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DEVELOPMENT OF EFFECTIVE MACHINING AND TOOLING TECHNIQUES FOR K--ETC(U)

JUN 82 R DOERR, E GREENE, B LYON, S TAMA

DAAK51-81-C-0008

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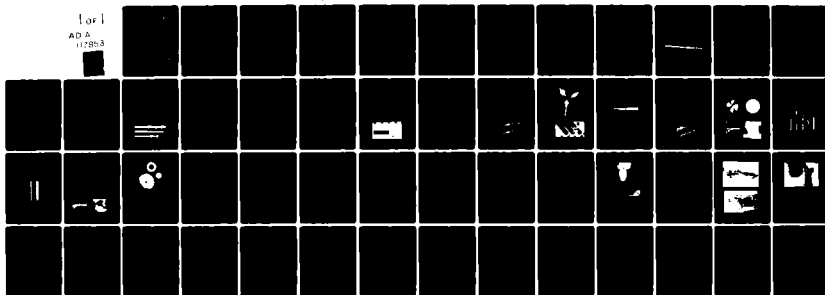
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DEVELOPMENT OF EFFECTIVE MACHINING AND TOOLING TECHNIQUES FOR KEVLAR COMPOSITE LAMINATES

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HUGHES HELICOPTERS, INC.
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June 1982

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APPLIED TECHNOLOGY LABORATORY
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Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report is considered to provide a reasonable insight into the manufacturing problems associated with the machining of Kevlar 49, an aramid fiber material used in helicopter structural applications, as well as the potential solutions to these problems. This program has identified and investigated several viable techniques for machining, cutting, and drilling Kevlar laminates. Results from the program will be disseminated to U.S. industries involved in manufacture of Kevlar structures and will also be integrated with other manufacturing technology efforts at the Applied Technology Laboratory.

Charles E. Stuhlman of the Aeronautical Technology Division served as project engineer for this effort.

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This report contains the results of the work performed for the development of the Kevlar laminate machining techniques program. The results include information assisting in the drilling, cutting and trimming of Kevlar/epoxy and Kevlar/polysulfone cured laminates. The program was in three phases. Phase I consisted of a technology survey and a tool vendors/developers survey. Fifty-one technical documents were reviewed and eight vendors/developers were visited.			

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Block 20. Abstract (continued)

During Phase II, eight different types of conventional tools were evaluated for Kevlar laminate machining effectiveness, and three state-of-the-art cutting systems were studied. Existing drill bits and saw blades were evaluated and modified for improved machining, and a special milling router was designed. Machining effectiveness was evaluated on Kevlar laminates having both epoxy and polysulfone matrices, in a thickness range of 0.06 to 0.38 inch.

Production scale-up problems and techniques such as tool life, tool materials, special coatings, and coolants were studied in Phase III. Additionally, automation equipment was identified and production automation concepts were developed.

Information gathered during the program was organized into a machining guide (Design Guide Handbook).

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PREFACE

The work described in the report was performed by Hughes Helicopters, Inc., Research and Development, Culver City, California, under Contract DAAK51-81-C-0008 with the Applied Technology Laboratory (ATL), US Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia. The period of technical performance was February 1981 through October 1981. Mr. Charles E. Stuhlman was the Army ATL Project Engineer. The authors wish to acknowledge the valuable assistance of Messrs. J. Waller and H. Reddick of ATL, Fort Eustis.

The performing organization within Hughes Helicopters, Inc. was the Research and Development Division Staff under Mr. D. C. Borgman. Mr. Saad Taha, manager of the Advanced Composite Section, was the program manager and Mr. Rod Doerr was the technical coordinator. Major contributions were made by Mr. Ed Greene, Tooling Design Specialist.

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INTRODUCTION AND SUMMARY

This program was initiated to investigate/develop tooling and techniques needed to perform clean, efficient machining operations on Kevlar laminates. Kevlar is the trade name for an aromatic polyamide fiber developed by E. I. DuPont. This high strength, low weight reinforcement is presently being used in many structural and nonstructural aircraft applications. The investigation included two different Kevlar laminates, one with an Epoxy matrix and one with a polysulfone matrix.

Kevlar reinforced laminates have presented the aerospace industry with machining difficulties due to their tendency to fibrillate or "fuzz" when machined with conventional tools. (See Figure 1 below.) Considerable data was generated in attempting to solve this problem; much of it was conflicting and applied only to specific applications. The cost of production has suffered due to ill-defined parameters such as feeds, speeds, and tool configuration.

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Figure 1. Fibrillation or "Fuzzing"
Caused by Router Cut

In this program a cross section of conventional tools, specialty tools, and modified tools was systematically evaluated. Advanced machining techniques were also evaluated. Recommendations based on these studies were made and incorporated into a separate document, The Design Guide Handbook (Reference 1).

The overall objectives of this program are:

- Determine and evaluate state-of-the-art cutting tools and machining techniques
- Identify deficiencies of existing tools and techniques
- Identify and verify tools and machining techniques to eliminate/reduce deficiencies

The program was organized into the following major tasks:

Phase I - Technology Survey

Survey of literature and selected vendors/developers to determine the state of the art relative to tools, processes, and techniques.

Phase II - Development of Evaluation

Evaluation of tooling and equipment identified in Phase I; modification of selected tools; investigation of state-of-the-art cutting equipment; investigation of Polysulfone/Kevlar laminate machining.

Phase III - Manufacturing Methods Development

Evaluation of production scale-up problems; investigation and integration of automation into the production line.

¹ Design Guide Handbook Efficient Machining Methods and Cutting Tools for Kevlar Composite Laminates, November 1981, Hughes Helicopters, Inc.

PHASE I - TECHNOLOGY SURVEY

A DOD/NASA and HHI library literature search initiated the technology survey. This survey covered manufacturers' data, technical conferences, periodicals, and Government-sponsored studies. In addition, eight selected vendors were visited in order to determine the latest state of the art in Kevlar laminate machining. The information collected covers tools, processes, and techniques. Appendix A, Technical Data, and Appendix B, Vendors/Developers, present detailed listings of documents reviewed and vendors visited during this program.

In general, considerable composite laminate machining data was available. However, only a small portion of this information was specific for Kevlar. Kevlar specific tools were offered by a limited number of vendors. Of the 51 technical reports reviewed, only 7 reports contained data concerning conventional tools specifically designed or modified for Kevlar machining. Some specific information on Kevlar was available from machining literature covering nonconventional cutting equipment such as the water jet and the laser.

Reports on state-of-the-art cutting methods present some data specific to Kevlar, with three sources presenting material specific to Kevlar laminates or Kevlar and other composites. The Grumman Aerospace Corp's study, "Manufacturing Methods for Cutting, Machining, and Drilling Composites", includes some limited specific Kevlar laminate machining information within the considerable data covering composite machining techniques. The balance of the surveyed literature covers associated areas such as production scale-up and production automation information, and metal cutting tools that have possible use in Kevlar laminate machining.

The following reports were found to be valuable during this program. They contain information which applies specifically to machining cured Kevlar composite laminates:

- "Cutting and Machining of Kevlar Aramid and Its Composites"
Louis H. Miner, Frank T. Penzo
21st National Symposium SAMPE, Apr. 1976
- "Industrial Tools for Cutting Kevlar"
Airtech International Inc.
P.O. Box 2930, Court M-1
Torrance, CA 90590

- "Industrial Tools for Cutting Kevlar Fabric and Laminates"
Pen Associates, Inc.
2639 W. Robino Drive
Wilmington, Del. 19808
- "Speciality Tools for Machining Fiber Reinforced Composite Structures"
Technology Assoc. Inc.
P.O. Box 7163
Wilmington, Del. 19803
- "A Guide to Cutting and Machining Kevlar"
DuPont Inc. Textile Fibers Dept.
Centre Rd. Building
Wilmington, Del. 19898
- "Cutting Fabric, Prepreg and Kevlar Aramid"
Sept. 19, 1975 DuPont Textile Fibers Dept.
(Same as above)
- "Characteristics of Laser Cutting Kevlar Laminate"
R.A. Van Cleave, Jan. 1979
Prep for Dept. of Energy Contract DE-AC04-76-DP00613
Bendix, Kansas City Div.
- "Laser Cutting of Kevlar Laminates"
R.A. Van Cleave, Bendix Corp., Kansas City
September 1977, BDX-613-1877
- "Flow Technology Report No. 7
Waterjet Cutting of Advanced Composite Materials"
Flow Industries, Inc.
21414 68th Ave. South
Kent, Washington 98031
- "Manufacturing Methods for Cutting, Machining and Drilling Composites"
Vol. 1 Composites Machining Handbook, Vol. 11 Test and Results
AFML-TR-78-103 Vol. 1 and Vol. 11, August 1978
Grumman Aerospace Corp.
Bethpage, N.Y. 11714

PHASE II - DEVELOPMENT OF EVALUATION

During Phase II, the performance of tools identified in Phase I was verified and their capabilities and limitations were further defined. Selected tools were modified and evaluated for increased efficiency. In addition, state-of-the-art machining procedures were examined. Tools and equipment were evaluated for machining rate and quality on both epoxy/Kevlar and polysulfone/Kevlar laminates.

TEST SPECIMEN PANEL DESCRIPTION

The epoxy/Kevlar panels were fabricated using vacuum pressure. Materials used were APCO 2434/2347, and style 281 Kevlar fabric. Thicknesses were 0.06, 0.12, 0.18 and 0.38 inch.

The polysulfone/Kevlar panels were autoclave cured using P1700 polysulfone and cross-plyed unidirectional Kevlar for one panel and Kevlar 285 fabric for the other. Thicknesses were 0.06 and 0.12 inch respectively. The target resin content for all test panels was 40 ± 5 percent.

MODIFIED TOOLS

Modified Drill Bits - A special tip grinding procedure was developed for modifying standard drills into drills capable of long run, quality Kevlar laminate drilling. Conventional drills are designed to start cutting the holes in the center. This forces chips against the walls of the hole, creating heat and swelling in a Kevlar laminate. The modified drills cut material toward the center of the drill and minimize packing. In addition, the modified drills cut with a shearing action at the hole diameter, eliminating fibrils and making a clean hole. The modified tip configuration is shown in Figure 2.

Three different standard drills were modified: one high speed steel (HSS) twist drill, one carbide twist drill, and one parabolic flute drill. (See Figure 3.)

The results of the testing of these three modified drills are presented in the following sections. The best results were obtained using the modified parabolic flute drill bit (Figure 3, bottom bit), probably because it offers more relief for the removal of chips. (See Figure 4.) These drill bits were effective both off-hand and bushing guided.

