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MANUFACTURING METHODS FOR CUTTING, MACHINING AND DRILLING COMPOSITES

VOLUME I — COMPOSITES MACHINING HANDBOOK

GRUMMAN AEROSPACE CORPORATION
BETHPAGE, NEW YORK 11714

AUGUST 1978

FINAL TECHNICAL REPORT AFML-TR-78-103, VOLUME I

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AIR FORCE MATERIALS LABORATORY
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This technical report has been reviewed and is approved for publication.

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Machining	Graphite/Epoxy	Kevlar/Epoxy	Radial Sawing
Drilling	Graphite-Boron/Epoxy	Fiberglass/Epoxy	Laser Cutting
Composites	Hybrid Composite	Ultrasonic Drilling	Water-Jet Cutting
		Bandsawing	Nondestructive Evaluation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

High-quality, low-cost manufacturing methods were established for cutting, machining and drilling of composites. Production nondestructive evaluation (NDE) techniques, capable of insuring structural integrity, were also developed. Materials addressed in this program included graphite/epoxy and hybrids/thereof, boron/epoxy, Kelvar/epoxy and fiberglass/epoxy. Program highlights are described below.

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Conventional cutting methods were compared to new technology methods such as water-jet, laser and reciprocating cutting. Although the high-speed water-jet and reciprocating cutters worked well with some uncured materials, the slower laser cutter was able to handle all of the materials studied. Steel-rule die blanking was found to be well suited for cutting multiple plies of uncured materials. With regard to cured materials, the water-jet could effectively cut graphite/epoxy, Kevlar/epoxy and fiberglass/epoxy, while the low-power (250 watts) laser could effectively cut only Kevlar/epoxy. The feasibility of producing preplaced holes by blanking was demonstrated and verified by tensile tests.

Several, new low-cost techniques were established for drilling of graphite/epoxy and hybrids thereof. High-speed (21,000 rpm) drilling of graphite/epoxy doubled the life of solid carbide tools. The use of ultrasonic adapters on portable drilling units increased drill life by 100 percent with graphite-boron/epoxy hybrids. Tool geometries that can be successfully applied to Kevlar/epoxy were established. New cutting tool designs for inserted-compacted diamond tools were generated.

Operating parameters were established for routing, trimming, beveling, countersinking and counterboring. In general, diamond-cut carbide router bits were effective for routing and trimming graphite/epoxy and fiberglass/epoxy. Diamond-chip and opposed-helix router bits had to be used to cut boron/epoxy and Kevlar/epoxy, respectively. Modification of the countersink relief and rake angles substantially improved tool life (from 50 to 300 holes)(when drilling graphite/epoxy.)

A comprehensive review of all available NDE techniques that could be applied to the inspection of cut, drilled and machined composites was made. The most effective technique that could reliably be applied in a low-cost production mode was tracer fluoroscopy. A prototype, automated inspection system was developed and evaluated under simulated production conditions to facilitate integration of the system with the manufacturing process. Projected time savings for the approach compared to that for manual techniques exceeded 80 percent.

FOREWORD

This Final Technical Report covers the work performed under Contract F33615-76-C-5280 for the contract period of 2 August 1976 through 2 August 1978. This contract with Grumman Aerospace Corporation, Bethpage, New York, was initiated under Manufacturing Methods Project No. 322-6, "Manufacturing Methods for Cutting, Machining, and Drilling of Composites". The work was administered under the technical direction of Mr. Paul Pirrung/AFML/LTN, Non-Metals/Composites Branch, Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The Composites Machining Handbook, Volume I, is a concise summary of program results and recommendations. A comprehensive discussion of the overall program is contained in Volume II, Tests and Results.

The program was directed by Mr. Warren Marx, Project Manager. Others assisting on the project were Mr. Sidney Trink, Principal Investigator, of Advanced Materials and Processes Development, Mr. Jack Jenkins and Mr. Leonard Ober of Manufacturing Technology, and Mr. Alfred Weyhreter of Quality Control.

The cooperation and assistance rendered by the following personnel are hereby acknowledged: Mr. John T. Connelly, Arvey Corporation; Mr. John B. Cheung and Mr. G. H. Hurlburt, Flow Research, Inc.; Mr. Roger Arel, Gerber Garment Technology, Inc.; Mr. Thomas J. Labus, ITT Research Institute; Mr. Edward More, Hamilton Standard Division of United Aircraft Corporation; Mr. Gerald K. Faaborg, McCartney Manufacturing Co.; Mr. Frank J. Penoza, Pen Associates, Inc.; Mr. Daniel Ford and Mr. William Hoyt, TFI Corp.; and Mr. Conrad M. Banas, United Technology Research Center.

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Section 1

INTRODUCTION

The purpose of this handbook is to provide starting recommendations for cutting, machining, and drilling of composites. These data will serve to formulate a baseline for efficient methodization and planning, but do not preclude the necessity for refinement testing based upon specific requirements.

The data presented herein represent a compilation of that generated by development testing and current industry experience. New approaches as well as recommended methods were evaluated by Grumman to establish comprehensive guidelines.

1.1 MATERIAL COMBINATIONS AND FORMS

Process evaluation was performed on a wide range of baseline materials and graphite/epoxy hybrid material combinations. The baseline materials used in the program include Avco 5505-III-F boron/epoxy, Hercules 3501-5/A-S graphite/epoxy, Kevlar 49-CS3481/CS800 preimpregnated cloth, and Hexcel F161-7781(E) fiberglass/epoxy. In addition, graphite/epoxy hybrids were used which included combinations with boron/epoxy, fiberglass/epoxy and Kevlar/epoxy. Evaluations were performed in the cured laminate condition and to a limited extent in the uncured condition. Rapid-access indexes for all material and process combinations are given in Figures 1-1 and 1-2.

1.2 USE OF THE HANDBOOK

Given a specific part description and an operation to be performed, operational, equipment and tooling requirements can be established as follows:

(1) Use the Table of Contents or Rapid-Access Indexes to locate the process to be used

(2) Consult machining recommendations and locate workpiece category most closely representing the specified part

(3) Select feed, speed and cutting tool design from the applicable table

(4) Find cutting tool design in Section 5 for the operational requirements

(5) Use Section 4 to determine equipment capability.

PROCESS / MATERIAL	3.1 SAW OPERATIONS			3.2	3.3	3.4 CONV. DRILL OPERATIONS				3.5 U/S DRILLING OPS			3.6
	STATIONARY RADIAL SAW	PORTABLE RADIAL SAW	BANDSAW	LASER CUTTING	WATER-JET CUTTING	DRILLING	REAMING	COUNTERSINKING	COUNTERBORING	DRILLING	COUNTERSINKING	COUNTERBORING	ROUTING
GRAPHITE/EPOXY	3-2	3-3	3-4		3-6	3-7 3-12	3-7 3-11	3-13	3-14				3-15
BORON/EPOXY		3-3	3-4		3-6	3-11 3-12	3-11	3-13	3-14	3-11	3-11	3-14	3-15
FIBERGLASS/EPOXY	3-2	3-3	3-4		3-6	3-7 3-12	3-11	3-13	3-14				3-15
KEVLAR/EPOXY	3-2	3-3	3-4	3-5	3-6	3-12		3-13	3-14				3-15
GRAPHITE/EPOXY + BORON/EPOXY	3-2	3-3	3-4		3-6	3-11 3-12	3-11	3-13	3-14	3-11	3-11	3-14	
GRAPHITE/EPOXY + FIBERGLASS/EPOXY		3-3	3-4		3-6	3-7 3-12	3-7	3-7	3-14				
GRAPHITE/EPOXY + KEVLAR/EPOXY		3-3	3-4		3-6				3-14				

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Figure 1-1 Rapid-Access Index for Cured Material and Process Combinations

PROCESS / MATERIAL	2.1 WATER JET CUTTING	2.2 LASER CUTTING	2.3 RECIPROCATING MECHANICAL CUTTER	2.4 STEEL RULE DIE BLANKING
GRAPHITE/EPOXY	2-1	2-2	2-3	2-4
BORON/EPOXY	2-1	2-2		2-4
FIBERGLASS/EPOXY	2-1	2-2	2-3	2-4
KEVLAR/EPOXY	2-1	2-2	2-3	2-4

2566-175W

Figure 1-2 Rapid-Access Index For Basic Advanced Composite Materials

Section 2

CUTTING UNCURED COMPOSITES

The most widely used method for cutting uncured composite materials has been manual cutting with a carbide disc cutter, scissors or power shear. However, alternate and/or advanced technology processes exist which are more amenable to rate production. Such processes include water-jet cutting, laser cutting, reciprocating mechanical cutting, and steel rule die blanking. Each of these processes poses different advantages or limitations (see Section 4.0) and must be considered in terms of the application requirements and constraints.

The following cutting recommendations should be considered as starting points which must be refined in terms of specific applications:

2.1 WATER-JET CUTTING

Water-jet cutting provides a fast, numerical control (N/C)-compatible, approach to composites cutting. A summary of water-jet cutting parameters for single-ply and multiple-ply laminates is shown in Figure 2-1. Cutting parameters shown are based upon best visual cuts.

2.2 LASER CUTTING

Laser cutting provides a programmable omni-directional cutting approach which requires accessibility from only one surface. Laser cutting parameters and feedrate capabilities for a 250-watt carbon dioxide laser are summarized in Figure 2-2.

2.3 RECIPROCATING MECHANICAL CUTTING

This technology is particularly applicable to broadgoods cutting, requires access from only one side and does not impose any heat damage to the edge of the composite. It may require a cover material for protection from the compacting foot which rides on the surface of the workpiece. Parameters are shown in Figure 2-3.

2.4 STEEL-RULE DIE BLANKING

Steel-rule die blanking is a fast method for trimming an entire part periphery. This process, although new to composites, is a relatively standard method for commercial cutting of metals and non-metals (see Figure 2-4).

MATERIAL	NUMBER OF PLIES	NOZZLE DIAMETER, inch	PRESSURE, ksi	FEED, ipm
GRAPHITE/EPOXY	1	0.003	50	3000
	3	0.003	55	2400
	30 (MAX)	0.010	55	60
BORON/EPOXY	1	0.014	60	600
	3	0.014	55	900
	24 (MAX)	0.014	55	480
KEVLAR/EPOXY	1	0.003	60	3000
	3	0.006	55	3000
	16 (MAX)	0.010	55	30
FIBERGLASS/EPOXY	1	0.006	60	3000
	3	0.010	55	600
	12 (MAX)	0.010	55	30

(1) STANDOFF DISTANCE CONSTANT AT 0.12 INCH.

