control flow for a constant pressure was determined by applying and maintaining a constant pressure and then measuring the resulting flow.

3.1 Test Condition

1. All flows were monitored with a calibrated laminar flowmeter.

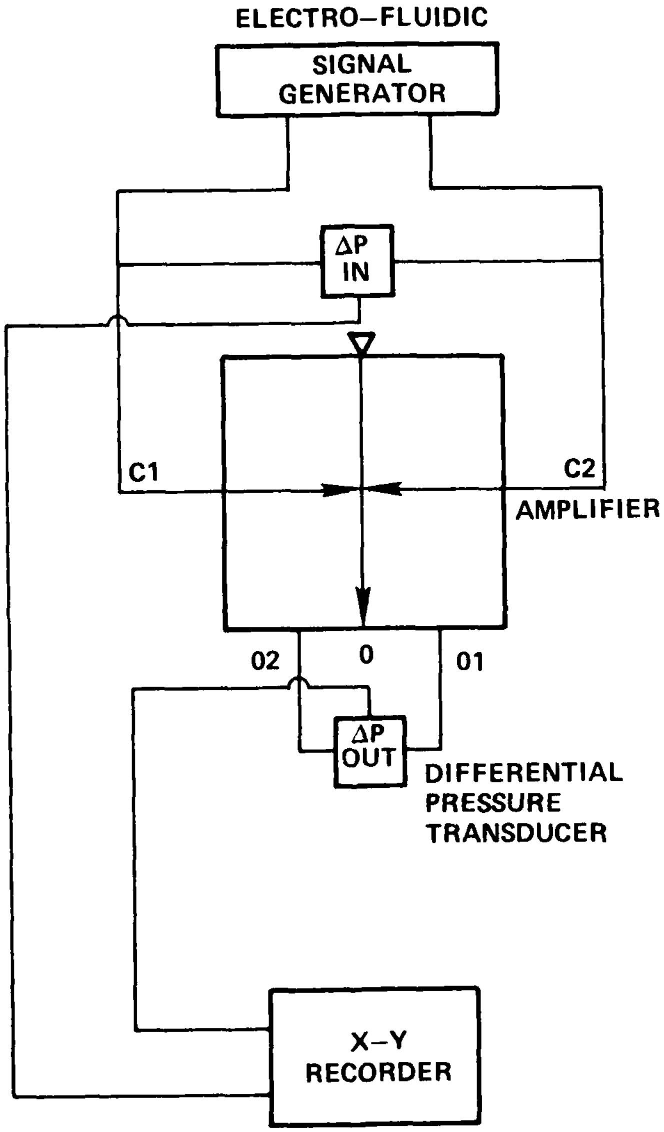

Figure A-1. Block diagram for determining gain of test setup

2. All pressures, including flowmeter differentials, were monitored with electronic pressure transducers

3. All tests were run at an identical modified Reynolds number by holding P_s constant for LPA's of similar thickness and power jet width, b_s.

4. The control pressure was held constant for similar LPA's of the same thickess and b_s.

4. OFFSET

The offset is defined as the ratio of $\Delta P_{OUT}/P_s$ as shown in Figure A-2. The ΔP_{OUT} parameter was recorded while the supply pressure was increased from zero to a pressure high enough to establish turbulence. The recorded offset was determined as the largest offset prior to the transition from laminar to turbulent flow.

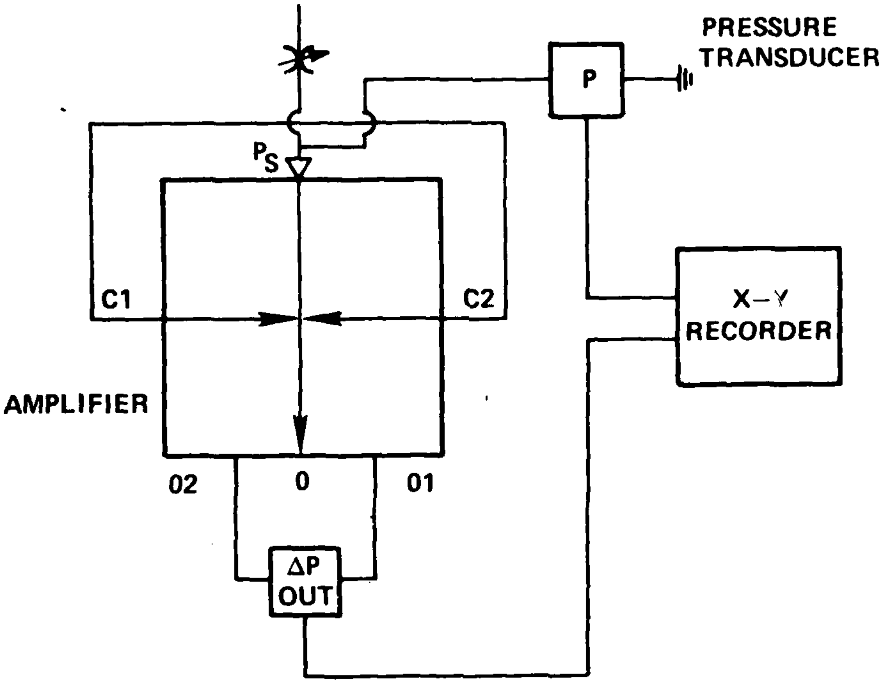

Figure A-2. Block diagram of test setup to determine offset.