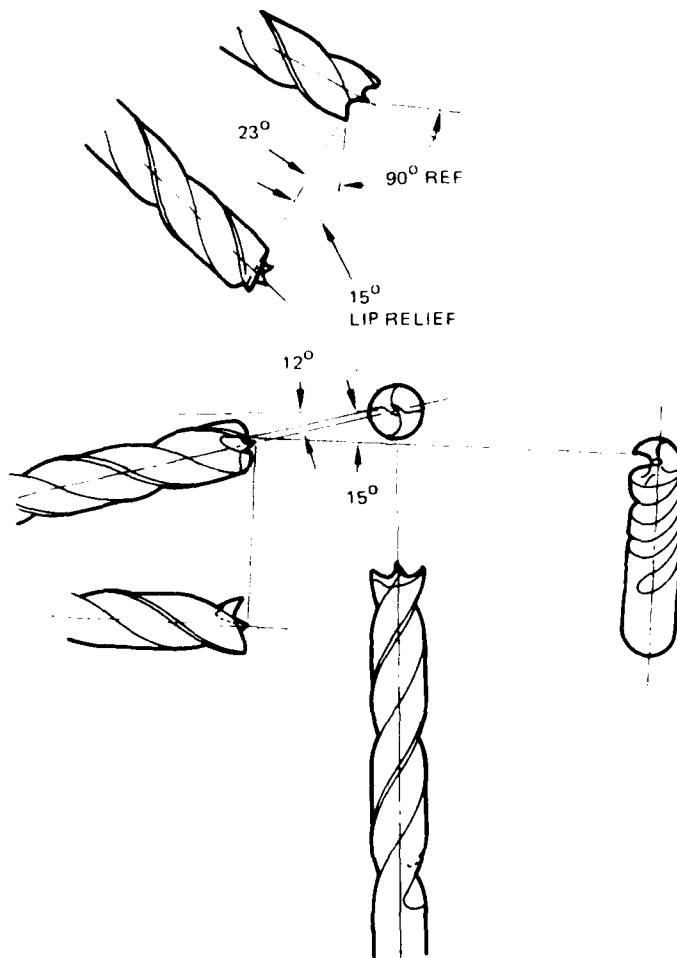


Figure 2. Modified Drill Tip

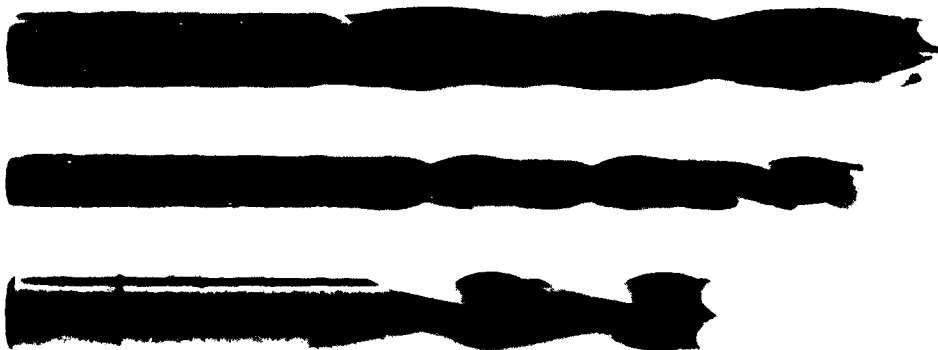
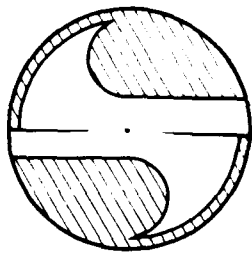
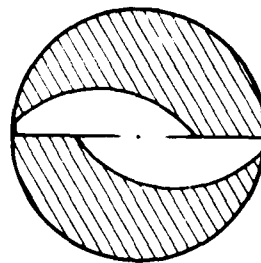


Figure 3. Modified Drill Bits



STANDARD TWIST DRILL



PARABOLIC FLUTE DRILL

Figure 4. Cross-Section View of Standard Twist and Parabolic Flute Drills (Shows the Difference in Chip Relief Area)

The modification of the standard drills for this program was done freehand on a conventional bench grinder. However, in order to maintain the center on the drill point and hence an accurate hole diameter, a grinding fixture is recommended. Figure 5 illustrates the procedure for modifying a standard drill.

The modified drill resembles the old "thin sheet" drill; however, there are important differences that, while they are not easily noticed, greatly affect performance. The steps illustrated in Figure 5 show the procedure for modifying drill bits freehand.

The setup for Steps 1 and 2 shows the tool rest at a 15-degree angle. This becomes the lip relief angle of the drill. The front view of the grinding wheel shows a 35-degree angle line which is the angle at which the drill is fed into the grinding wheel. The 35-degree angle allows the center of the drill to extend beyond the forward cutting points of the land after the drill has been ground.

In grinding Steps 1 and 2, the rotational position of the drill bit is very important. The chisel edge must be in a vertical position so that the grinding cut is parallel to the chisel edge angle. After grinding one lip, the drill is rotated 180 degrees to grind the opposite lip.

The final grinding steps, Steps 3 and 4, are done without the tool rest. The drill bit is ground on each side to reduce the helix angle, forming a cutting edge at the center of the web and bringing the chisel edge to a point.

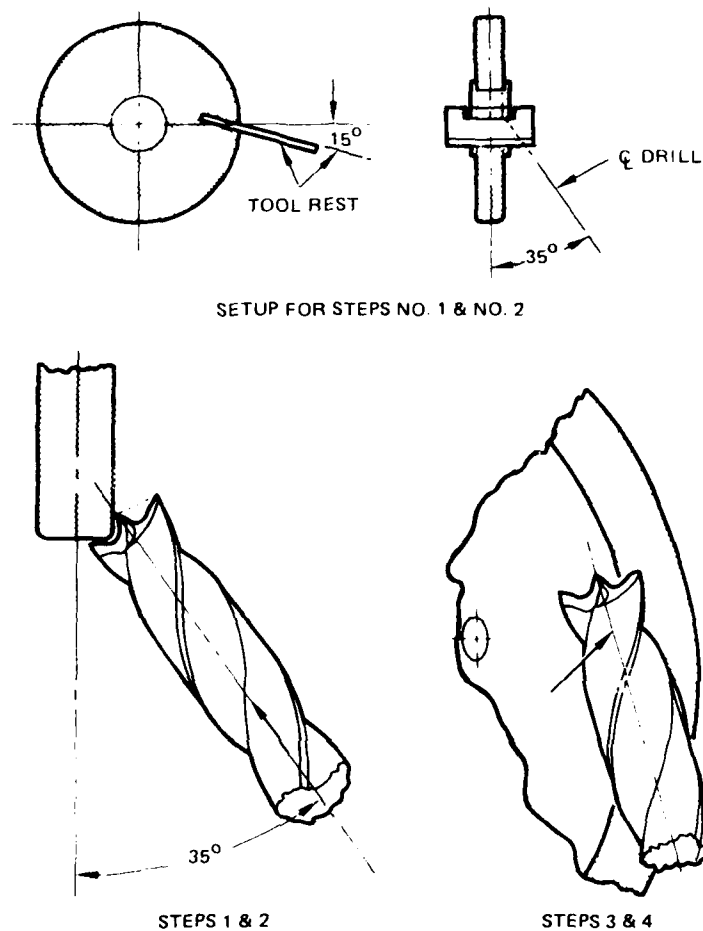


Figure 5. Grinding Procedure for Modifying Standard Drill

Modified Circular Saw Blade - A 60-tooth carbide tipped blade was specially ground to cleanly and efficiently cut Kevlar laminates. After several attempts, a grinding procedure was developed that resulted in a noticeable improvement in cutting over standard carbide tipped blades. Figure 6 shows the tooth angles of the specially ground blade.

Finishing Mill Cutter - A mill cutter was designed especially for edge finishing Kevlar laminates. (See Figure 7.) This mill cutting tool is limited in depth of cut, but is effective for cleaning up rough edges.

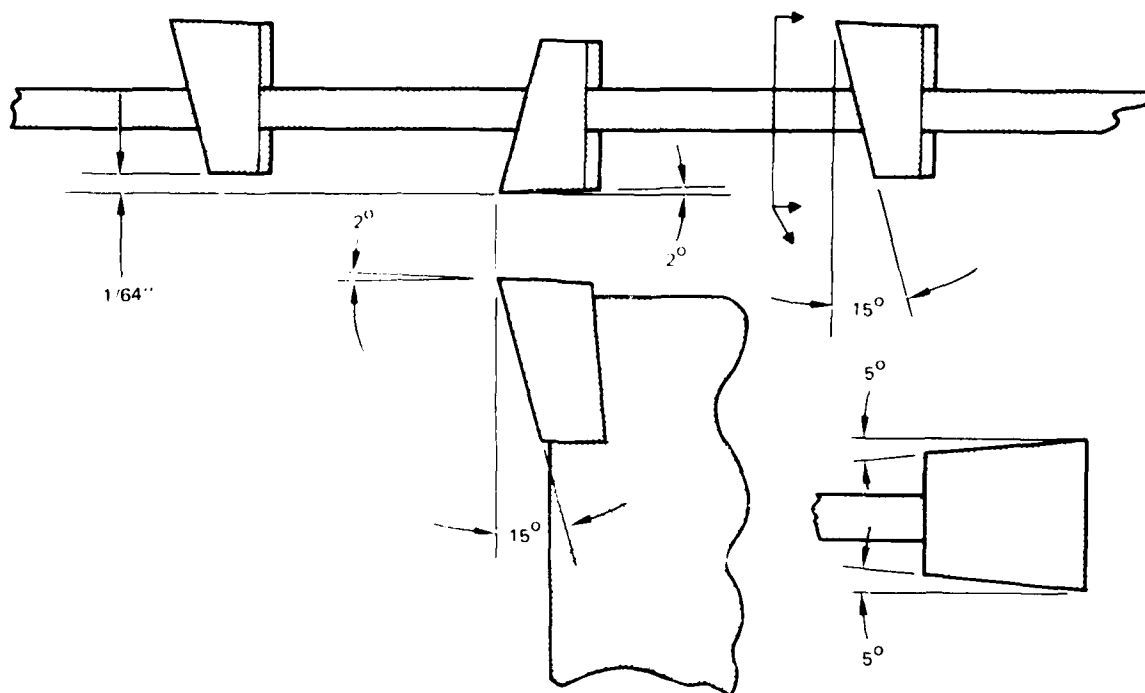


Figure 6. Tooth Angles of Specially Ground Carbide Tipped Circular Saw Blade

EVALUATION OF CONVENTIONAL TOOLS

Contrary to popular belief, Kevlar is not appreciably more difficult to machine than graphite or fiberglass. Although the Kevlar fibers are tough, they are easily cut by sharp tools with the proper cutting angles. It should be noted, however, that since heat over 350° F tends to permanently swell the edges of the cut, tools must be kept cool during the machining operations.

In the study of the conventional tools, a brief preliminary evaluation was conducted on a wide variety of tools, and the tools that appeared less efficient were dropped from evaluation. Although this type of evaluation was necessary because of time constraints, some tools may have been prematurely eliminated. (See Table 1, Conventional Tool Evaluation.)

Drill Bits - Among the drills evaluated were the Standard HSS twist, solid carbide twist, single flute (spade), and standard parabolic flute; in addition, the Standard HSS twist, solid carbide twist, and parabolic flute were each evaluated with the modified tip.