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Figure 2-1 Water-Jet Cutting of Uncured Composites

MATERIAL	NUMBER OF PLIES	ASSIST GAS PRESSURE, psi	FEEDRATE, ipm
KEVLAR/EPOXY BROADGOODS	1 2 3 4 5 8	8 8 8 8 8 8	300 300 300 300 300 100
FIBERGLASS/EPOXY BROADGOODS	1 2 3 4	8 8 8 8	300 150 90 60
GRAPHITE/EPOXY TAPE	1 2 3	8 8 8	300 150 90
BORON/EPOXY TAPE	1 2 3 4	8 8 8 8	270 120 60 30
GRAPHITE/EPOXY BROADGOODS	1	5	300

(1) LASER PARAMETERS INCLUDED: 2.5-INCH FOCAL LENGTH LENS, NITROGEN ASSIST GAS, 0.060-INCH NOZZLE GAP, AND 0.03-INCH NOZZLE ORIFICE DIAMETER.

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Figure 2-2 Cutting of Uncured Composites With a 250-Watt CO_2 Laser

MATERIAL	NUMBER OF PLIES	CUTTING MODE	CUTTER WIDTH, in.	CUTTER SPEED, strokes/ min	FEED, ipm
GRAPHITE/EPOXY	1	CHOPPING OR SLICING	0.25	5000	900
	5	CHOPPING OR SLICING	0.25	5000	900
	8	SLICING	0.25	6000	900
	13	SLICING	0.25	5500	600
	21	SLICING	0.25	5500	600
FIBERGLASS/EPOXY	1	CHOPPING	0.25	5300	600
	4	CHOPPING	0.25	3100	600
KEVLAR/EPOXY	1	CHOPPING	0.25	3700	600
	6	CHOPPING	0.25	5000	600
BORON/EPOXY	N/A	YIELDS EXCESSIVE CUTTER DAMAGE			

2566-098W

Figure 2-3 Reciprocating Mechanical Cutting of Uncured Composites

MATERIAL	MAXIMUM NUMBER OF PLIES	CUT EDGE APPEARANCE
GRAPHITE/EPOXY	18	EXCELLENT
BORON/EPOXY	18	EXCELLENT
KEVLAR/EPOXY	12	GOOD-SOME FRAYED FIBERS
FIBERGLASS/EPOXY	27	EXCELLENT

NOTES: (1) ALL BLANKING WAS DONE WITH POLYETHYLENE COVER SHEETS.
(2) MATERIAL WAS CUT AGAINST A MILD STEEL PLATE.

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Figure 2-4 Steel-Rule Die Blanking of Uncured Composites

Section 3

MACHINING RECOMMENDATIONS FOR CURED COMPOSITES

This section addresses those processes related to cured composites that are required for edge contouring or fastener hole generation at either the detail part or assembly level. The data presented are generally related to pure machining parameters without consideration of specific application constraints or requirements. Effective use of the "Composite Machining Handbook" requires that, as a minimum, these data be tempered by equipment, cutting tool and quality characteristics (see Sections 4, 5 and 6).

The data presented within this section represent many sources which include both industry-wide inputs and data generated during developmental testing. As such, both conventional and advanced technology techniques are included to reflect the latest state-of-the-art. A criteria summary reflecting pertinent process considerations is shown in Figure 3-1 to aid in application selection.

3.1 SAWING

Radial sawing and bandsawing represent conventional approaches to composite cutting that utilize readily available, low-cost capital equipment.

3.1.1 Stationary Radial Sawing

Stationary radial sawing provides a fast and accurate approach to composite cutting, but is limited to straight-line cuts and parts which can be easily handled. As-cut quality is of high standard (see Figure 3-2).

3.1.2 Portable Radial Sawing

Portable radial sawing offers cutting features similar to those for the stationary approach except that, being portable, it offers a greater degree of freedom and can be utilized on the production floor. One of the drawbacks with portable sawing, however, is high tool wear (see Figure 3-3).

3.1.3 Bandsawing

Bandsawing lends itself to rough cutting; however, a post-process finishing operation is normally required. Contour trimming can be performed within minimum cutting radius constraints. Cutting tolerances are a function of operator skill (see Figure 3-4).

PROCESS	OPERATING PARAMETERS	COST FACTORS	LIMITATIONS & POTENTIAL PROBLEMS	ADVANTAGES
SAW RADIAL	• FEED (IPM) • SPEED (SFM) • CUTTER MAT'L • COOLANT	• CUTTING RATE • CUTTER WEAR RATE • CUTTER COST	• STRAIGHT CUTS ONLY • MANUAL OPERATION • SLOW CUTTING RATES • OUT-OF-PLANE CUTTING	• EQUIPMENT AVAILABLE • NO CAPITAL INVESTMENT • FINISHED CUT • PORTABLE
BAND SAW	• FEED (IPM) • SPEED (SFM) • BLADE MAT'L • BLADE GEOMETRY • COOLANT	• CUTTING RATE • BLADE WEAR RATE • BLADE COST	• ROUGH CUTTING ONLY • MANUAL OPERATION • MATERIAL BREAKOUT • STATIONARY PROCESS	• EQUIPMENT AVAILABLE • EASY TO OPERATE • CUT PATTERNS
DRILLING REAMING	• FEED (IPR) • SPEED (SFM) • TOOL MAT'L • COOLANT	• PENETRATION RATE • TOOL WEAR • TOOL COST • TOOL CHANGE TIME	• MATERIAL BREAKOUT • HOLE TOLERANCES • LOCAL DELAMINATION • MANUAL OPERATION	• STANDARD PROCESS • EQUIPMENT AND TOOL AVAILABLE • PORTABLE
COUNTERSINKING AND COUNTER BORING	• FEED (IPR) • SPEED SFM • TOOL MA'L • COOLANT	• PENETRATION RATE • TOOL WEAR RATE • TOOL COST • TOOL CHANGE TIME	• TOLERANCE CONTROL • HIGH WEAR • MANUAL OPERATION	• STANDARD PROCESS • EQUIPMENT AVAILABLE • PORTABLE
ROUTING, BEVELING AND TRIMMING	• FEED (IPR) • SPEED (SFM) • TOOL MAT'L • COOLANT	• CUTTING RATE • TOOL WEAR • TOOL COST	• HIGH CUTTING FORCES • DIRTY PROCESS • SLOW CUTTING RATES	• FINISHED CUT • CUTS PATTERN
WATER JET	• FEED (IPM) • PRESSURE (PSI) • NOZZLE DIA	• CUTTING RATE • NOZZLE LIFE	• REQUIRES ACCESS TO BOTH SIDES OF WORK PIECE • POOR PORTABILITY • HIGH CAPITAL COST • EXIT SIDE DELAMINATION	• OMNI DIRECTION CUTTING PROCESS • FINISHED CUT • LOW CUTTING FORCES • CLEAN PROCESS • ADAPTABLE TO AUTOMATION
LASER	• FEED (IPM) • POWER (WATTS) • OPTICS • GAS PRESSURE (PSI) • BACKUP MAT'L	• CUTTING RATE • OPERATING COSTS	• HEAT DAMAGE • HIGH CAPITAL COST • THICKNESS LIMITATIONS	• OMNI-DIRECTIONAL • ADAPTABLE TO AUTOMATION • REQUIRES ACCESS TO ONE SIDE OF PART ONLY

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Figure 3-1 Process Criteria Summary

MATERIAL	THICKNESS, in.	SPEED, sfm	FEED, ipm	TOOL TYPE	AVERAGE TOOL DIAMETRAL WEAR, in./in.^{2} X 10^{-5} (1)	COOLANT APPLICATION
GRAPHITE/EPOXY	TO 0.50	7000	40-90	5-1	0.5	MIST
FIBERGLASS/EPOXY	0.12 TO 0.25	7000	40-60	5-1	0.5	MIST
BORON/EPOXY + GRAPHITE/EPOXY	0.25 TO 0.50	7000	15-40	5-1	1.5	MIST
KEVLAR/EPOXY	TO 0.12	7000	65	5-3	N/A	MIST
(1) AFTER HIGH POINTS ARE WORN.						

2566-100W

Figure 3-2 Stationary Radial Sawing

MATERIAL	THICKNESS, in.	SPEED, sfm	FEED ipm	TOOL TYPE	DIAMETRAL WEAR, in./in.^{2} (X 10^{-5})	COOLANT APPLICATION
GRAPHITE/EPOXY	TO 0.06 0.06 TO 0.12 0.12 TO 0.25	7500 7500 7500	100-130 80-100 45-80	5-1	6	MIST
BORON/EPOXY	TO 0.12	7500	50-90	5-1	70	MIST
FIBERGLASS/ EPOXY	TO 0.12	7500	80-100	5-1	2	MIST
KEVLAR/EPOXY	TO 0.12	7500	50	5-2	N/A	MIST
GRAPHITE/EPOXY + BORON/EPOXY	TO 0.09 0.09 TO 0.35	7500	80-100 40-80	5-1	20	MIST
GRAPHITE/EPOXY + FIBERGLASS/ EPOXY	TO 0.06 0.06 TO 0.25	7500 7500	100-160 60-100	5-1	2.5	MIST
GRAPHITE/EPOXY + KEVLAR/EPOXY	TO 0.06 0.06 TO 0.25	7500 7500	80-100 30-80	5-3	N/P	MIST

2566-101W

Figure 3-3 Portable Radial Sawing

MATERIAL	THICKNESS, in.	SPEED, sfm	FEED, ipm	TOOL TYPE	WEAR RATE, in./in.^{2} (X 10^{-5}) (1)	COOLANT APPLICA-TION
GRAPHITE/EPOXY	TO 0.06 0.06 TO 0.25	2000-4000 2000-4000	40-100 20-40	5-4	7	NR
FIBERGLASS/EPOXY	TO 0.12	2000-4000	17-80	5-4	7	NR
BORON/EPOXY	TO 0.12	4000	25-85	5-5	20	MIST
KEVLAR/EPOXY	TO 0.12	5000	75	5-6	N/A	NR
GRAPHITE/EPOXY + BORON/EPOXY	TO 0.091 0.09 TO 0.50	4000 4000	35-120 20-35	5-5 OR 5-4	20 6	MIST NR
GRAPHITE/EPOXY + FIBERGLASS/EPOXY	TO 0.06 0.06 TO 0.25	2000-4000 2000-4000	50-130 20-50	5-4	7	NR
GRAPHITE/EPOXY + KEVLAR/EPOXY	TO 0.06 0.06 TO .25	4000 4000	20-30 10-20	5-4 OR 5-6	6 N/A	NR

(1) BLADE LENGTH OF 9.5 FEET.