4.1 Test Conditions

1. The control ports were shunted and at zero control level.
2. Unless otherwise noted, only one laminate thickness was tested at a time.
3. The output ports were blocked and loaded into the differential pressure transducer.

APPENDIX B.--FINAL SPECIFICATION

1. INTRODUCTION

1.1 This specification provides procedures and requirements for fine blanking and precision stamping sheet and strip stock to fabricate fluidic laminates.

2. APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent referenced herein.

2.1.1 Controlling Specifications

Marking and Traceability Requirements
Laminate Plating

3. SPECIAL EQUIPMENT

3.1 10X and 20X shadowgraph or comparator.

3.2 Fine blanking or precision stamping equipment with repeatable setting adjustments.

3.3 Jeweler's loupe

3.4 Inspection tooling

3.5 Microscope

3.6 Dial indicator

4. MATERIAL

4.1 The material shall be as indicated on the applicable drawing.

5. GENERAL REQUIREMENTS

5.1 The sheets and strips to be fine blanked or precision stamped shall be delivered to the vendor in 8- to 20-foot lengths or mounted on a reel with an ID of not less than 16 inches.

5.2 The strip width is determined by the minimum laminate width requirement plus four times the material thickness (0.125 in. each side).

5.3 Sheets and strips shall be plated according to a controlled specification.

5.4 No writing or scratching on the material is permitted.

6. MANUFACTURING OPERATION

6.1 Specific laminates selected from lots manufactured in sequence shall be given detailed analysis. These laminates shall be numbered and separated from but included with the lot number from which they are selected. The laminate numbers selected for this analysis are indicated below. A tolerance around the specific laminate is given as indicated for the convenience of selection using a machine counter.

6.1.1 Laminate Numbers

Laminates selected for inspection shall be 10 ±1, 200 ±3, 500 ±4, 1000 ±5, and every 500 ±10 for lots in excess of 1000.

6.2 Orders for laminates from a given material of 200 or less shall be packaged in bags of 100. The package size may be increased to 200 laminates per bag for orders in excess of 200.

6.3 Fabricated parts shall be thoroughly cleaned, inspected, and packaged in a manner which will prevent contamination, scratches, and deformation. Parts shall be tightly stacked in bundles and overwrapped for shipping and storage. Contamination,fluids, or packaging materials detrimental to plating for braze must be avoided.

6.4 Each package or bag shall contain an identification sheet with the following information.

Material Thickness

Material

Packaged by ______________________________ Date ___________

Inspected by _____________________________ Date ___________

6.5 Dies shall be sharpened before beginning manufacture and when any of the parameters shown in Figure B-1, as defined by inspection, are exceeded.

CLASS	DESCRIPTION	BREAK	BURR	DIE ROLL
1	LPA, VENTS, NOZZLES, ETC.	0.4t	>(0.0010 IN.)	0.5t
2	GASKETS, TRANSFERS, ETC.	0.6t	>(0.0015 IN.)	0.7t

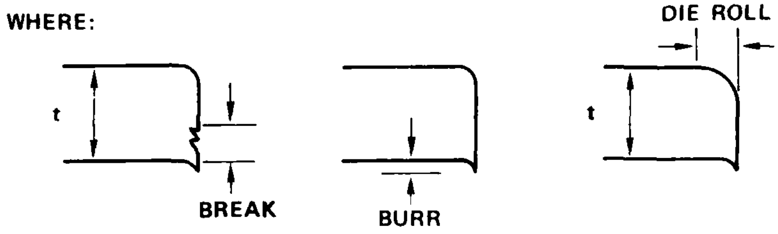

Figure B-1. Fluidic inspection parameters.

6.6 Die Calibration Procedure

The procedure applies to laminates capable of being performance tested at the vendor shop, where slight modification to the die will change the output characteristics.

1. Run 20 parts - Check the 10th, 12th, 15th, 18th, and 20th part. Ensure that offset is consistent and repeatable for these LPA laminates. (See Appendix A for offset test procedures.)

2. Establish which output port is at the higher pressure level.

3. Modify the power jet throat on the pierce punch on the side of output port which is receiving the higher pressure. Use a diamond grit compound or a drill rod that is equal to or smaller than the smallest radius in the nozzle exit region. Modification is made by rubbing the drill rod (with the diamond grit compound) along the length of nozzle throat as shown in Figure B-2.