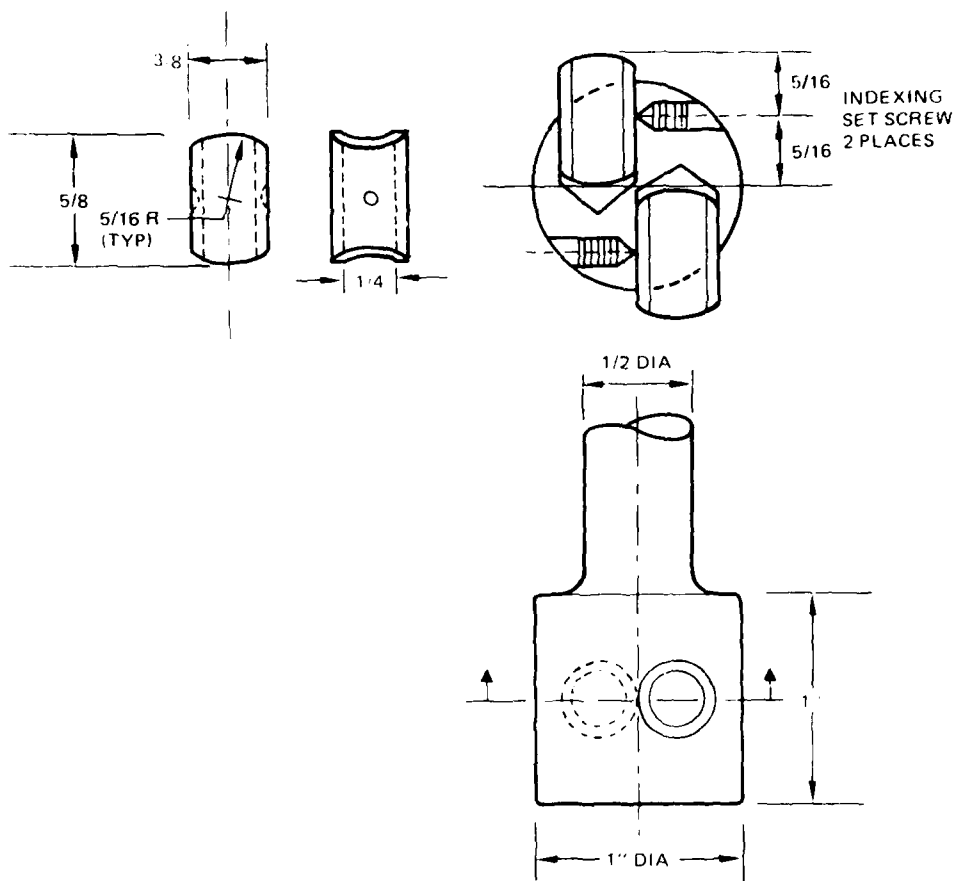


Figure 7. Mill Cutter, Special Design

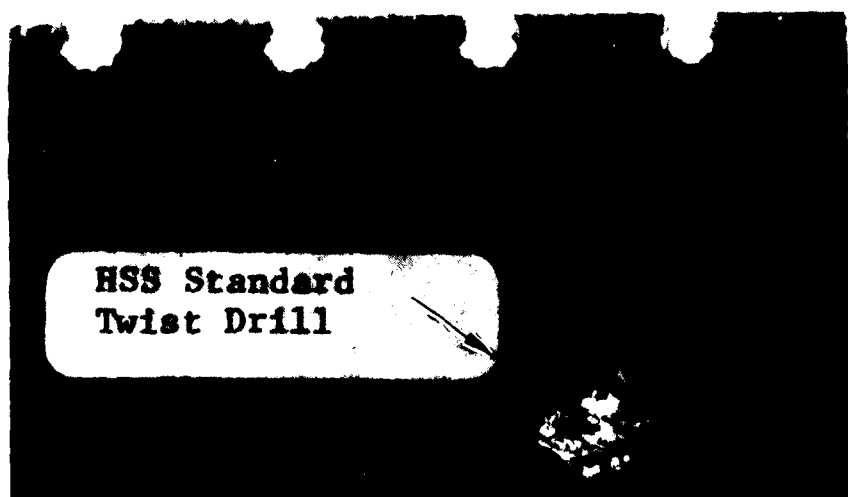


Figure 8. Hole Quality Using Standard HSS Drill

TABLE 1. CONVENTIONAL TOOL EVALUATION MATRIX

TOOL DESCRIPTION	SIZE	SPEED	CUTTING RATE	E V A L U A T I O N	
				QUALITY	COMMENTS
Circular Saw Carbide Tipped	7 1/2" 40 Tooth	3500 SFPM	4 Mat's 5 FPM	Good	Light fuzz downside only
Remington Grit Edge Circular	10" Dia	4500 SFPM	6 FPM	Good	Not recommended due to dirt loading
Cutoff Blade-Composition	10" Dia	4500 SFPM		Poor	Generates heat and swells edges
Band Saw Wavy Set	1 1/2" 32 Tooth	650 SFPM	4 Mat's 2 FPM	Good	
Band Saw Knife Edge	1 1/2"	1000 SFPM	10 FPM	Good	32 plies 281 style dry woven fabric
Band Saw Scalloped Knife Edge	1 1/2"	1000 SFPM	10 FPM	Poor	32 plies 281 style dry woven fabric
Saber Saw - Bosch T118A	1 1/2" 20 TPI	191 SFPM	2 FPM	Good	
Saber Saw - Bosch T101P		191 SFPM	4 FPM	Good	
Saber Saw - Airtach AR3925		191 SFPM	2 FPM	Good	Special blade high cost
Saber Saw - Bosch T130 Course		191 SFPM	1 FPM	Good	Grit coated blade for special applications
Saber Saw - Knife Edge Bosch 118A	2 1/2"	191 SFPM	10 FPM	Good	2 plies 281 style dry woven fabric
Scroll Saw					Not available
Drill HSS Standard Twist	1/2" 135°	600 RPM		Poor	Rejected.
Drill Solid Carbide Twist	1/2" 135°	600 RPM		Poor	Rejected.
Carbide Single Flute Drill	1/2"	600 RPM		Poor	Rejected.
Turboflute Drill	1/2"	600 RPM		Poor	Rejected.
Countersink 2 Flute Standard		600 RPM		Poor	Rejected.
Weldon Countersink		600 RPM		Good	Overheats fast
Router - Opposed Helical	1/2"	24,000 RPM	6"/min.	Good	Carbide bit broke diameter too small
Router - Diamond Cut Carbide	1/2"	24,000 RPM		Poor	Rejected.
Hoq Mill - Omcut	1"	4,000 RPM	6"/min.	Good	Suitable for heavy sections
Bosch Nibbler Model 7501	14 GA	1460 Strokes per min.	2 FPM	Excellent	Clean and economical
Circular Saw Carbide Teeth (Modified) Mod #1	10" 60 Tooth	4500 SFPM	6 FPM	Good	No advantage over standard blade
Countersink Serrated		600 RPM	N/A	Poor	Unsatisfactory finish
HSS Twist Drill Modified	1/4", 3/8", 1/2", 5/8"	600 RPM	24 sec/in	Good	Excellent with backup
Solid Carbide Twist Drill (Modified)	1/2"	600 RPM	20 sec/in.	Good	Excellent for graphite composite
Turboflute or Paraflute Drill (Modified)	1/2"	750 RPM	24 sec/in	Good	Excellent with backup
Router - Special Design					
Circular Saw Carbide Teeth (Modified) Mod #2	10" 60 Tooth	4500 SFPM	6 FPM	Good	More effective than standard

All of the unmodified drill bits except the spade bit produced unsatisfactory holes that were rough, fuzzy, and had backside delaminations. The spade drills produced satisfactory holes in the thinner laminates, but being centerless they required guides or bushings. In addition, the spade drill was delicate and subject to a high breakage rate.

The modified twist drill and the modified parabolic flute made satisfactory holes in laminate ranging in thickness from 0.06 to 0.38 inch. The drills performed satisfactorily off-hand with a drill press and using drill bushings. During Phase III tests, 100 holes were drilled in a 0.18-inch-thick laminate without a decrease in hole quality.

The modified parabolic flute is the most effective of all the evaluated drills, probably because of the greater chip relief area discussed previously. (See Figure 9.)

Countersinks - Three countersinks were evaluated: a standard severance two-fluted bit with micro stop, a four-fluted severance countersink with serrated lips (made especially for Kevlar), and the Weldon deburr and countersink tool. (See Figure 10.)

Of the three countersinks evaluated, the Weldon countersink tool made the cleanest countersink surface, as is shown in Figure 11. The standard two-fluted countersink left a rough countersink surface and dulled quickly. The serrated four-fluted countersink had better tool life but again made a rough surface.

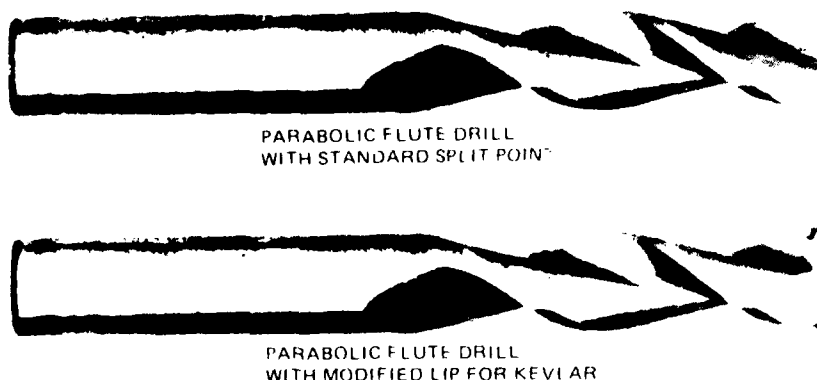


Figure 9. Parabolic Flute Drill Modification

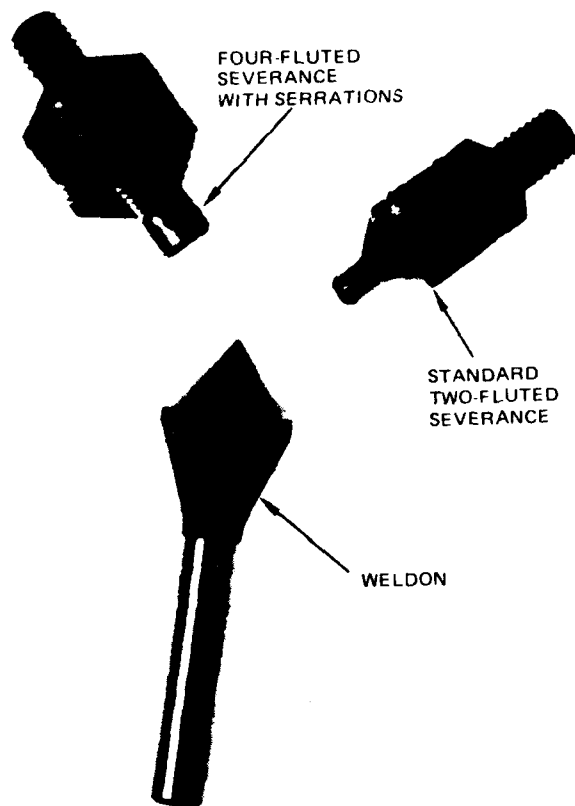


Figure 10. Countersinks

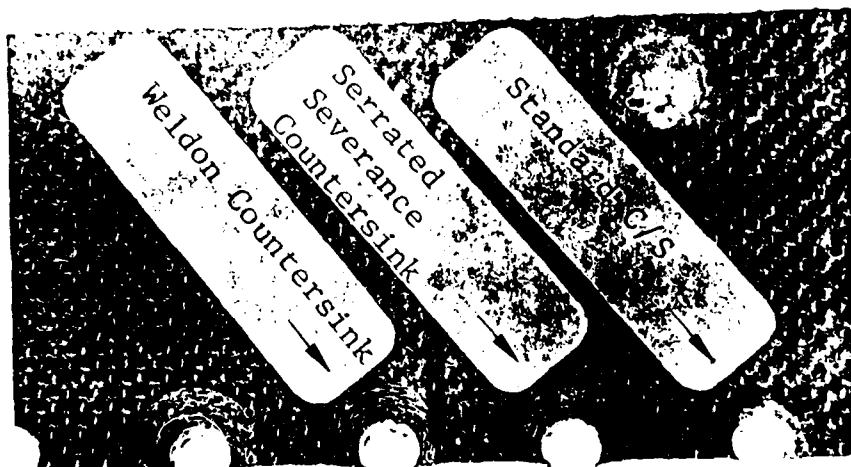


Figure 11. Countersink Evaluation

The Weldon countersink does not require modification. It is designed with the proper cutting configuration for Kevlar composites. However, care must be taken to prevent overheating, and a water coolant is recommended.

Router Bits and Mill Cutters - The result of an edge trimmed with a diamond cut carbide router (Figure 12) is shown in Figure 1. Most conventional routers produce the same results.

The opposed helical router (Figure 13), which is designed especially for routing Kevlar composites, produces a very satisfactory cut. However, care must be taken to keep the laminate on the cutting center line. In addition, the configuration makes the bit somewhat subject to breakage, and cutting speeds less than the usual 20,000 rpm are recommended for the smaller diameter bits.