2566-102W

Figure 3-4 Bandsawing

3.2 LASER CUTTING

Laser cutting is limited to Kevlar/epoxy because of charring effects encountered with both graphite/epoxy and boron/epoxy (see Figure 3-5).

3.3 WATER-JET CUTTING

Water-jet cutting systems can penetrate reinforced epoxy systems of which graphite/epoxy and Kevlar/epoxy can be most readily severed. The balance of the materials can also be cut as shown in Figure 3-6, but at extremely slow feedrates. For each of these materials, the tendency to delaminate occurs as discussed in Section 7.0.

3.4 DRILLING, COUNTERSINKING AND COUNTERBORING

Conventional operations are normally applied to those materials not containing boron/epoxy because of tool life considerations. Summary drilling data charts are given in Figures 3-7 and 3-11 for both high-speed steel and carbide tools. In general, due to poor tool life and hole quality, high-speed steel cutting tools are not recommended for more than a few holes in composite materials. Two exceptions are the Jancy counterbore for drilling Kevlar/epoxy and the Weldon countersink for countersinking Kevlar/epoxy. Parameter selection within the data chart is based upon workpiece and operational requirements. Cutting speeds are obtained directly from the chart while feed and tool life are obtained in conjunction with Figures 3-8 and 3-9, respectively. If manual operations are involved, operator effort requirements can be obtained from Figure 3-10. Summary of countersinking and counterboring data charts are given in Figures 3-13 and 3-14.

3.5 DIAMOND DRILLING, COUNTERSINKING, COUNTERBORING AND REAMING

Diamond cutting tools are utilized in a metal matrix form for cutting, machining, and drilling. Application is usually to boron/epoxy laminates or hybrids containing boron/epoxy. Since diamond cutting tools are sensitive to heat generation, the use of coolant is recommended in most applications to extend tool life. These cutting tools can be utilized in either conventional or rotary ultrasonic drilling equipment. Specific tool selection criteria and designs are presented in Section 5. Summary drilling charts for metal matrix diamond tool is given in Figures 3-11 and 3-12. Information contained within this chart highlights hole size limitations, diamond grit size and concentration, feed, speed and projected tool life. Summary countersinking and counterboring data charts are shown in Figures 3-13 and 3-14.

THICKNESS, in.	ASSIST GAS	ASSIST GAS PRESSURE, psi	NOZZLE DIAMETER, in.	FEEDRATE, ipm
0.035	N_2	8	0.03	150
0.105	N_2	8	0.03	20

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Figure 3-5 Laser Cutting of Kevlar/Epoxy Laminates

MATERIAL	THICKNESS, in.	WATER-JET CUTTING PARAMETER		
		PRESSURE, ksi	NOZZLE DIA, in.	FEEDRATE, ipm
GRAPHITE/EPOXY	1/16 1/8 1/4	55 60 60	0.008 0.010 0.014	60 30 7
BORON/EPOXY	1/16 1/8	60 60	0.012 0.010	120 120
KEVLAR/EPOXY	1/16 1/8	55 55	0.006 0.010	120 30
FIBERGLASS/EPOXY	1/8	60	0.010	6
HYBRID BORON-GRAPHITE/ EPOXY	1/16 1/8 1/4	60 60 60	0.012 0.012 0.014	14 12 9
HYBRID GRAPHITE-KEVLAR/ EPOXY	1/16 1/4	60 60	0.010 0.014	15 5
HYBRID GRAPHITE-FIBERGLASS/ EPOXY	1/16 1/4	55 55	0.012 0.012	9 9

2566-104W

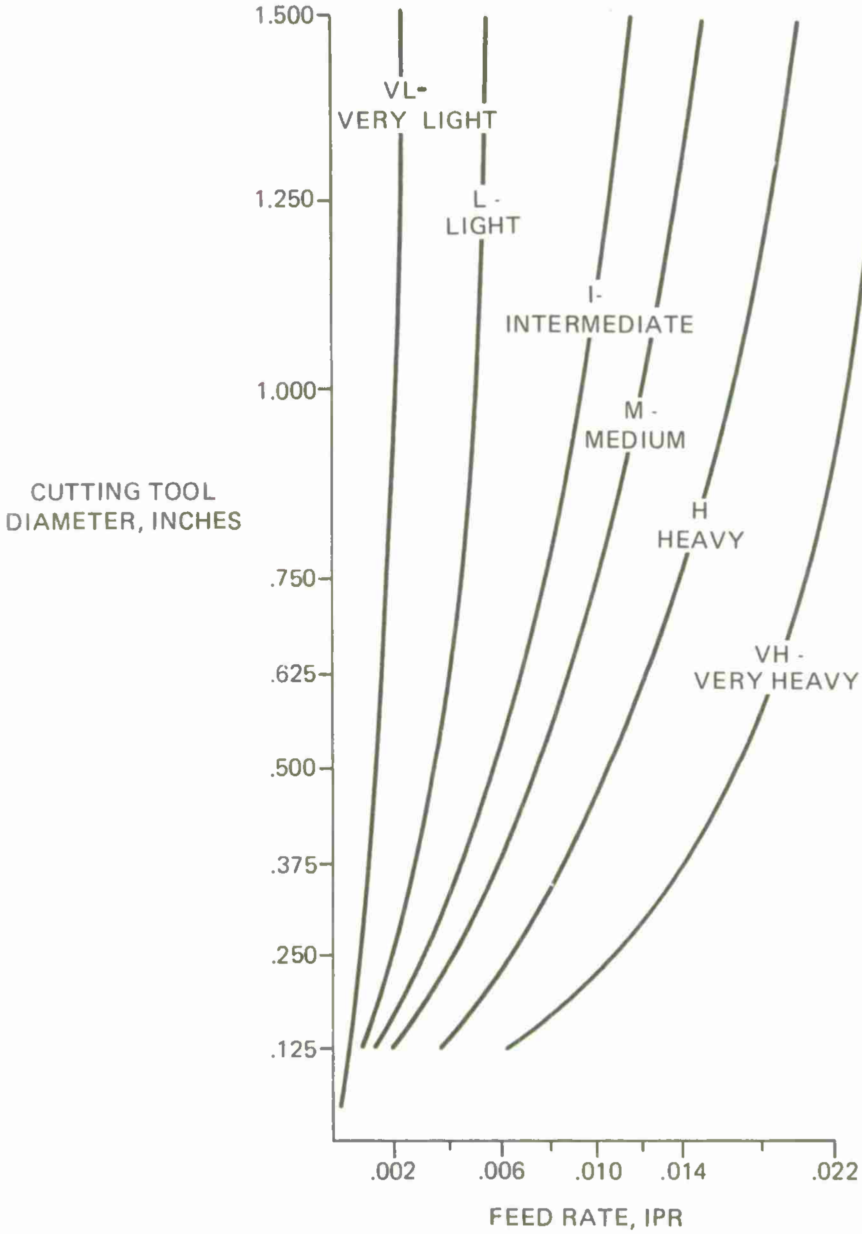
Figure 3-6 Water-Jet Cutting Parameters for Cured Composite Laminates

MATERIAL	PARAMETERS	HSS (M2, M77, M10, M33, M42)								CARBIOE (C2 or C6)							
		CORE DRILL (OFFHANO)	POWER FEED	OFF HAND DRILL	ORILL C'SINKING (MACH)	C'SINKING (OFFHANO)	C'BORING (OFFHAND)	REAMING (OFFHANO)	REAMING (MACH.)	CORE ORILL (OFFHANO)	POWER FEED	OFF HAND DRILL	DRILL C'SINKING (MACH.)	C'SINKING (OFFHAND)	C'BORING (OFFHAND)	REAMING (OFFHANO)	REAMING (MACH.)
	FEEO SPEEO (SFM) WEAR	LH 100/125 H	I 175/225 H	MH 200/250 H	VL 75 H	HH 50/100 LA	HH 200 H	LH 100/120 H	L 100/120 H	LH 200/250 LA	VL 900/1050 L	LH 300/500 LA	VL 900/1050 L	HH 250/275 LA	HH 500 LA	LH 200/250 L	L 400/500 L
60% FG/EP +40% GR/EP	FEEO SPEEO (SFM) WEAR	LH 100/125 H	VL/L 75/100 H	MM 125/150 H	VL/L 40/50 H	MH 50 H	MH 100 H	LH 60/75 H	L 60/75 H	LH 125/150 LA	VL/L 300/400 L	LH 250/300 L	VL/L 400/500 L	HH 225/275 LA	HH 450/550 LA	LH 125/150 LA	L 200/250 L
FIBERGLASS/ EPOXY	FEEO SPEEO (SFM) WEAR	LH 60/75 H	VL/L 80/100 H	MH 125/150 H	VL/L 40/50 H	MH 50 H	MH 100 H	LH 60/75 H	L 60/75 H	LH 125/150 L	VL/L 300/400 L	LH 250/300 L	VL/L 225/275 L	LH 225/275 L	MH 450/550 L	LH 125/150 LA	L 150/200 L
GR/EP+AL LAM (AL >030)	FEEO SPEEO (SFM) WEAR	MH 120 H	M 200 H	MH 200 H	M 150 H			MH 100/120 H	M 100/120 H	MH 200 A	M 250 LA	MH 300 A	M 150 LA			MH 200 A	M 200 LA
GR/EP+AL ALLOY (AL ≤030)	FEEO SPEEO (SFM) WEAR	LH 100/125 H	I 175/225 H	LH 200/250 H	L 200/250 H			LH 100/120 H	L 100/120 H	LH 200/250 LA	L 250/300 L	LH 300/500 L	LH 300/500 L			LH 200/240 LA	L 200/240 LA
GR/EP+FG LAM (¼+010/.014)	FEEO SPEEO (SFM) WEAR	LH 100/125 H	L 150/200 H	LH 200/250 H	L 75 H	HH 50/100 H	MH 125/150 H	LH 100/120 H	L 100/120 H	LH 200/250 LA	L 300/400 L	LH 300/500 LA	VL 400/500 L	HH 225/275 LA	HH 400/500 LA	LH 200/240 L	L 200/240 L
GR/EP+Ti LAM (Ti ≤ .030)	FEEO SPEEO (SFM) WEAR	MH 50/60 H	I 60/75 H	MH 100/120 H	I 50 H			MH 50/60 H	I 50/60 H	MH 125/150 A	I 125/150 LA	MH 150/200 A	I 100/120 LA			MH 125/150 A	I 125/150 A
GR/EP+Ti LAM (Ti >.030)	FEEO SPEEO (SFM) WEAR	HH 15/20 H	I 20/30 H	HH 20/30 H	I 10/15 H			HH 15/20 H	I 15/20 H	HH 60/80 A	I 70/100 A	HH 70/100 HA	I 80/85 A			HH 60/80 HA	I 75 LA