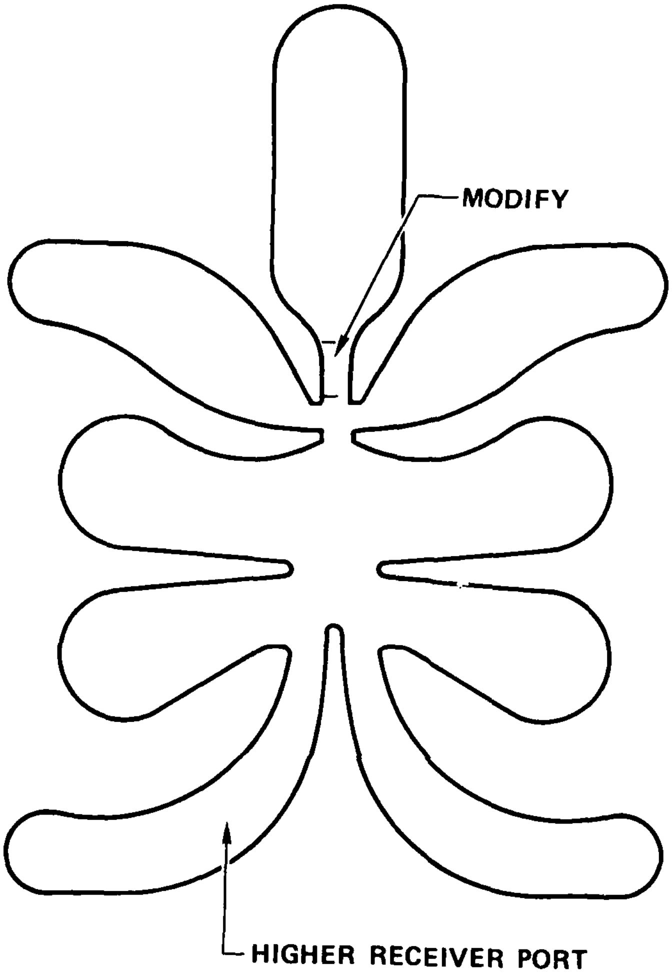

Figure B-2. Amplifier Pierce punch.

4. Run 20 LPA laminates and repeat Steps 1, 2, and 3 as required to reduce offset to below one percent.

7. PROCESS CONTROL

7.1 During fabrication of sample parts for approval, vendors shall use appropriate manufacturing procedures, processes, and methods of inspection to comply with this specification. Procedures shall be documented in accordance with Manufacturing Operations and Tooling (MOT) documents to be submitted by the vendor. These procedures shall be reviewed and approved in writing by AiResearch prior to use. Any change of approved procedures must be reviewed and approved by AiResearch prior to use.

7.2 Mechanical or thermal operations (e.g., sand blast, thermal cycle to dry, etc.) which might cause stress or other changes in the physical or chemical properties of the material shall not be performed on the sheet stock or laminations. An exception to this requirement may be made when rolling to achieve strip flatness prior to manufacture.

7.3 The laminates of a specific order are to be specially tagged and separated for detailed inspection to ensure adherence to applicable drawings as defined by paragraphs 6.2, 6.3, and 6.4.

8. INSPECTION

8.1 The fabricated parts shall meet the requirements of the designated class as defined in Figure B-1. An inspection sheet shall be made on each part inspected as follows:

A. Comparator chart Yes _____ No _____

    Within limits Yes _____ No _____
    Symmetrical about centerline Yes _____ No _____

B. Dial indicator and micrometer

    Thickness
    Burr die roll metal
    Flatness

C. Microscope

    Amount of tear __________ in.

D. Performance test

    Offset __________
    Gain __________

Material __________ Inspector: QC ______________

Identification Number __________ Date ______________

Lab ______________

Date ______________

8.2 The sum total of the material flatness and any burrs shall be no larger than 0.001 in.

8.3 A 10X or 20X comparator template shall be used to assure symmetry and general conformance to the applicable drawing. Where tolerance lines are provided, the part shall not exceed these limits.

8.4 The vendor shall inspect at least five laminates of each material used from each 100 laminates or less (depending upon lot size). Five laminates of each 100 for lots in excess of 100 shall be inspected. For order lots in excess of 1000, sample inspection shall be made after each 500 laminates are fabricated. This will permit sharpening of the die at an appropriate time without the generation of a significant number of rejections.

9. QUALITY CONTROL

9.1 Laminates shall be degreased prior to packaging. Each shall be properly packaged and marked in accordance with MC5014, Class VI or VIII and Paragraphs 6.2, 6.3, 6.4, and 6.5, Appendix B herein.

9.2 Parts not conforming to the requirements of this specification shall be marked accordingly, giving the reason for rejection, and shall be packaged separately.