Figure 12. Diamond Cut Router Bit

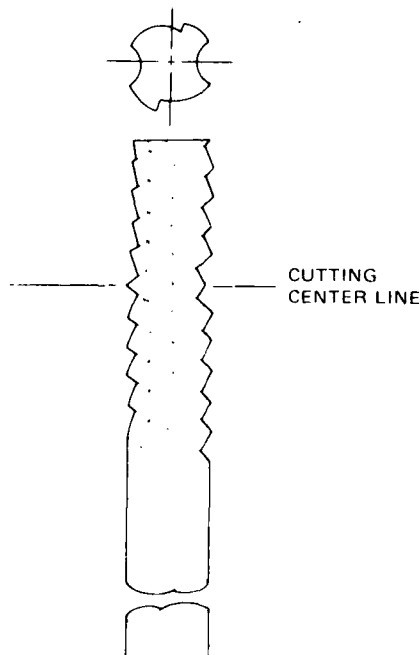


Figure 13. Opposed Helical Router Bit

A 1-inch-diameter Hogmill (Figure 14) was used to route the edge of a 0.38-inch-thick Kevlar panel. The cutter appears to be a satisfactory method of removing thick sections of material, although the cut is left with slight lateral grooves and requires finishing.

The specially designed mill cutter discussed in the Modified Tools section and shown in Figure 7 is effective for finishing Kevlar laminate edges.

Circular Saws - Since circular saws make only straight cuts, they are somewhat limited in their application to aircraft composite production. These blades do have a wide thickness capability and easily cut the full range of thicknesses investigated in this program (0.06 to 0.38 inch).

For most applications a standard 60 to 64 tooth carbide tipped blade is sufficient. For more demanding jobs a carbide tipped blade ground to the configuration shown in Figure 6 will give superior results.

Best results were obtained at a cutting speed of 4,500 surface feet per minute (SFPM). Also, a water coolant is required for heavier cuts. A small amount of fuzz clings to the bottom edge of the cut, but it can be easily removed with a finishing wheel.

Grit-edged circular saw blades make a clean cut but become clogged with Kevlar fibers after a few inches.

The composition blade used for metal cutoff purposes is useful for cutting cross sections of investigative samples of Kevlar with metal inserts, but here again, the blade becomes clogged within a few inches.

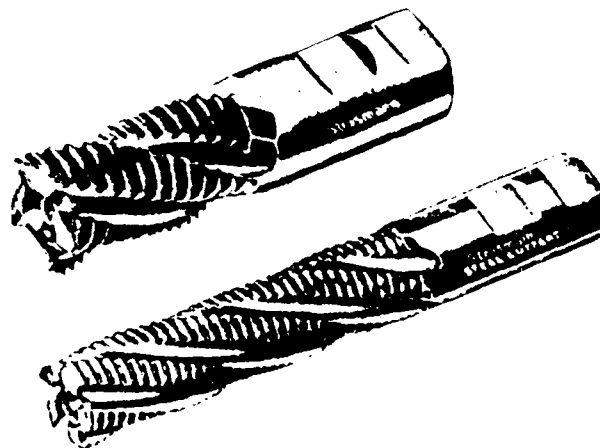


Figure 14. Hogmill

Figure 15 shows the carbide tipped and the grit-edged saw blades.

Sabre Saw Blades - Five sabre saw blades were evaluated using an air-driven sabre saw with a 1-inch stroke and a 2,000- to 2,500-stroke-per-minute capability. (See Figure 16.) This saw was also equipped with a blade orbiter; however, cuts made with the blades using straight reciprocation were cleaner and faster.

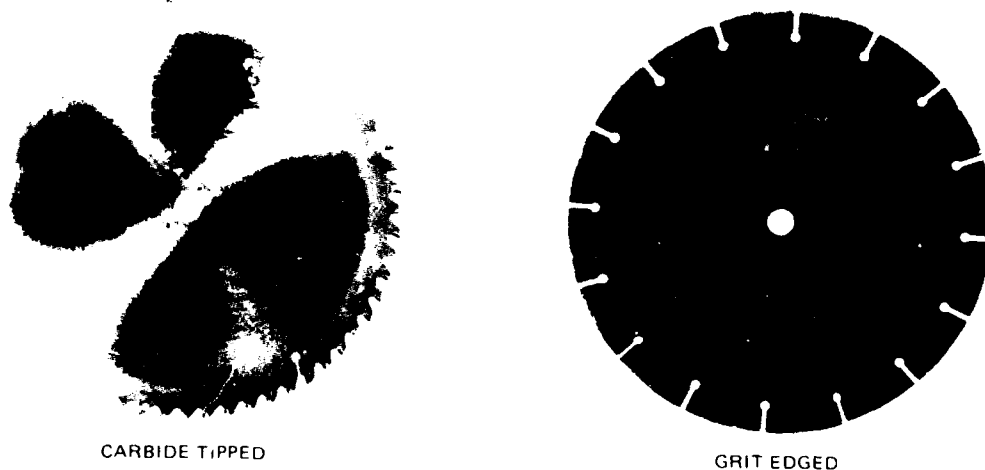


Figure 15. Circular Saw Blades

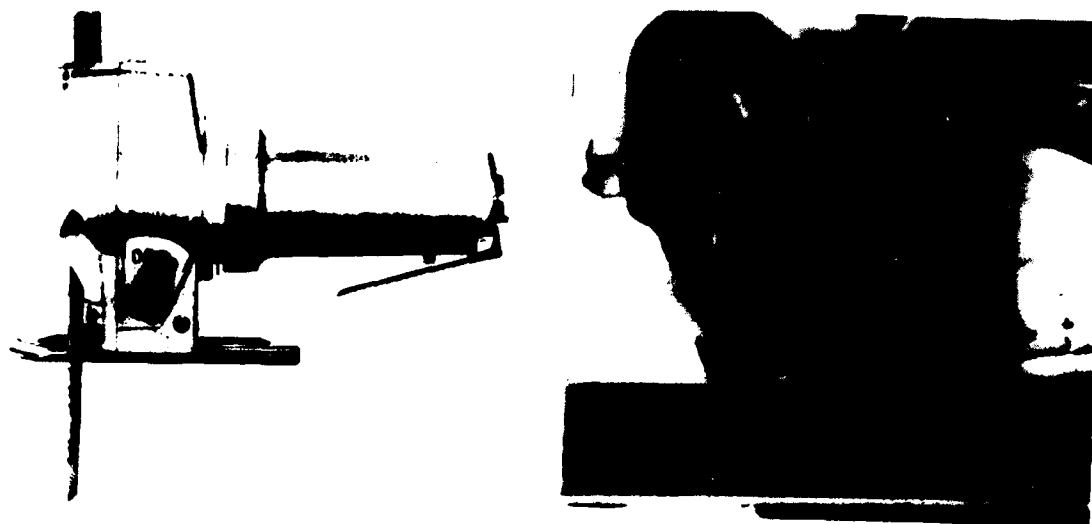


Figure 16. Sabre Saw

Of the five sabre saw blades investigated (see Figure 17), the 22-tooth-per-inch wavy set blade made one of the best cuts. A special Kevlar cutting blade with a repeated pattern of reversed teeth made an equivalent cut but is a much more expensive tool. A 10-tooth-per-inch wavy set blade made a faster but somewhat rougher cut. A coarse, carbide grit blade also made a satisfactory cut and did not have the severe clogging problem exhibited by the grit-edged circular saw blades.

An unsuccessful attempt was made to use a knife-edged blade for cutting thin laminates. However, this blade proved outstanding for cutting dry Kevlar fabrics.

Band Saw Blades — Most band saw operations are done as a rough trim close to a scribed line. A sander and finishing wheel are then used to complete the trimming to the line. With the exception of this inability to precision cut, band sawing is effective for Kevlar laminate trimming.

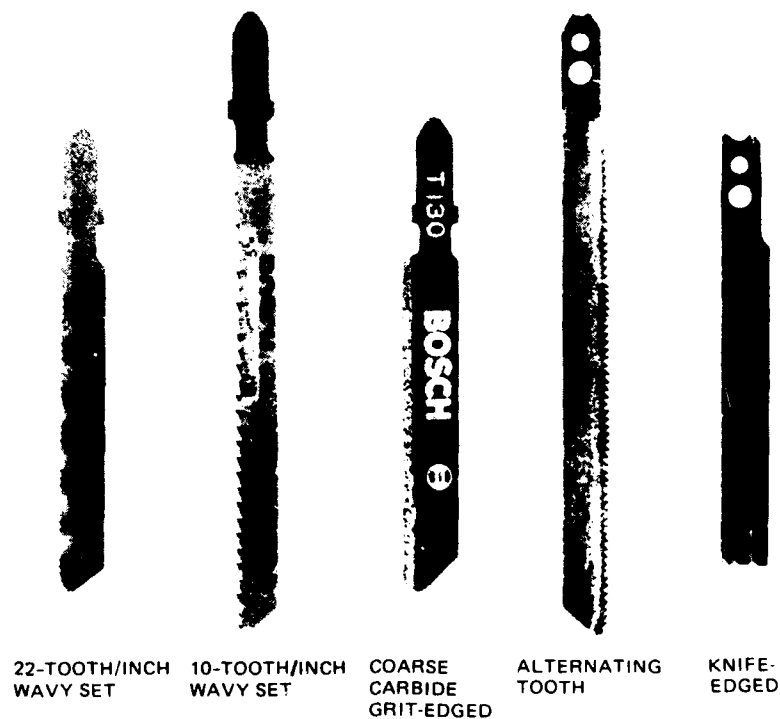


Figure 17. Sabre Saw Blades

Of the many band saw blades available, the standard blades perform as well as any. A 1/4-inch-wide, 32-tooth-per-inch wavy set blade is recommended for cutting Kevlar laminates up to 0.125 inch thick. A 1/2-inch-wide, 22-tooth-per-inch wavy set blade is recommended for thicker laminates (see Figure 18). Specially ground band-saw blades do not appear to have an appreciable advantage over the much less expensive standard blades discussed above.

As with the sabre saw blades, a knife-edged band saw blade is very effective for cutting stacks of dry Kevlar fabric.

Table 2 gives recommended cutting speed for various Kevlar laminate thicknesses.

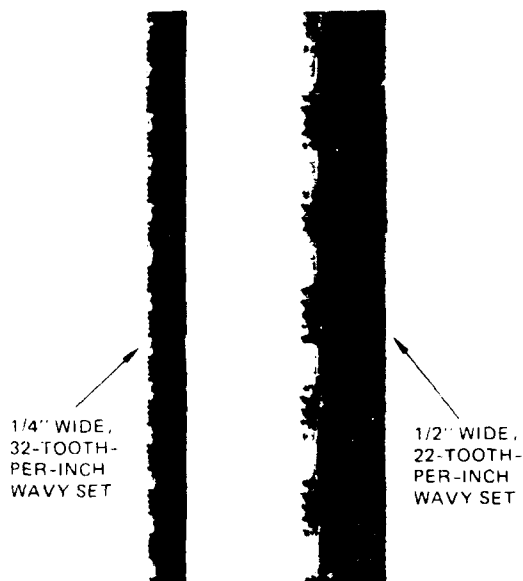


Figure 18. Band Saw Blades

TABLE 2. RECOMMENDED SPEEDS FOR
BANDSAWING VARIOUS LAMINATE
THICKNESSES

THICKNESS (IN.)	0.060	0.125	0.180	0.250	0.50	1.0
BAND SAW TYPE	SURFACE FEET PER MINUTE					
1/4" 32 TOOTH WAVY SET	1500	1200	900	600		
1/2" 22 TOOTH WAVY SET	1500	1200	1000	1000	800	600

Nibbler — The nibbler (see Figure 19), which cuts by punching a series of interconnecting holes, is also an effective Kevlar laminate trimming tool. The nibbler operates at 1,400 to 1,600 strokes per minute and produces a kerf width of 0.2 inch. The nibbler is effective up to a thickness of 0.70 inch. The cut edge requires light cleanup.

Finishing Disks and Wheels — As noted previously, many cutting operations leave an irregular surface or some fuzz on the bottom side of the cut. The edges can be cleaned up using sanding disks and sanding wheels (see Figure 20).

Where very light cleanup is needed, a sanding wheel (synthetic fiber wheel shown in Figure 20) will do an adequate job by itself. For rougher cuts, sand off rough edges with a 16-grit sanding disk, smooth out with an 80-grit disk, and finish off with the sanding wheel.