NOTE: COOLANT REQUIREO ONLY WHEN ORILLING COMPOSITES INTERWEAVEO WITH/OR BONOEO TO TITANIUM

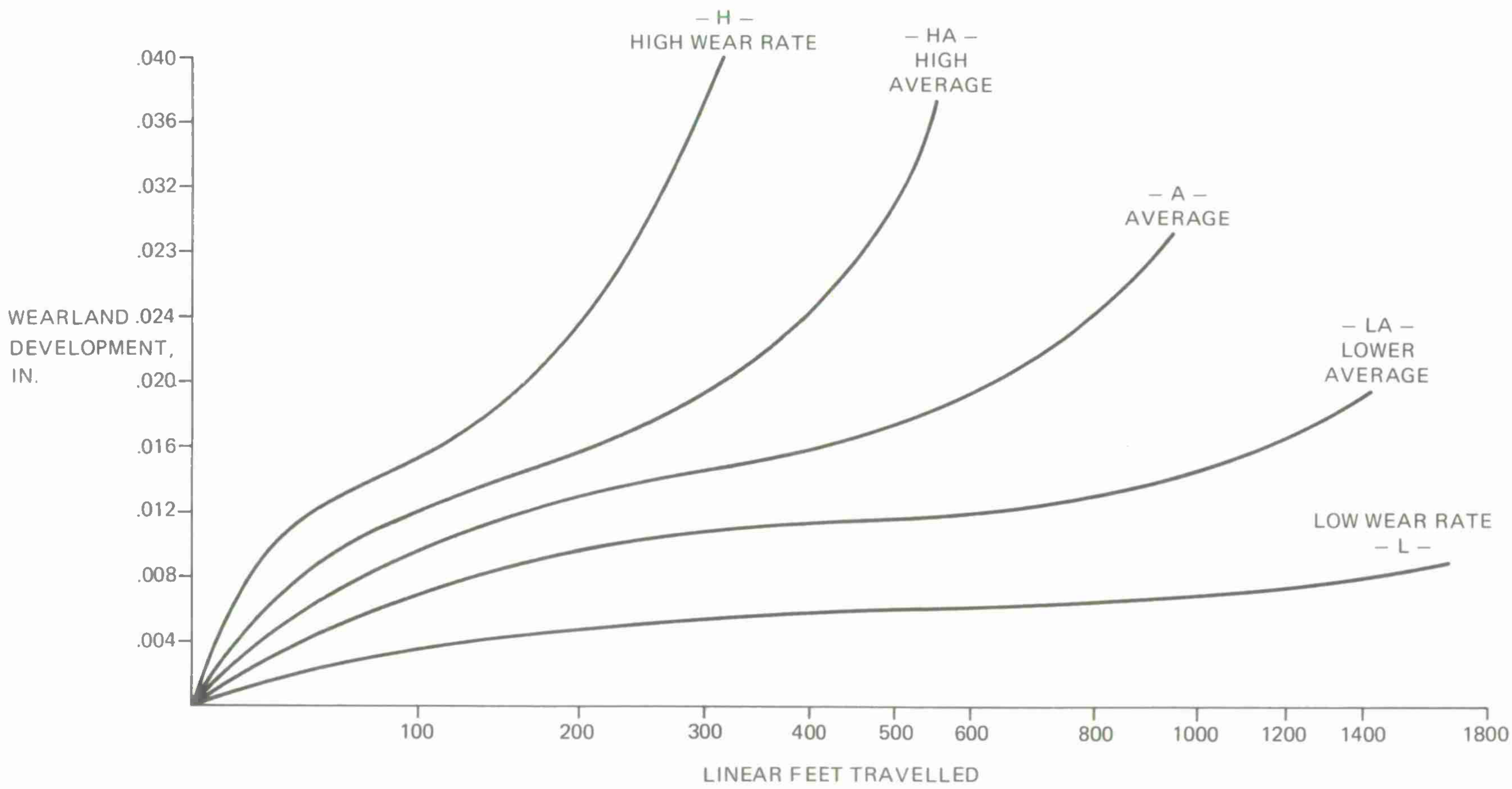
2566-105W

Figure 3-7 Summary Matrix of Compiled Drilling Data



2566-199W

Figure 3-8 Effect of Tool Diameter on Feedrate for HSS and Carbide Cutting Tools



2566-106W

Figure 3-9 Effect of Linear Feet Travelled on Wear Land Development

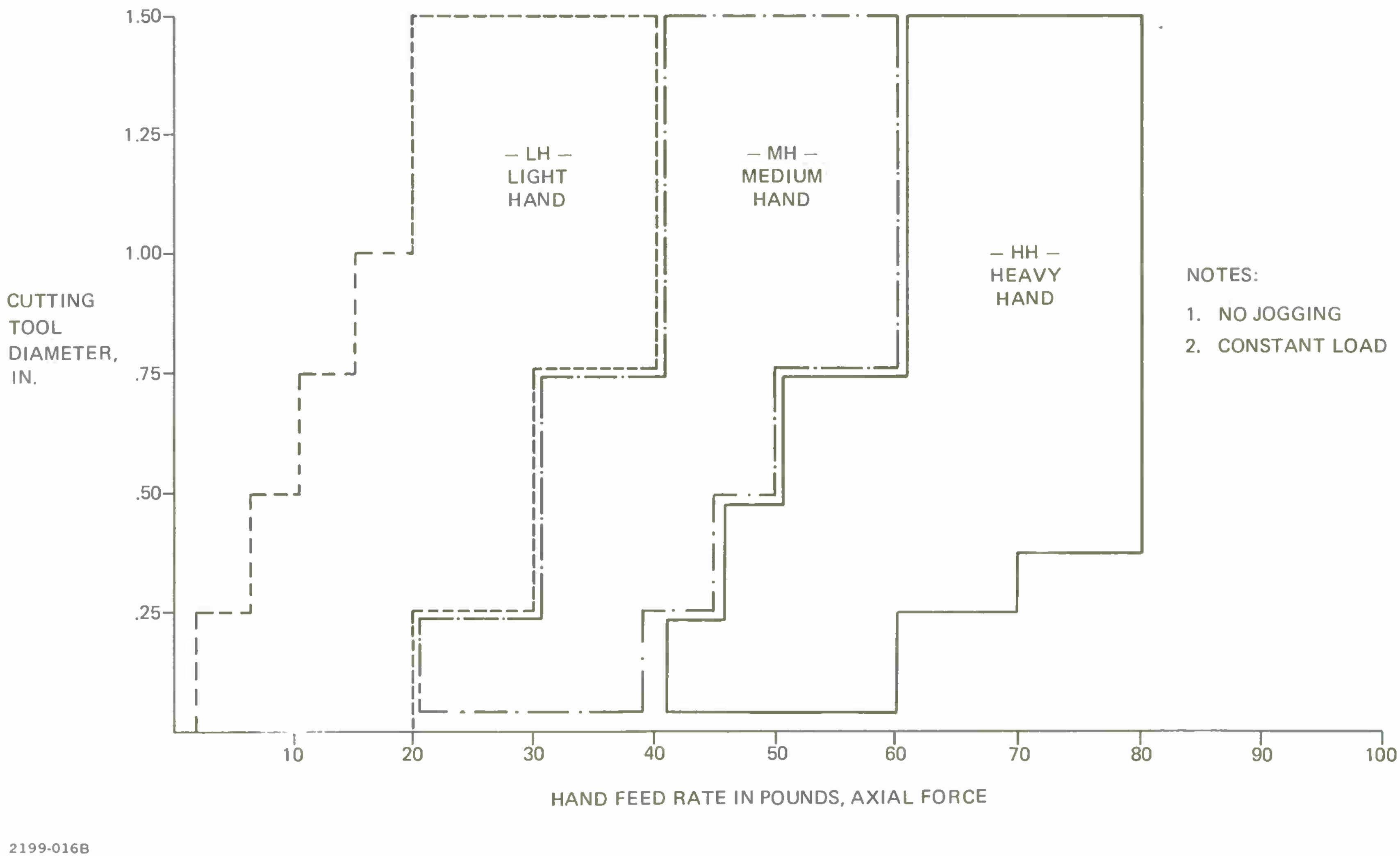


Figure 3-10 Diameter-Hand Feedrate Selection Chart

MATL	OPERATING PARAMETER	U/S CORE DRILLING 1, 2, 4	U/S DRILL C'SINKING 1,2,3,4,6	U/S C'SINKING 1,2,3	PWR FEED CORE DRILLING	HONING 7	OFF-HAND C'SINKING 3
GRAPHITE/EPOXY	SIZE (IN.)				.190 – .50	.190 – .50	.190 – .50
	GRIT				60 – 80	220 AVG	60 – 100
	CONCEN.				100	100	100
	FEED				2"-4"/MIN	LH	LH
	SPEED (RPM)				4500 – 3500	500 – 400	500 – 450
	LIFE (NO. HOLES)				300 MIN	250 – 400	300 MIN
30, 40 & 50% B-G/E	SIZE (IN.)	.190 – .500	.190 – .500	TO .500	.190 – .50	.190 – .500	.190 – .500
	GRIT	60 – 80	60 – 80	60 – 80	60 – 80	220 AVG	60 – 100
	CONCEN.	100	100	100	100	100	100
	FEED	1-1 1/4" MIN/AIR	1-1 1/4" MIN/AIR	1-1 1/4" MIN/AIR	1"/MIN	LH	LH
	SPEED (RPM)	4000 – 2250	4000 – 2250	4000 – 2250	4500 – 3500	500 – 400	500 – 400
	LIFE (NO HOLES)	200 – 400	75 – 100	75 – 150	100 – 200	75 – 150	30 – 60 [5]
BORON/EPOXY	SIZE (IN.)	.190 – .500	.190 – .500	TO .37	.190 – .50	.190 – .500	.190 – .500
	GRIT	80 – 100	60-80DR / 80-100 CSK	60 – 80	60 – 80	220 AVG.	60 – 100
	CONCEN.	100	100	100	100	100	100
	FEED	1-1 1/4" MIN/AIR	1-1 1/4" MIN/AIR	1-1 /4" MIN/AIR	1"/MIN	LH	LH
	SPEED (RPM)	4000 – 2250	4000 – 2250	4000 – 2250	5000 – 3000	500 – 400	500 – 400
	LIFE (NO HOLES)	150 – 300	50 – 100	50 – 100	75 – 150	50 – 100	20 – 40 [5]

NOTES:
1. U/S FREQ–20 kHz
2. WATER COOLANT
3. PLATED COUNTERSINK
4. SINTERED CONSTRUCTION
5. FINISHING OPERATION
6. LIFE DEPENDS ON COUNTERSINK
7. FREON TB-1 COOLANT

2566-107W

Figure 3-11 Summary of Metal-Matrix Diamond-Tool Operating Parameters

MATERIAL	THICKNESS, inch	SPEED, rpm	FEED, ipr	TOOL TYPE 1, 2, 7	EQUIPMENT TYPES 8	COOLANT APPLICATION
GRAPHITE/EPOXY	UP TO 0.50	21,000	0.001	5-11	CONVENTIONAL	NONE
GRAPHITE/EPOXY PLUS FIBERGLASS/EPOXY	UP TO 0.50	4,000	0.001	5-18 6	CONVENTIONAL	WATER
	UP TO 0.50	6,000	0.001	5-10	CONVENTIONAL	NONE
GRAPHITE/EPOXY PLUS BORON/EPOXY	UP TO 1.00	4,000 - 2,250	1-1¼ IN/MIN IN AIR	5-16 OR 5-17 3, 5	ULTRASONIC	WATER
	UP TO 0.40	4,000 - 3,000	.0005	5-17 4, 5	ULTRASONIC	WATER
BORON/EPOXY	UP TO 1.0	4,000 - 2,250	1-1¼ IN/MIN IN AIR	5-16 OR 5-17 3, 5	ULTRASONIC	WATER
	UP TO 0.40	4,000 - 3,000	.0005	5-17 4, 5	ULTRASONIC	WATER
KEVLAR/EPOXY	UP TO 0.250	6,000	0.001	5-19	CONVENTIONAL	NONE
FIBERGLASS/EPOXY	UP TO 0.50	5,500	0.001	5-11 OR 5-12	CONVENTIONAL	NONE

NOTES

1 LIFE, 0.006 INCH WEARLAND, EXCEPT AS NOTED
2 PARAMETERS FOR DRILL DIAMETERS 0.125 THROUGH 0.250 INCH, EXCEPT AS NOTED
3 DRILL DIAMETERS UP TO 0.50 INCH
4 DRILL DIAMETERS UP TO 0.375 INCH
5 LIFE FOR DIAMOND TOOLS SEE FIGURE 3-11
6 BACKUP HOLES WITH POLYURETHANE FOAM
7 BACKUP HOLES TO ELIMINATE BREAKOUT
8 SEE SECTION 4

2566-108W

Figure 3-12 Cutting Tool and Equipment Selection Chart for Assembly Drilling

MATERIAL	SPEED, rpm	FEED, ipr	TOOL TYPE [1]	EQUIPMENT TYPES [3]	COOLANT APPLICATION
GRAPHITE/EPOXY	2400 - 2700	HEAVY HAND	5-22	CONVENTIONAL	NONE
	21,000	0.001	5-23	CONVENTIONAL	NONE
GRAPHITE/EPOXY PLUS BORON/EPOXY	500 - 600	LIGHT HAND	5-24 & 5-25 [2]	CONVENTIONAL	WATER
	4,000	1-1¼ IN/MIN IN AIR	5-24 [2]	ULTRASONIC	
BORON/EPOXY	500	LIGHT HAND	5-24 & 5-25 [2]	CONVENTIONAL	WATER
	4,000	1-1¼ IN/MIN IN AIR	5-26 [2]	ULTRASONIC	WATER
KEVLAR/EPOXY	1350 - 1950	LIGHT HAND	5-27	CONVENTIONAL	NONE
FIBERGLASS/EPOXY	2400	.002	5-12	CONVENTIONAL	NONE

NOTES

1 LIFE – 0.006 INCH WEARLAND EXCEPT AS NOTED
2 LIFE FOR DIAMOND TOOLS SEE FIGURE 3-11
3 SEE SECTION 4

2566-109W

Figure 3-13 Summary of Countersinking (100°) Parameters for Fasteners Up to 0.250-Inch in Diameter

MATERIAL	SPEED, rpm	FEED, ipr	TOOL TYPE [1]	EQUIPMENT TYPES [4]	COOLANT APPLICATION
GRAPHITE/EPOXY	4800	0.005	5-28	CONVENTIONAL	NONE
GRAPHITE/EPOXY PLUS BORON/EPOXY	500	MEDIUM HAND	5-29 [2]	CONVENTIONAL	HANGSTERFERS HE-2 (20-1) MIX
	4000	1.0/M/MIN IN AIR	5-30	ULTRASONIC	WATER
GRAPHITE/EPOXY PLUS KEVLAR/EPOXY	3600	0.001	5-28	CONVENTIONAL	NONE
GRAPHITE/EPOXY PLUS FIBERGLASS/ EPOXY	3600	0.001	5-28	CONVENTIONAL	NONE
BORON/EPOXY	500	MEDIUM HAND	5-29 [2]	CONVENTIONAL	HANGSTERFERS HE-2 (20-1) MIX
	4000	1.0 IN/MIN IN AIR	5-30	ULTRASONIC	WATER
KEVLAR/EPOXY	6000	0.0006	5-28	CONVENTIONAL	NONE
FIBERGLASS/EPOXY	3600	0.001	5-28	CONVENTIONAL	NONE

NOTES

1 LIFE – 0.006 INCH WEARLAND EXCEPT AS NOTED

2 LIFE FOR DIAMOND PLATED TOOLS IS 0.0064 (AMOUNT OF EXPOSED DIAMOND)

3 LIFE FOR DIAMOND SINTERED TOOLS (60-80 GRIT) IS 6×10^{-5} PER 0.200 INCH DEPTH

4 SEE SECTION 4

2566-110W

Figure 3-14 Summary of Counterboring Parameters for Holes Up to 0.625-Inch in Diameter

3.6 ULTRASONIC DRILLING, COUNTERSINKING AND COUNTERBORING

Diamond cutting tools are utilized in a metal matrix form to drill, countersink and counterbore. Sintered diamond cutting areas are used in core drills and counterbores. Water is used as a coolant to cool the seals, gland and the tool, and also to wash away cutting debris. The combination of water pressure and ultrasonic excitation ejects the material core from the drill. In general, when drilling is done conventionally, high tool wear and breakage occur. The application of ultrasonic excitation to core drilling has been found to reduce these problems and give higher cutting rates. Specific tool selection criteria and designs are presented in Section 5. Summary drilling charts for metal-matrix diamond tools are given in Figures 3-11 and 3-12. The information contained in these charts highlights hole size limitations, diamond grit size and concentration, feed, speed and projected tool life. Summary countersinking and counterboring data charts are given in Figures 3-13 and 3-14.

3.7 ROUTING, TRIMMING AND BEVELING

Routing, trimming and beveling are presented together, since they are similar operations using, in most cases, the same cutting tools. Basically, routing involves plunging a cutter through a flat or contoured part with the aid of an offset template that describes the part perimeter. Trimming is used in finishing operations and gives a fractional depth of cut. Beveling is performed similarly but at a specified angular cut. Basic routing parameters are shown in Figure 3-15 while the effects of depth of cut upon manual feedrate are shown in Figures 3-16 and 3-17.

MATERIAL	THICKNESS, in.	SPEED, sfm	FEED, ipm	TOOL TYPE	TOOL DIAMETRAL WEAR, in./in.^{3} (X 10^{-4})	COOLANT APPLICATION
GRAPHITE/EPOXY	TO 0.12 0.12 TO 0.25	850	25-50 10-25	5-9	2.5 TO 4.0	MIST MIST
FIBERGLASS/EPOXY	TO 0.12	850	20-50	5-9	2.5	MIST
KEVLAR/EPOXY	TO 0.12	1300	60-80	5-8	N/A	NONE
BORON/EPOXY	TO 0.125	850	4-10 (1)	5-7	4.0 TO 10.0	MIST