EVALUATION OF STATE-OF-THE-ART MACHINING EQUIPMENT

Two advanced technology cutting methods are finding acceptance throughout industry: the laser and the water-jet cutter. The principal work of this program was directed to water-jet cutting technology because of both the availability of the water-jet to HHI and the belief that the water-jet is more adaptable to the aircraft production environment.

In addition to these rapid cutting systems, the slow cutting reciprocating diamond coated wire saw was also investigated.

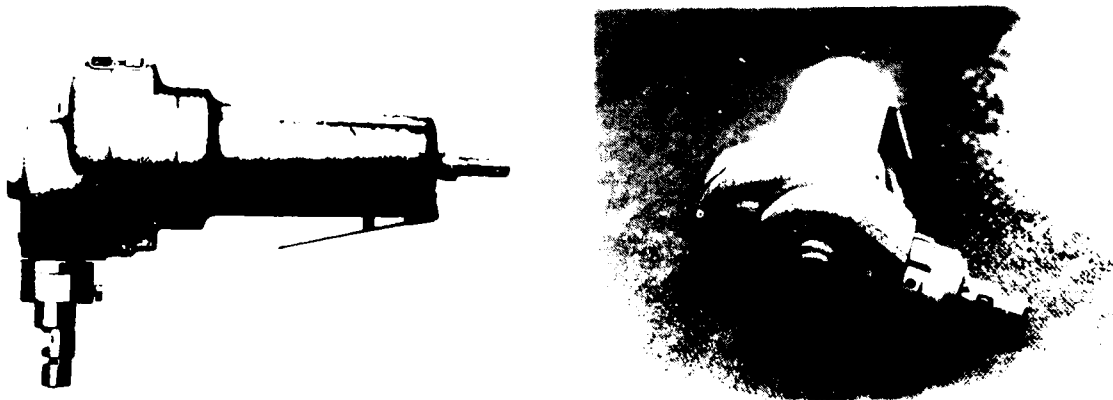


Figure 19. Nibbler

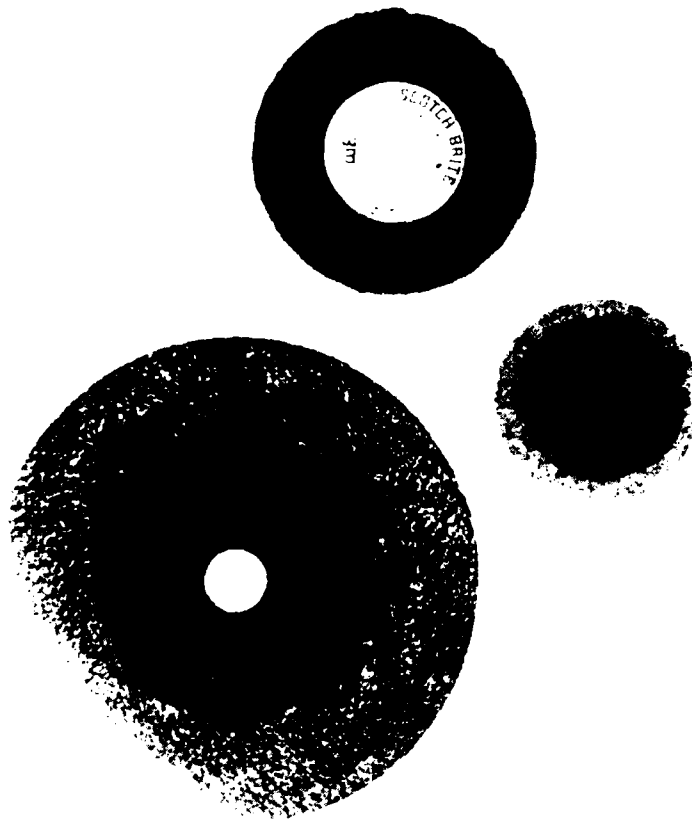


Figure 20. Abrasive Disks and Finishing Wheel

Laser - Laser cutting of Kevlar/epoxy laminates produces a sharp, clean edge with little discoloration at speeds unrivalled by other methods. However, the depth of cut is restricted (approximately 3/8 inch for a 1,000 watt laser), and expertise is required by the operator because of the dangers of high voltage, radiation exposure, and hazardous fumes.

The laser lends itself to automated cutting of flat or slightly contoured parts, but has not to date been used for complex contour part machining.

Two references are presented below that detail laser cutting techniques and methodology.

1. For general laser information:

Lasers in Modern Industry
By John F. Ready

Published by:
Society of Manufacturing Engineers
One SME Drive, P. O. Box 930
Dearborn, Michigan 48128

2. For specific Kevlar laser cutting:

Laser Cutting of Kevlar Laminates

By R.A. Van Cleave

Ref: BDX-613-1877

U.S. Dept. of Commerce

National Technical Information Service

Water-Jet — Water-jet cutting is accomplished by severing material with a highly columnated stream of water, traveling at high speed and under extreme pressure. The schematic below (Figure 21) illustrates the basic components of the water-jet cutter. The major components are a low pressure pump, intensifier, accumulator, on-off valve, nozzle, and catcher (drain).

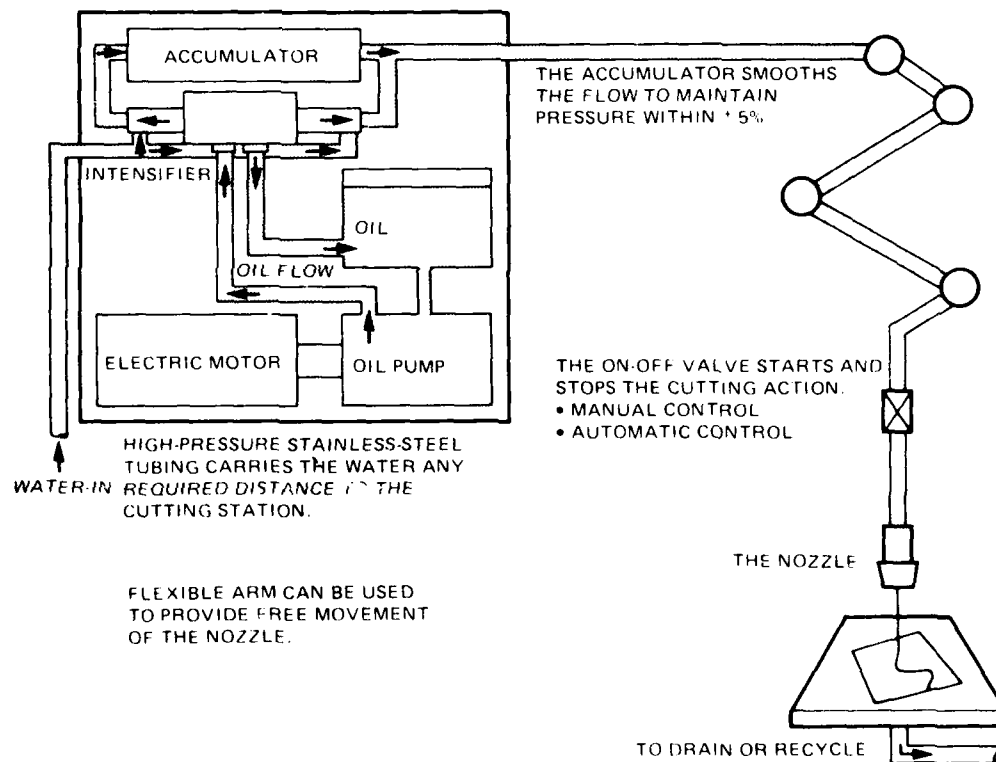


Figure 21. Water-Jet Schematic

HHI evaluated two different water-jet setups. The major portion of the work was done with a water router. This is a hand-held device with an overhead counterbalance support (see Figure 22).

This system was effective to about a 1/8 inch thickness. Thicker specimens began to show roughness and backside delaminations. In order to eliminate nozzle maintenance and orifice wear, the pressure setting is limited to 50,000 psi, resulting in a working pressure of about 45,000 psi.

The water router was evaluated for cutting speed and quality of cut through the full range of Kevlar laminate thicknesses under investigation. The results of this evaluation are presented in Table 3, Water-Jet Router Evaluation. The test results show the quality of the cut beginning to degrade at 0.18 inch thickness with unsatisfactory cuts at 0.31 inch thickness.

The second water-jet evaluated was a fixed position nozzle with a variable-speed feed table. The pressure on this equipment was set at 55,000 psi. This fixed position water-jet was easily able to cut the maximum thickness laminate investigated on this program (0.38 inch) and appeared to have capabilities up to 1.0 inch thickness. See Table 4, Fixed Heat Water-Jet Evaluation.

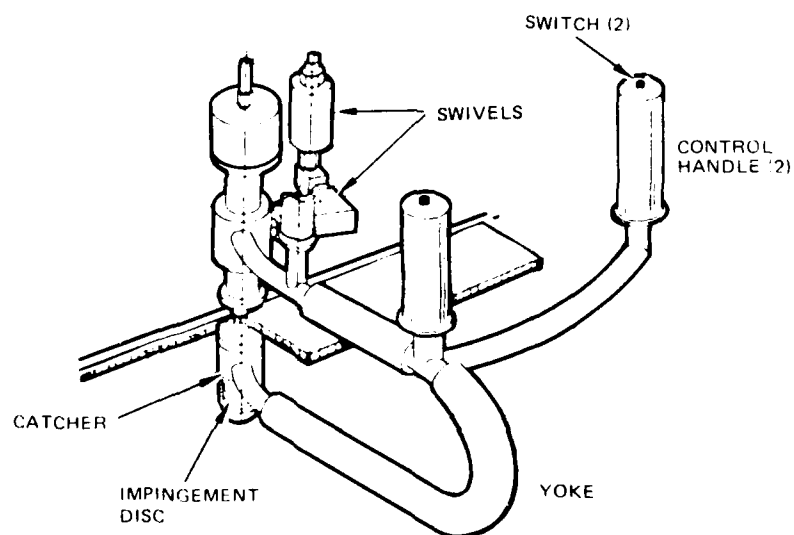


Figure 22. Water-Jet Router

TABLE 3. WATER-JET ROUTER EVALUATION

THICKNESS (IN.)	JEWEL HOLE DIA. (IN.)	PRESSURE (PSI)	CUTTING TIME (SEC)	AREA OF CUT (IN ²)	CUTTING TIME FOR 100 IN ² (MIN)	QUALITY
0.125	0.012	45,000	41	6	11.4	FAIR
0.125	0.012	45,000	28	6	7.77	FAIR
0.125	0.012	45,000	57	6	15.83	FAIR
0.180	0.012	45,000	100	8.64	19.29	POOR
0.180	0.012	45,000	90	8.64	17.36	POOR
0.180	0.012	45,000	105	8.64	20.25	POOR
0.060	0.012	45,000	14	2.88	8.1	GOOD
0.060	0.012	45,000	11	2.88	6.3	GOOD
0.060	0.012	45,000	8.5	2.88	4.9	GOOD
0.060	0.016	45,000	14	2.88	8.1	GOOD
0.060	0.016	45,000	9	2.88	5.2	GOOD
0.060	0.016	45,000	12	2.88	6.9	GOOD
0.180	0.016	45,000	134	8.64	25.84	FAIR TO GOOD
0.180	0.016	45,000	131	8.64	25.27	GOOD
0.180	0.016	45,000	66	8.64	12.73	GOOD
0.125	0.016	45,000	45	6	12.49	GOOD
0.125	0.016	45,000	47	6	13.05	GOOD
0.125	0.016	45,000	44	6	12.22	GOOD
0.310	0.012	45,000	140	14.88	15.68	POOR
0.310	0.016	45,000	186	14.88	21.04	POOR

TABLE 4. FIXED HEAD WATER-JET EVALUATION

Thickness (in.)	Working Pressure (psi)	Orifice Size (in.)	Cutting Speed (FPM)	Results
0.06	50,000	0.007	10	Good
0.38	50,000	0.012	1	Good

A new development in water-jet cutting is the oscillating head. The water-jet head is oscillated in such a manner that a tapered kerf is cut in the laminate; in this way the jet is not dissipated against the walls as rapidly and thicker cuts are possible (see Figure 23).