2566-111W (1) 60 STROKES/MINUTE

Figure 3-15 Basic Routing Parameters

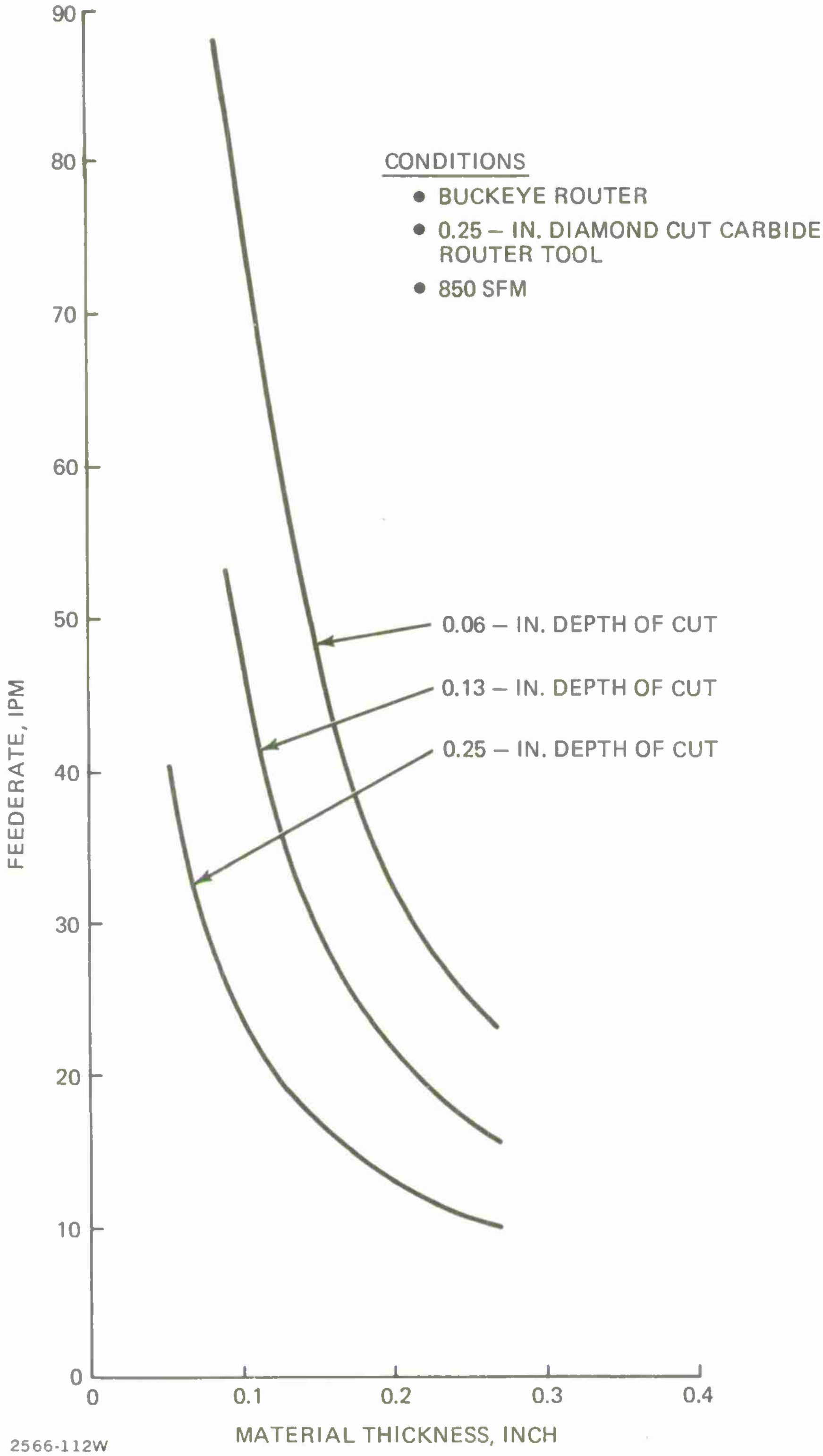
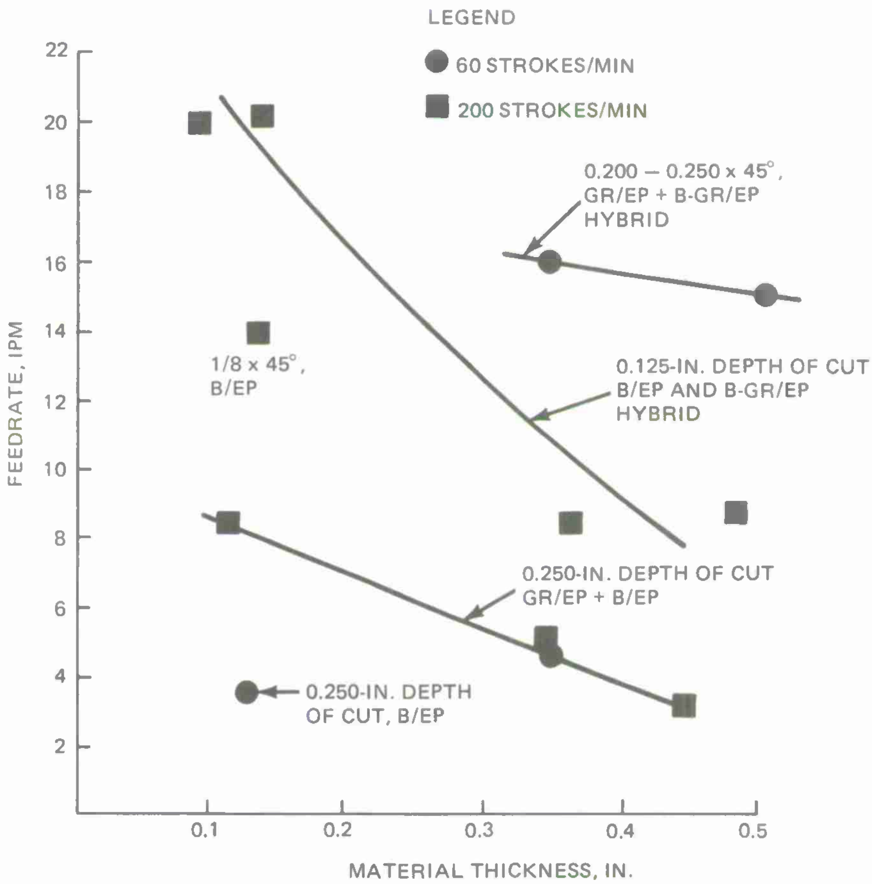


Figure 3-16 Effect of Cut Depth on Routing of Graphite/Epoxy



2566-113W

Figure 3-17 Effect of Cut Depth on Roto-Recipro Routing, Beveling and Trimming of B/Ep and B-Gr/Ep Hybirds

Section 4

EQUIPMENT

A variety of machine tools, both portable and stationary, were evaluated for their effectiveness in cutting, machining, and drilling advanced composites. Characteristics of those types which were found to be acceptable are discussed. It should be pointed out that, although a specific manufacturer's equipment was shown to be acceptable, it should not be construed as the best available. It was not the intent of this program to compare various manufacturer's equipment but rather to identify basic performance requirements.

4.1 STATIONARY AND PORTABLE RADIAL SAWS

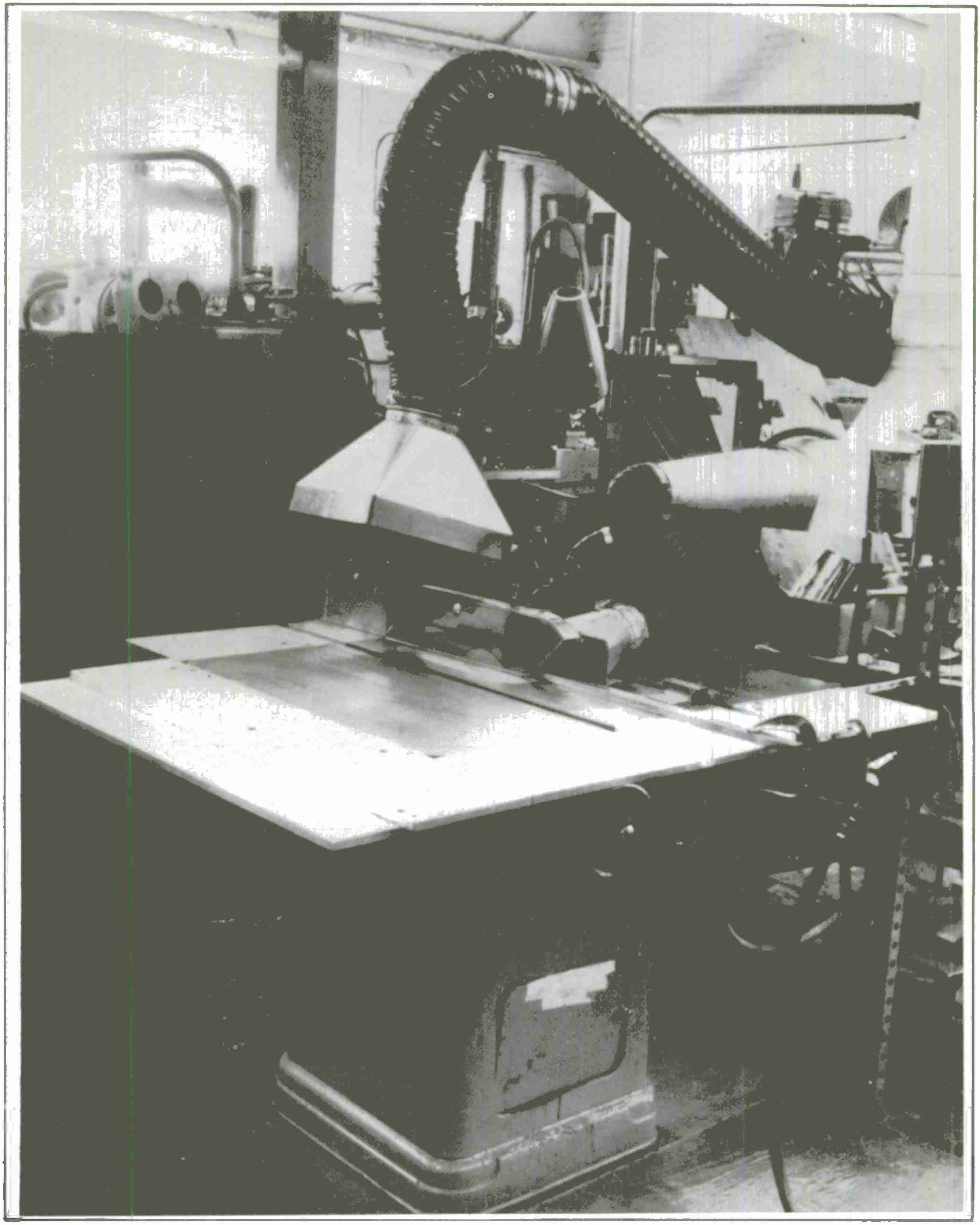
There are general-purpose machines (Figures 4-1 to 4-4) capable of cutting the complete range of cured composite materials. Appropriate saw blades must be used with each material to give the best finished edge. In all cases, finish cuts are made that require little or no post-processing. In general, radial saws are very versatile machines when making straight or cutoff cuts. Use of guides on the machine or accessory tooling gives accurate net cuts. Coolant (soluble oil/water mix) should be used whenever possible. Dry cutting creates more heat, thereby shortening the life of the saw blade and increasing cutting effort.

4.2 BANDSAWS

There are also general-purpose machines (Figures 4-5 and 4-6) capable of cutting the complete composite range of cured materials. Appropriate saw blades must be used with each material to give the best cut. In most cases, a bandsaw cut is a rough cut, requiring post-processing. Straight cuts or gentle curves can be made.

4.3 LASER CUTTER

This is usually a computer-directed system (Figures 4-7 and 4-8) capable of cutting the complete range of uncured and some cured advanced composite materials. Cutting energy is supplied by a 250-watt (minimum), continuous-wave carbon dioxide gas laser. The installation consists of four basic parts: the laser, a transport carriage to move the laser, a numerical control (N/C) unit to guide the carriage and a cutting table to support the workpiece. The benefits of laser-cutting composites are low cutting forces and omnidirectional cutting which facilitates trimming of many configurations. One to five plies of uncured laminates can be cut successfully, even though a bead of partially cured epoxy resin develops along the cut edge. Except for 1/16-inch-thick, cured graphite/epoxy and Kevlar/epoxy



2199-020B

Figure 4-1 Stationary Radial Saw

MANUFACTURER	ROCKWELL MANUFACTURING CO.
MODEL/SIZE	NO. 34-450, TABLE SIZE 27 METERS X 36 INCHES
BLADE SIZE	8-INCH DIAMETER
HORSEPOWER	1-1/2 HP
SPEED	3400 RPM
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING. WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATION	1.0 INCH
ACCESSORIES FOR COMPOSITE CUTTING	DUST EXHAUST AND COOLANT SPRAY

2199-022B

Figure 4-2 Stationary Radial Saw Specification

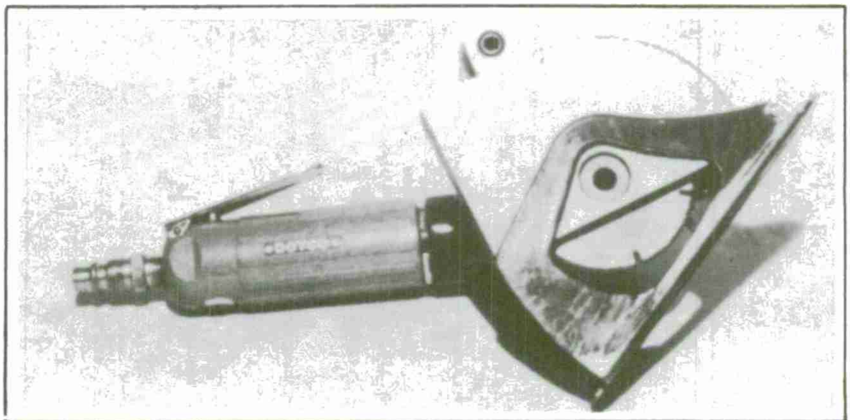


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Figure 4-3 Portable Radial Saw

MANUFACTURER	DOTCO INC.
MODEL	NO. 106-2749, (HAND-HELD)
BLADE SIZE	3-INCH DIAMETER
HORSEPOWER	0.8 HP
SPEED	11,000 RPM
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATION	0.5 INCH
ACCESSORIES FOR COMPOSITE CUTTING	DUST EXHAUST AND COOLANT SPRAY.

2199-023B

Figure 4-4 Portable Radial Saw Specification

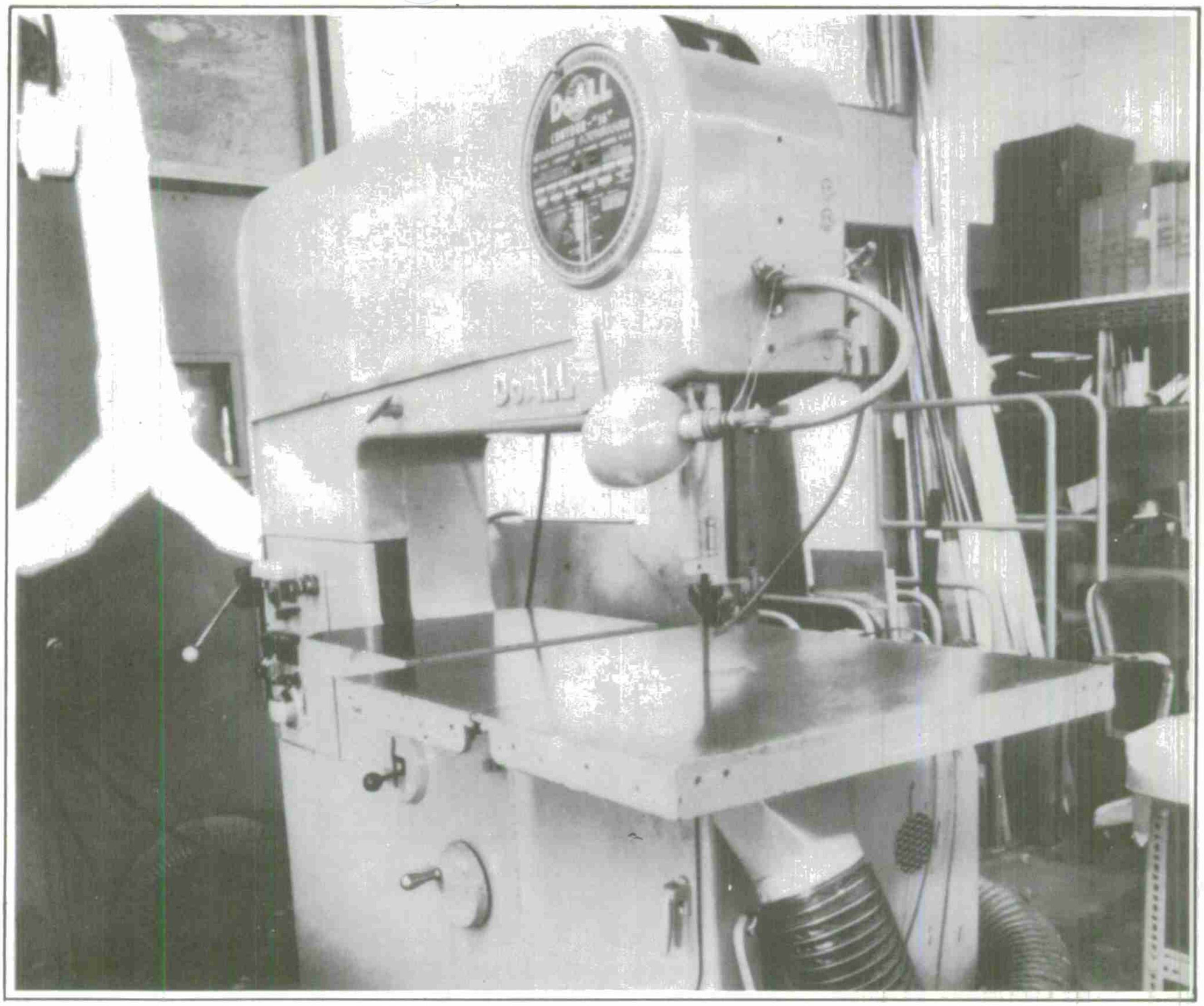

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Figure 4-5 DoAll Zephyr Friction Saw

MANUFACTURER	DOALL
MODEL	NO. 36-2A
BLADE SIZE	1/2 (OR 1/4) X 174 (OR 120) INCHES
SPEED	25-6000 SFM (VARIABLE)
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PRE-VENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE CUTTING	DUST EXHAUST

2199-025B

Figure 4-6 Stationary Bandsaw Specification

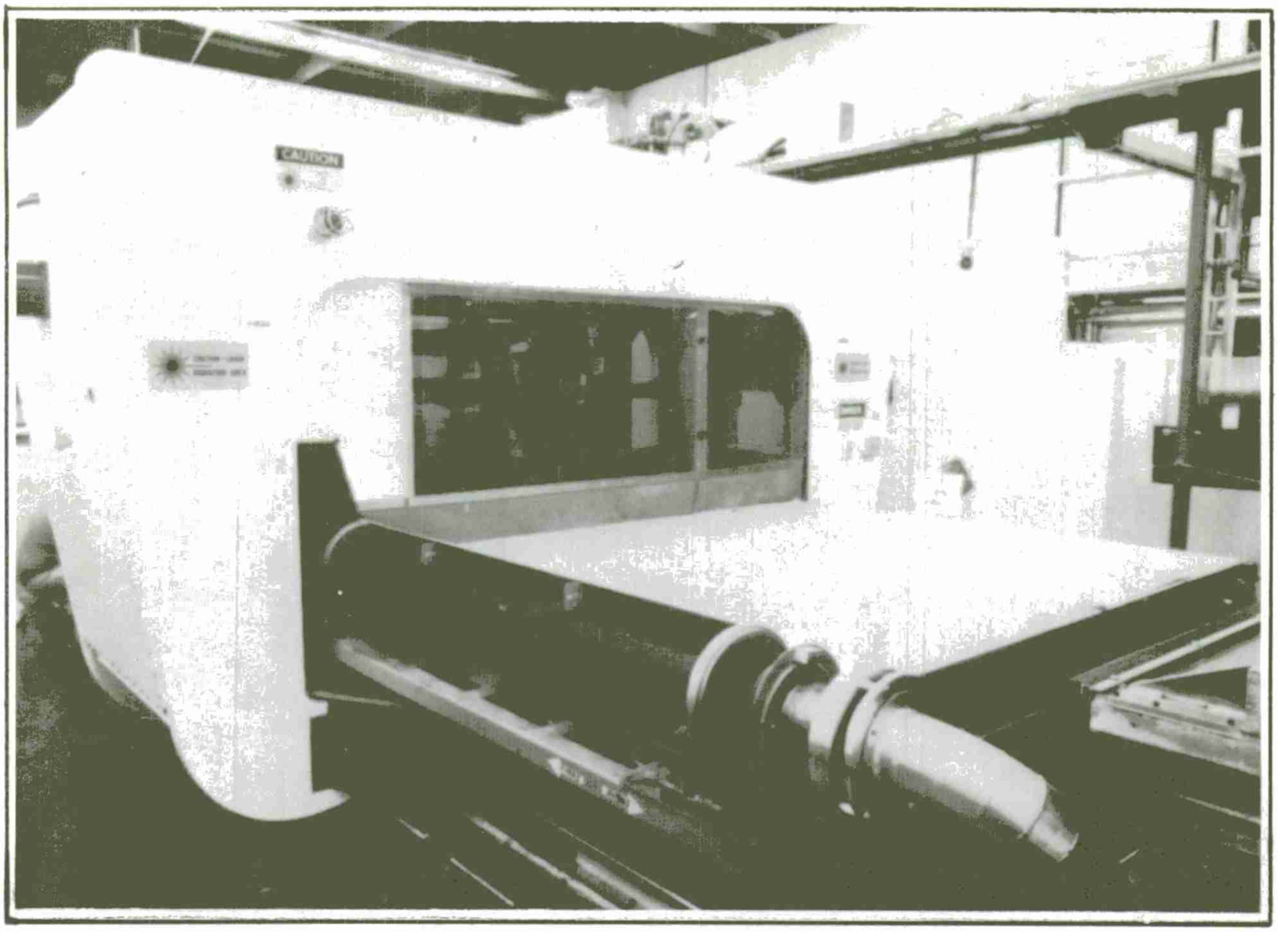

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Figure 4-7 250-Watt Laser Cutting System

TYPE	250-WATT, CONTINUOUS-WAVE, CARBON DIOXIDE GAS LASER, COMPUTER-DIRECTED
MANUFACTURER	COHERENT RADIATION LABORATORIES/GRUMMAN
MODEL	NO. 41
FEEDRATE (RANGE)	30 – 300 IPM
CUTTING AREA	UNLIMITED
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATION	DEPENDS ON MATERIAL TYPE (SEE TEXT).
ACCESSORIES FOR COMPOSITE CUTTING	NITROGEN ASSIST GAS

2566-115W

Figure 4-8 250-Watt Laser Cutting System Specification materials, none of the other composite materials can be penetrated with this 250-watt laser. The laser produces a heat-affected charred area on the cut edge of cured materials that may require postprocessing. Although higher powered lasers can cut thicker materials, the heat-affected zone is correspondingly greater.