Although the oscillating head is not needed to cut the maximum thickness investigated in this program (0.38 inch), it may be advantageous for much thicker cuts.

Reciprocating Wire Saw - Kevlar laminates of any thickness can be cut with a reciprocating wire saw. (See Figure 24.) This reciprocating mechanical wire cutter uses diamond impregnated wire, sized 0.003 through 0.016 inch diameter, that reciprocates on a grooved drum. The saw cuts with a type of lapping action and does not generate appreciable heat. It does not load, and produces a cut of very high quality.

Unfortunately, the very slow cutting speed of this equipment relegates it to specialized cutting applications such as sample cutting. The ability of the wire saw to cut Kevlar laminates in combination with any hard material makes it a good method for cutting investigative samples.

Specifics of the panel cutting operation are shown in Table 5.

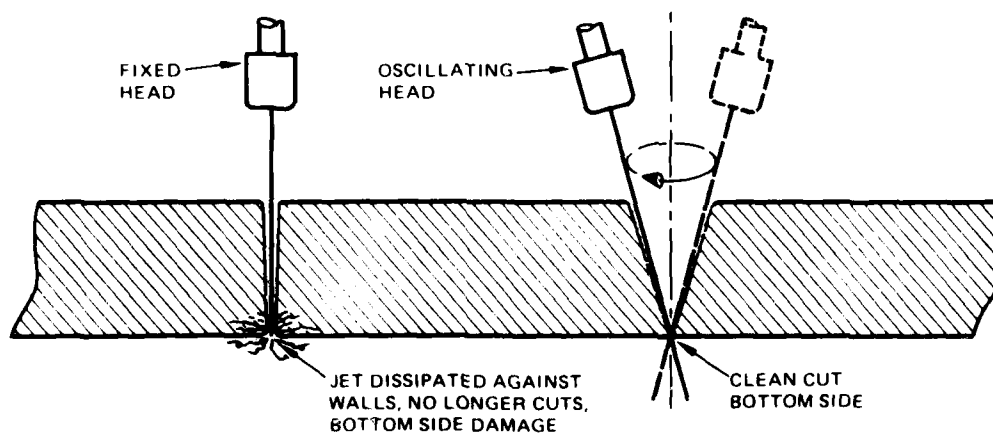


Figure 23. Theory of Oscillating Head

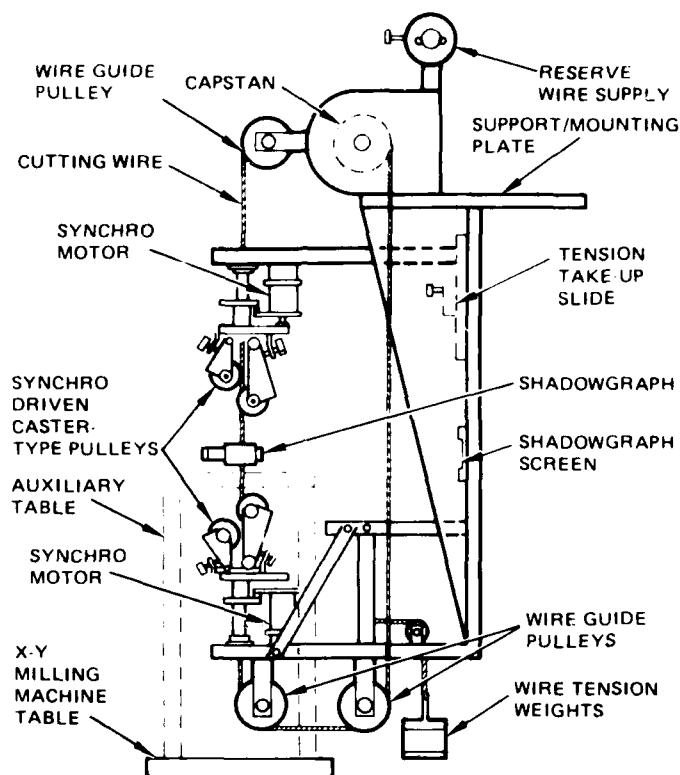


Figure 24. Reciprocating Wire Saw

MACHINING POLYSULFONE/KEVLAR PANELS

Fabrication of the two polysulfone/Kevlar test panels was described on page 13. Each panel was made with a different reinforcing system - one having woven fabric and the other a cross-plyed unidirectional reinforcement.

The woven Kevlar fabric/polysulfone panel machined easily using the same tools that were acceptable for machining the woven Kevlar/epoxy panels; however, a little care must be exercised to prevent generation of excess heat. The unidirectional Kevlar/polysulfone test panel, on the other hand, does not machine well using the tools in a normal manner. It was very difficult to prevent delamination of the outer unidirectional plies on the surfaces adjacent to the cut or hole. The only acceptable cuts were made by using the nibbler and the water-jet. It is expected that the reciprocating wire saw and the laser would work as well.

Acceptable holes were made only by casting plaster on each side of the panel and drilling with the modified tip parabolic flute drill.

TABLE 5. RECIPROCATING SAW CUTTING EVALUATION

SAMPLE CUT NO.	THICKNESS AND LENGTH (IN.)	TIME OF CUT (MIN)	TIME PER 100 IN ² (HRS)	AREA OF CUT (SQ IN.)	WIRE DIA (IN.)	TENSION ON WIRE (GR)	WEIGHT ON WIRE (GR)	WEIGHT ON YOKE	SPEED SETTING	SLURRY USED	COOLANT USED
1	0.38 x 6	50	36.549	2.28	0.010	3500	40	1 MAIN WT + 100 G	80	SILICONE	WATER
2	0.38 x 6	27	19.7	2.28	0.010	3500	60	1 MAIN WT + 100 G	80	SILICONE	WATER
3	0.195 x 6	16	22.79	1.17	0.010	3500	60	1 MAIN WT + 100 G	80	SILICONE	WATER
4	0.121 x 6	8	18.36	0.726	0.010	3500	60	1 MAIN WT + 100 G	80	SILICONE	WATER
5	0.38 x 6	21	15.35	2.28	0.010	3500	160	1 MAIN WT + 100 G	80	SILICONE	WATER

PHASE III - MANUFACTURING METHODS DEVELOPMENT

During Phase III production scale-up, characteristics of hole drilling in relation to the quality, cost, and tool durability were evaluated. Tool life under normal operating conditions, tool life using special tooling materials, and tool life improvement when using coolants and special coating were evaluated.

Production application problems were also addressed and concepts were developed for production machining of complex aircraft components. Automation methods were studied and integration of automated machining into labor efficient production lines was conceptualized.

DRILL LIFE STUDY

During Phase II testing it was determined that the modified tip drill bits out-performed all other drill bits evaluated on this program. In order to determine relative production life expectancy of modified tip drill bits with different materials in different configurations, three distinct bits were evaluated: high speed steel (HSS) standard twist, cobalt standard twist, and HSS parabolic flute. One hundred holes were drilled with each bit into an 0.18-inch-thick laminate. (See Figure 25.) In all three cases the one-hundredth hole had the same quality and took the same time to drill as the first hole. The average time for drilling each hole was 6 seconds. The drills were cooled with water as frequently as was necessary.

From these drilling exercises, it was concluded that the working life of the modified HSS drill was adequate for most Kevlar laminate drilling operations. The more expensive drill bit materials such as cobalt or solid carbide need only be used when drilling Kevlar hybrids or combinations with fiberglass or graphite.

The modified parabolic flute drill was the least expensive and produced the cleanest holes. This is probably due to its greater chip relief area.

MACHINING BACKUP, COOLANTS, AND COATINGS

Machining Backup - Even with the best of cutting tools some of the top and bottom Kevlar fibers adjacent to the cut or hole may be broken loose when machining without a backup. Ideally, the laminate should be clamped between two flat plates of hardwood, or acrylic sheets. Laminates that

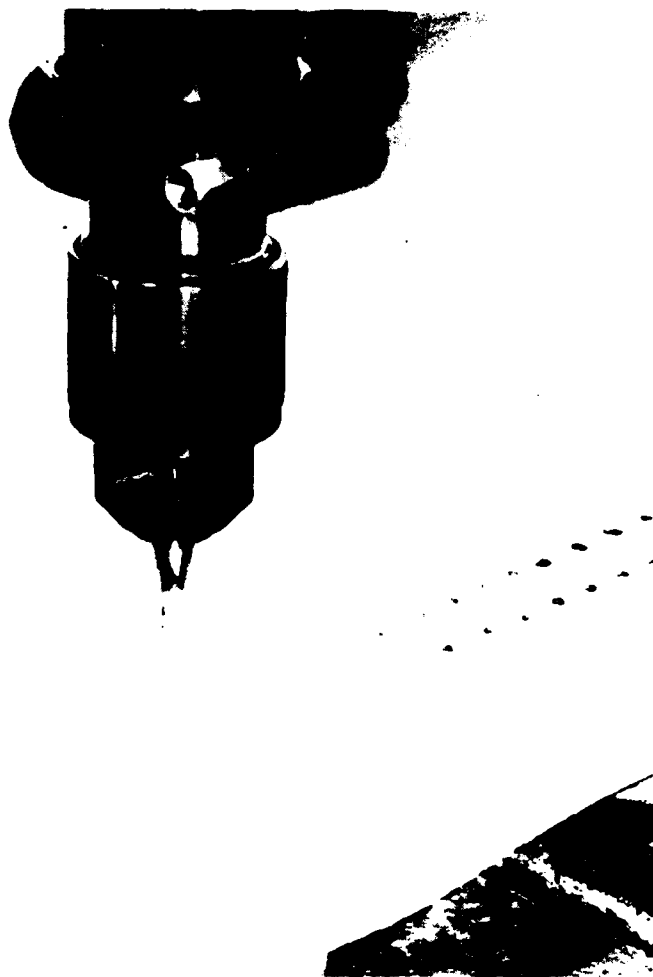


Figure 25. Drill Exercise, 100 Holes

are machined with a down acting shear component, such as the circular saw, band saw, or drill, perform with less bottom side fiber dislocation or delaminating if a backup board is used.

Coolants - All Kevlar laminate cutting tools should be held below 350 F during machining operations to prevent swelling of the cut edge. This can generally be accomplished by keeping the tool sharp and tool speed at a low operating level. However, when maximum production is required a coolant will allow machining at a faster rate.

Water has been found to be an inexpensive and entirely satisfactory coolant for Kevlar laminate machining. It can be applied as either a spray or periodic dip.

Coating and Release Agents - Dry lubricants are useful on circular saws, band saws, drills, and countersinks. Dry lubricants prevent galling and allow chips to move more freely without sticking to the tool.

Tools may also be coated with liquid release agents such as Release-all. Best results are obtained by applying three coats of the release agent and then baking for 1 hour at 300°F.

Drill bushings are very damaging to drills, and drill guides (adapters which locate the drill without touching the lands) should be used whenever possible. Bushings, when used, should always be kept well lubricated by using dry lubricants or fluorocarbon sprays. New bushings should be broken in with old drill bits.

PRODUCTION SCALE-UP AND AUTOMATION

Production Cutting System - The tedious tasks of trimming Kevlar composites with saws and hand grinding are being eliminated by the use of optically or numerically controlled machining equipment. The water-jet setup with either of these control systems could handle the thickness range investigated in this program (0.06 to 0.38 inch) and eliminate the dust control problem associated with cutting and grinding. The Phase II investigation indicated a controlled feed water-jet has Kevlar laminate thickness cutting capabilities up to approximately 1 inch. Figure 26 shows an optically controlled system for water-jet cutting flat Kevlar laminates, and Figure 27 shows a biaxial, tape controlled water-jet trimming system.

Robotics - The employment of lightweight robotics for the trimming and drilling of complex Kevlar parts is in the early stages of development. Present off-the-shelf equipment lacks the necessary precision needed for jig-free machining. However, considerable effort is being expended by the robotics industry to develop the necessary precision and repeatability.

It is noted that the milling, routing, drilling, and countersinking tools identified in Phase II would be suitable for robotic machining, as would the laser and the water-jet.

Figure 28 shows a typical robotic station employing a rotary cutter.

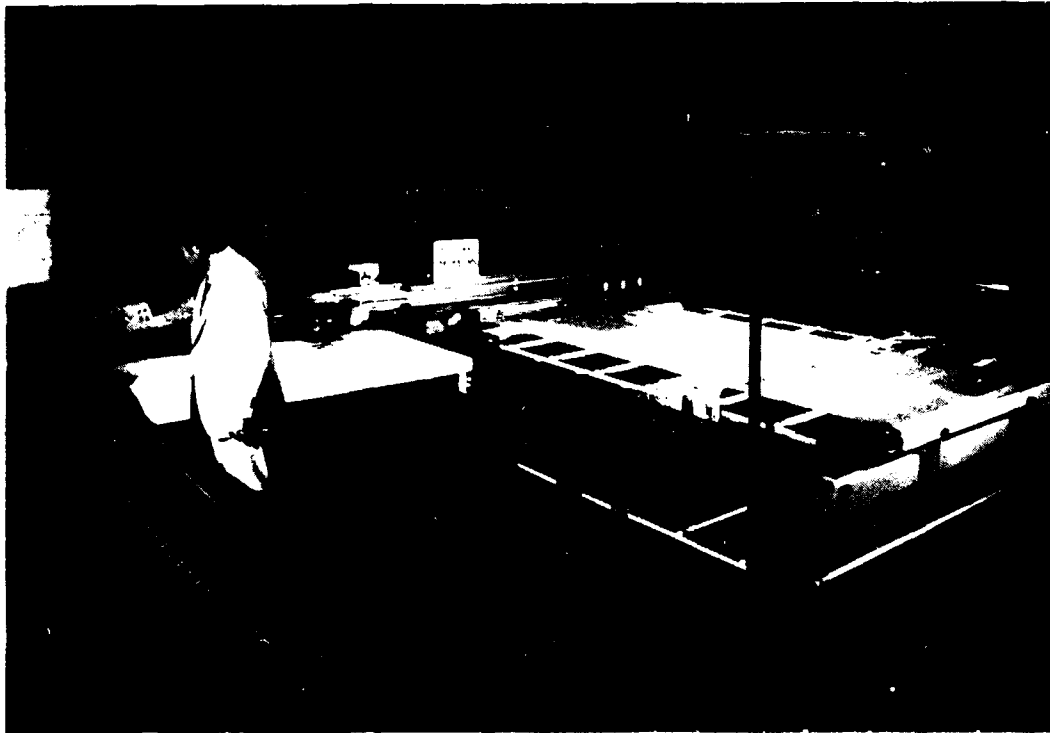


Figure 26. X-Y Optical Tracing System, Water-Jet Cutting of Flat Sheet

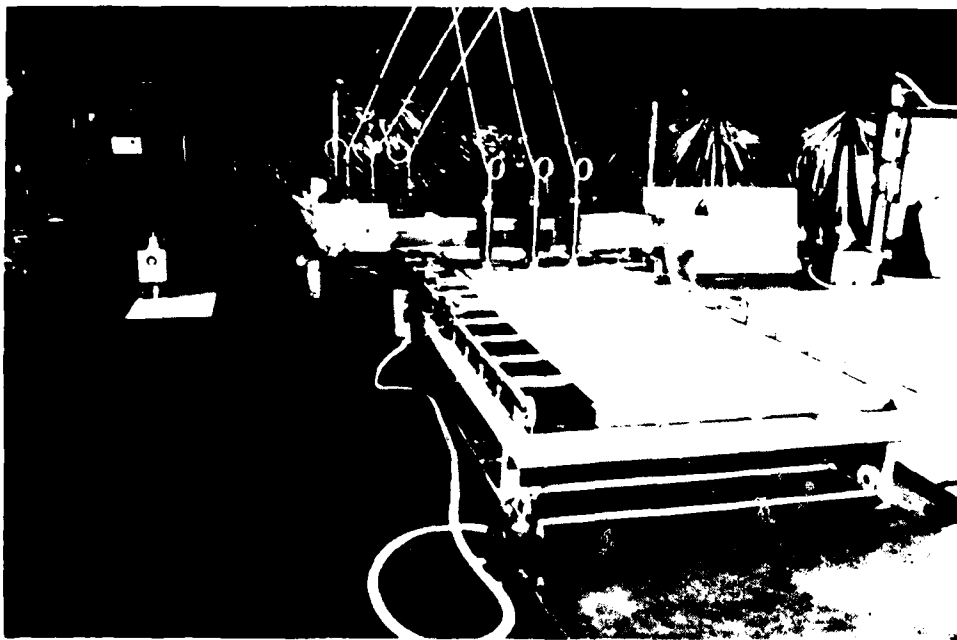


Figure 27. Tape Controlled Water-Jet Trimming System



Figure 28. Robotic Trim Station

INTEGRATION OF AUTOMATION INTO ADVANCED COMPOSITE PRODUCTION LINES

The performance evaluation in the first segment of this program has shown that tools and equipment presently available have suitable quality and durability for incorporation into automated production lines. The use of a spray mist of water will be adequate in most cases to keep the tools cool and achieve long tool life. Both the water-jet and the laser appear to be adaptable to **automated** machining.

In this section we will discuss the integration of automated Kevlar composite machining equipment into typical automated composite fabrication lines. The discussion can best be presented by breaking it into three paragraphs:

- Present Day - Equipment available for production today.
- Near Term - Equipment that will be available in 3-5 years.
- Future - Equipment that will be production ready in 10-15 years.

Present Day - Presently available are the numerical control (N/C) (tape controlled) and optical tracing trimming equipment. Figure 29 shows a five-axis N/C water-jet trimming station integrated into a present-day production line along with an N/C controlled pattern cutter.

Near Term - In the near term, the automated composite production line is expected to incorporate computer storage and self-contained tooling. The contribution in the automated machining area in addition to N/C machining will be robotic drilling. As near-term robotics will not yet have the accuracy and repeatability for precision aircraft hole patterns, this equipment will be used in conjunction with drill templates for accurate location. Figure 30 shows the robotic drilling station integrated into the composite production line as well as the N/C trimming station.

Future - Future composite production lines will further reduce costly labor by introducing robotic handling, automated curing, and automated non-destructive testing. The automated machining contribution will be in the form of robotic trimming and drilling of sufficient accuracy such that no trimming or drilling jigs will be required. Figure 31 shows the future composite production line with the automated production equipment integrated into the system.

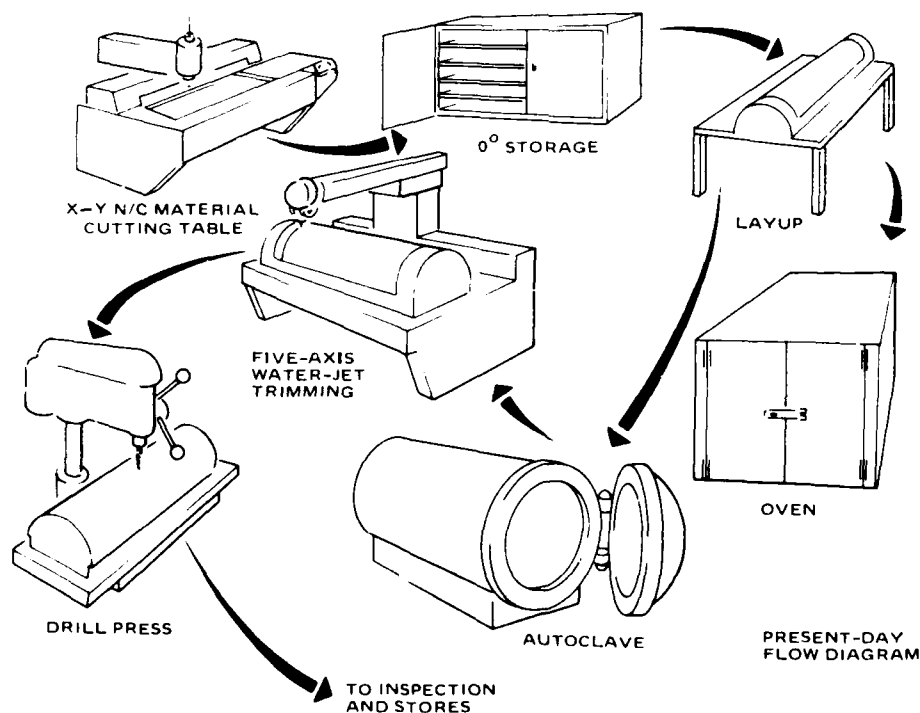


Figure 29. Present-Day Automated Composite Production Line

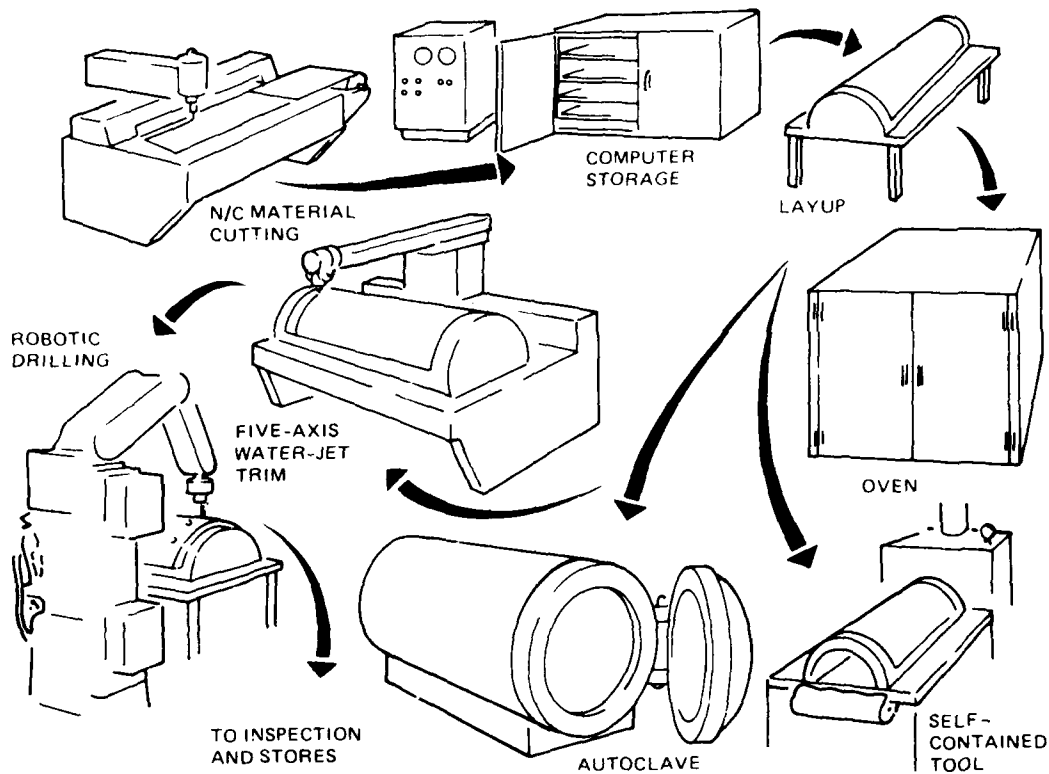


Figure 30. Near-Term Automated Composite Production Line

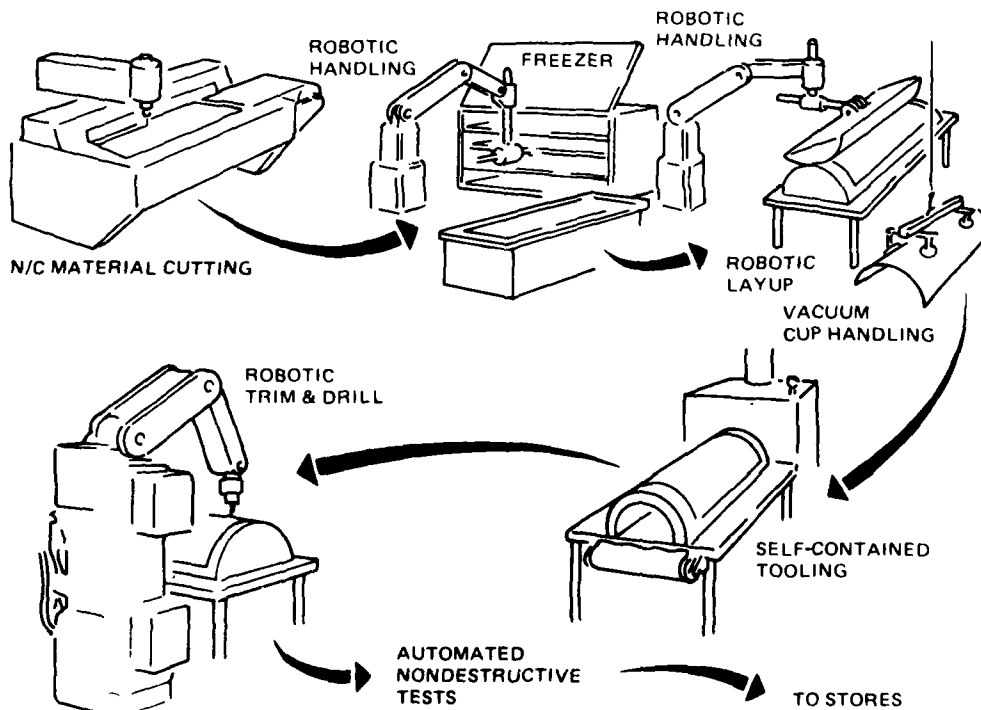


Figure 31. Future Automated Composite Production Line

CONCLUSIONS AND RECOMMENDATIONS

The technology survey of current tools and practices performed during this program shows that for many applications existing tools and technology are adequate. In the area of cutting, recommended tools and practices are adequately developed and verified for cutting of raw materials (yarns, rovings, and pre-impregnated fabrics). However, during the evaluation phase of this program, many of the recommended tools for cutting laminates proved ineffective for laminates reinforced with Kevlar 49. Notable exceptions were the laser, water-jet, and reciprocating wire saw.

In the area of machining of cured Kevlar/epoxy and Kevlar/polysulfone laminates (drilling, countersinking, counterboring, and milling operations) special tools are required in many cases and only a limited range of feeds and speeds may be successfully used. Particular attention must be given to cutting the outermost layers of the composite laminate. Many of the tools recommended for these operations were found to have limited cost effectiveness in a production environment.

Evaluation of cutting tools and systems was followed by a study of advanced machining methods that are presently being introduced and those envisioned for the future. Near-term applications such as multi-axis and automated trimming and robotic drilling were found to be in the initial stages of development. Both the water-jet cutter and the laser that were found to be efficient cutting systems for both Kevlar/epoxy and Kevlar/polysulfone laminates may be readily adapted for automated trimming systems.

Outstanding problems on which resources could be allocated and approaches recommended include the following:

a. Complex Shapes

Kevlar machining activity to date has concentrated on the machining of simple shapes which are either flat or of simple contour. Techniques for machining the complex shapes found commonly among aircraft components are needed.

b. Thick Laminates

The present program performed extensive studies on laminates up to 0.38 inch thick and limited studies on cutting laminates up to 1.0 inch thick. Additional study is needed to develop techniques to cut and machine laminates of 1.2 to 2-inch thickness, for both straight and complex cuts.

c. Automated Trimming

In order to push forward the concepts already under initial study, two areas need investigation and development.

1. Universal, automated trim stations with capabilities for trimming different configurations of complex parts
2. Specialized trim stations with accurate, low-cost tools designed for automated trimming of a specific part (applicable to inline production tooling)

d. Routing/Milling Techniques

The routing/milling tools developed under this program have characteristics (rough cut, required precise cutter positioning) that limit their use. Further work is needed to locate/develop more versatile cutters.

APPENDIX A
LITERATURE SURVEY

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35 Annual Tech Con. 1980
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"Fabrication of Low-Cost Primary Aircraft Structures with Thermoplastic Composites"
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"Problems in Testing Aramid/Epoxy Composites"
Lawrence Livermore Lab, L.I. Clements

"Cutting and Machining of Kevlar Aramid and Its Composites"
Louis H. Miner, Frank T. Penzo
21st National Symposium SAMPE
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"Producibility Aspects of Advanced Composites for an L-1011 Aileron"
Society of Manufacturing Engineers
20501 Ford Rd.
Dearborn, Michigan 48128

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Murry Hill, NJ 07974

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Product Engineering - P. West
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"Diamond Tools Solve New Machining Problems"
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Hughes Helicopters, Inc. DAAG46-74-C-0100, Apr. 75
Head, Leach, Goodall, Sitterly

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Bethpage, N.Y. 11714

"Characteristics of Laser Cutting Kevlar Laminate"

R.A. Van Cleave, Jan. 1979

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"Manufacturing Methods for Machining Processes for High Modulus Composite Materials"

Vol. I, Composite Machining Handbook, Born

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"Laser Cutting of Kevlar Laminates"

R.A. Van Cleave, Bendix Corp., Kansas City

September 1977, BDX-613-1877

GOVERNMENT-SPONSORED STUDIES (CONT)

"Ultrasonically Assisted Machining of Aircraft Parts"

J. DeVine, P.C. Krause - Sonobond Corp.

AVRADCOM Report No. TR80-F-18, October 1980

"Study of the Influence of Hole Quality on Composite Materials"

J.J. Pengra, Lockheed, CA

Contract NAS1-15599, February 1980

"Investigation of Hole Preparation and Fastener Installation for Graphite/
Epoxy Laminates"

E.F. Condon, McDonnell Aircraft

Tech Report N00019-79-C-0293

Design Guide Handbook

Efficient Machining Methods and Cutting Tools for Kevlar Composite
Laminates

Hughes Helicopters, Inc., Nov 1981

Contract No. DAAK51-81-C-0008

VENDOR LITERATURE

"Industrial Tools for Cutting Kevlar Fabric and Laminates"

Pen Associates, Inc.
2639 W. Robino Drive
Wilmington, Del. 19808

"Speciality Tools for Machining Fiber Reinforced Composite Structures"

Technology Assoc. Inc.
P.O. Box 7163
Wilmington, Del. 19803

"A Guide to Cutting and Machining Kevlar"

DuPont, Inc. Textile Fibers Dept.
Centre Rd. Building
Wilmington, Del. 19898

"Environmental Effects on Aramid Composites"

DuPont, Inc., Textile Fibers Dept.
Centre Rd. Building
Wilmington, Del. 19898

"Cutting Fabric, Prepreg and Kevlar Aramid"

Sept. 19, 1975
DuPont Textile Fibers Dept.
Centre Rd. Building
Wilmington, Del. 19898

"Laser Shop Cutting"

MG Cutting Systems
Dw of CLR-0 Inc.
W1441 N 9427 Fountain Blvd.
Menomonee Falls, Wis. 53051

"Cutting With Wire"

Laser Technology, Inc.
10624 Ventura Blvd.
No. Hollywood, CA 91604

"Flow Technology Report No. 7 Waterjet Cutting of Advanced Composite Materials"

Flow Industries, Inc.
21414 68th Ave. South
Kent, Washington 98031

VENDOR LITERATURE (CONT)

Laser Inc. Sub of Flow Industries, Inc.

"Lasers for Industry"

"Everpulse and Everlase Machine Tools PR 980"

"Everlase, Laser Machine Tools"

Coherent Inc.

3210-C Porter Dr.

Palo Alto, CA 94304

"Weldon Tools Cat No. 12"

"Weldon C.S. and Deburring Tools"

Weldon Tool Co.

3000 Woodhill Rd.

Cleveland, Ohio 44104

"Hendricks Panel Saws"

Hendrick Mfg. Corp.

32-36 Commercial St.

Salem, Mass 01970

"Grit-Edge Tungsten Carbide Saw Blades"

Abrasive Product Sale

Remington Arms Co., Inc.

939 Barnum Ave.

Bridgeport, Conn. 06602

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"Special Carbide Tipped Tooling"

Guhring, Inc.

1445 Commerce Ave.

Brookfield, WI 53005

"Industrial Diamond Tool Blanks"

Megadiamond Ind. Inc.

3418 N. Knox Ave.

Chicago, Ill. 60641

"Bendix Drill"

Bendix Ind. Tools Div.

"High Speed Steel End Mills"

Crest-Kret, Multi-Flute

Weldon Tool Co.

3000 Woodhill Rd.

Cleveland, Ohio 44104

VENDOR LITERATURE (CONT)

"Acra-Bore"
Roase-Acia Tools
2212 N. Wayne Ave.
Chicago, Ill. 60614

"High Pressure Water Jet Technology - Principles and Applications"
T.J. Labus, IIT Research Inst.

"Suggestions for Machining Scotchply" B78-2
Industrial Specialties Div., 3-M
Saint Paul, MN

APPENDIX B

VENDORS/DEVELOPERS VISITED DURING
PHASE I LITERATURE SEARCH

- Pen Associated, Inc., Wilmington, Delaware
(F. Penozza)
- Technology Assoc., Inc., Wilmington, Delaware
(J. Madden)
- Kevlar Special Products, E.I. DuPont, Wilmington, Delaware
(K. Keith)
- Laser Technology, Inc., North Hollywood, California
(H. McLaughlin)
- Airtech International, Inc., Carson, California
(R. Moore)
- Grumman Aerospace Corp., Bethpage, N.Y.
(S. Trink)
- J.K. Smith Diamond Industrial Products, Philadelphia, PA
(R. Sgro)
- Flow Industries, Kent, Washington
(H. Parks)

APPENDIX C
MACHINE AND TOOL SOURCES

Nibbler

Bosch Model 7501

Robert Bosch Corporation
2800 South 25th Avenue
Broadview, Illinois 60153

Triumph America Inc.
Farmington Industrial Park
Farmington, Conn. 06032
(203) 677-9741

Wire Cutter

Laser Technology, Inc.
10624 Ventura Blvd.
North Hollywood, CA 91064
(213) 763-7091

Water Jet Cutter

Flow Systems, Inc.
21414 - 68th Ave. South
Kent, Washington 98031
(206) 938-FLOW Telex: 152983

Mill Cutter

Airtech International, Inc.
2542 East Del Amo Blvd.
P.O. Box 6207
Carson, CA 90749
(213) 603-9683 Telex: 194757

Circular Saw

Simonds Ref. No. 08882

Simond Cutting Tools
15619 Blackburn Ave.
P.O. Box 505
Norwalk, CA 90650
(213) 802-2689

Drills

Airflute HSS and Airtip Solid Carbide

Airtech International, Inc.
2542 East Del Amo Blvd.
P. O. Box 6207
Carson, CA 90749
(213) 603-9683 Telex: 194757

Band Saw

The L.S. Starrett Company
Athol, Maine 01331

Simonds International
Fitchburg, Massachusetts 01420
(617) 343-3731 Telex: 928414

Finishing Wheel

Scotch-Brite 4" General Purpose

Building Service and Cleansing
Productions Division/3M
3M Center
St. Paul, Minnesota 55101

Special Tools - Sabre Saw Blade and Opposed Helical Router

Pen Associates, Inc.
3639 W. Robino Drive
Wilmington, DE 19808
(302) 995-6868

Airtech International, Inc.
2542 East Del Amo Blvd.
P. O. Box 6207
Carson, CA 90749
(213) 603-9683 Telex: 194751

Carbro Corporation (Router Only)
15724 Condon Ave.
Lawndale, CA 90260
(213) 675-0355

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