4.4 WATER/FLUID-JET CUTTER

This new equipment can cut the complete range of both uncured and cured advanced composite materials. The equipment (Figures 4-9 and 4-10) can be easily adapted to a photoelectric trace system or computer-directed. The benefits of cutting composites by a fluid jet are low cutting forces, no heat damage, narrow cutting width requiring minimal energy input to the workpiece and omnidirectional cutting which facilitates trimming of many configurations. Cut quality improves with increasing nozzle pressure, increasing nozzle orifice diameter, decreasing traverse speed and decreasing material thickness and hardness. The softer materials cut with a better edge quality than the harder ones. Cutting is accomplished by a water or fluid jet stream 0.003 to 0.014 inch in diameter. It should be noted that a hand-held cutting head has been recently marketed.

4.5 RECIPROCATING MECHANICAL CUTTER

This is a very versatile, computer-directed machine capable of cutting the complete range of uncured composites only (Figures 4-11 and 4-12). The automated cutting system is built around a 12x6-foot, two-axis plotting table equipped with a stepper-motor-driven, dual carriage. Several controllable tools mounted on the carriage are designed to perform scribing, drafting, cutting or pickup operations. Tool and carriage motions are controlled by a prepunched binary tape reader and attached computer, or by manual console. The automated system provides position accuracy of ± 0.005 inch and a head displacement of 1200 ipm. Cutting of the composite material is accomplished by a reciprocating knife operating at 6000 strokes per minute in two modes -- chopping or slicing. The cutting knife penetrates through the material into closely packed plastic bristles that constitute the surface of the vacuum cutting table.

4.6 ULTRASONIC DRILLING EQUIPMENT

4.6.1 Portable Rotary Drilling Unit

This drilling system (Figure 4-13) was originally designed and developed for Air Force Contract No. F33615-71-C-1706 ("Ultrasonic Machining") completed in December 1972. It was subsequently implemented in production for drilling F-14 titanium alloy sheet engine ducts. The completely portable unit is capable of drilling and countersinking boron/epoxy and hybrids of boron/epoxy and graphite/epoxy. The Quackenbush drill provides positive

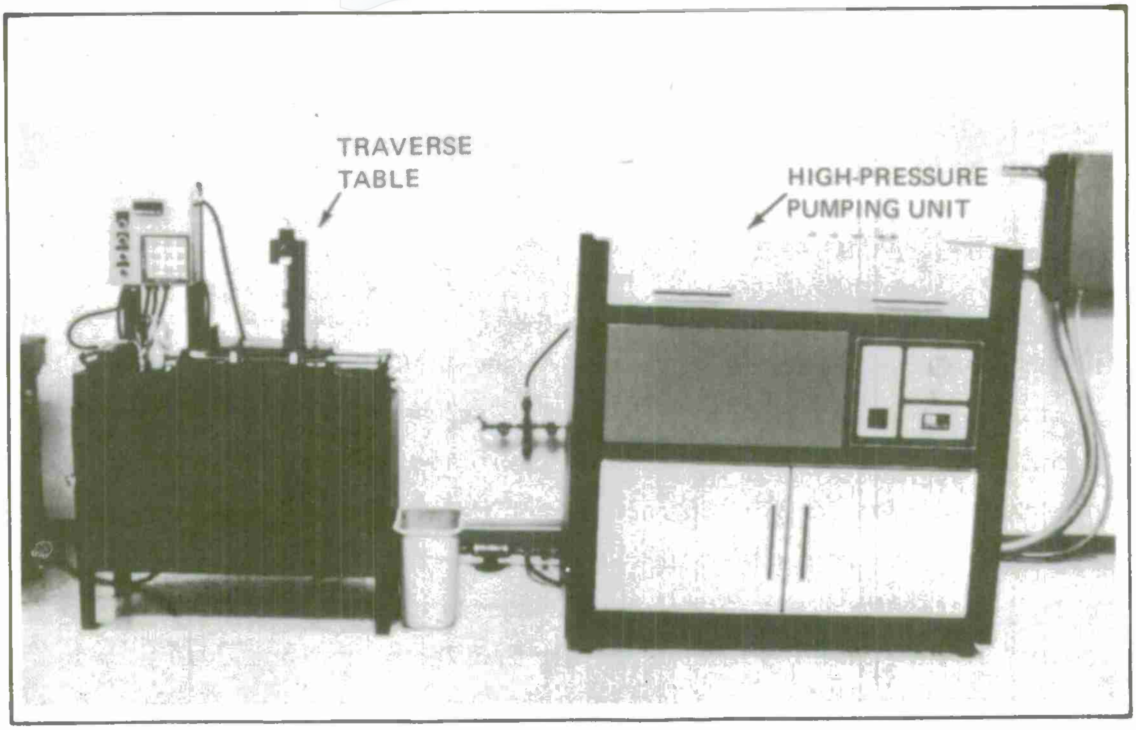

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Figure 4-9 Water-Jet Cutting System

TYPE	WATER-JET STATIONARY PHOTOELECTRIC TRACE, COMPUTER DIRECTED OR PORTABLE MANUALLY OPERATED.
MANUFACTURER	FLOW INDUSTRIES, McCARTNEY OR CAMSCO
MODEL	NO. 55/50
HORSEPOWER	50 HP AND 60,000 PSI
FEEDRATE (COMPOSITES)	1-3000 IPM
CUTTING AREA	VARIABLE
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT, NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATION	DEPENDS ON MATERIAL TYPE (SEE TEXT)
ACCESSORIES FOR COMPOSITE CUTTING	WATER AND PARTICLE DISPOSAL

2566-200W

Figure 4-10 Water-Jet Cutting System Specification

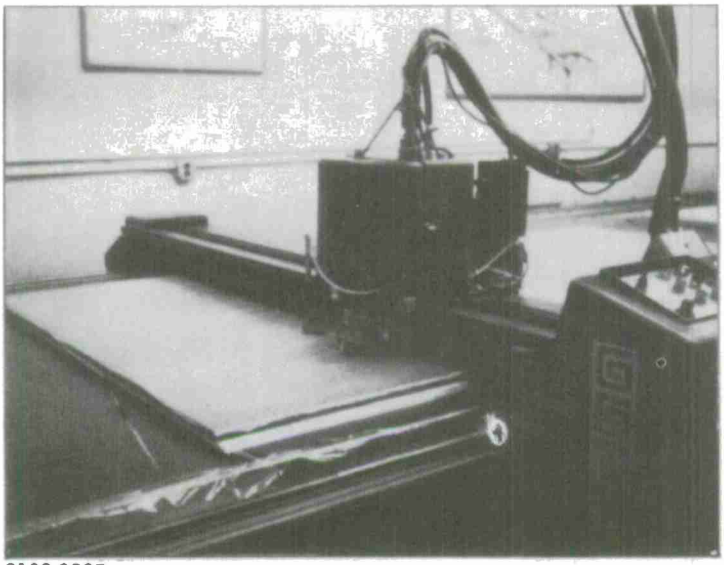

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Figure 4-11 Reciprocating Mechanical Cutting System

MANUFACTURER	GERBER GARMENT TECHNOLOGY, INC.
MODEL	SYSTEM 90 COMPUTER-DIRECTED
FEEDRATE (COMPOSITES)	300-600 IPM
CUTTING TABLE (STANDARD)	12 X 6 FEET
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT, NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL (UNCURED) THICKNESS LIMITATIONS	DEPENDS ON MATERIAL (SEE TEXT)
ACCESSORIES FOR COMPOSITE CUTTING.	NONE REQUIRED

2199-031B

Figure 4-12 Reciprocating Mechanical Cutter Specification

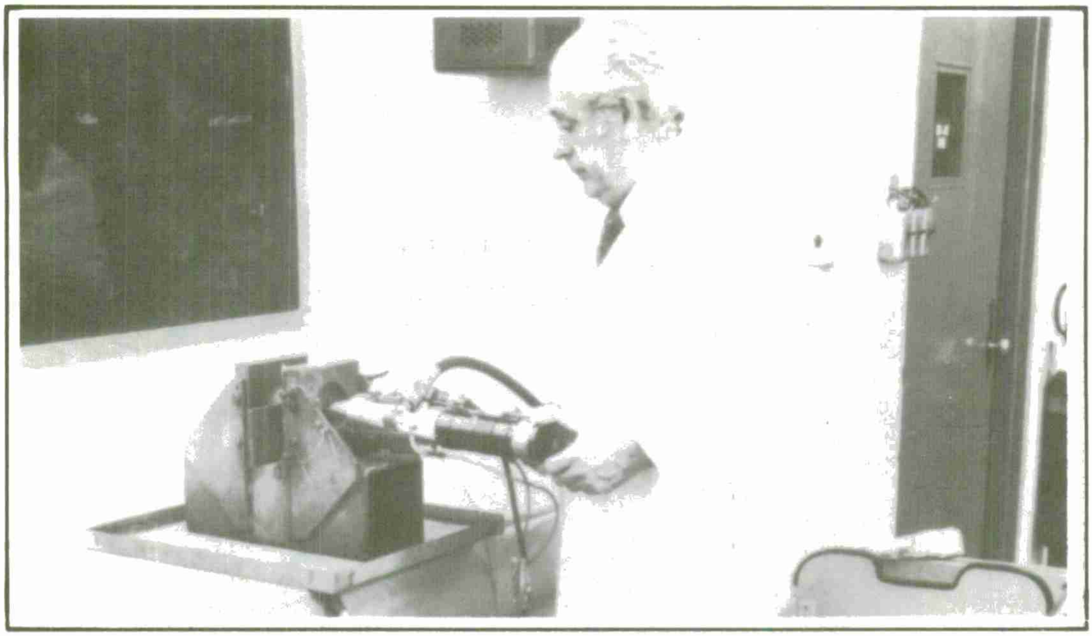

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Figure 4-13 Portable Rotary Ultrasonic Drilling Unit

TYPE	ROTARY ULTRASONIC DRILL
MANUFACTURER	DRESSER INDUSTRIES (OUACKENBUSH) – AIR-POWERED DRILL – BRANSON SONIC POWER CO. (ULTRASONIC POWER SUPPLY & ADAPTOR).
MODEL	15BOGDABV-S150 (OUACKENBUSH DRILL). UD-12 (POWER SUPPLY) 150 WATT, 20,000 Hz. UDP–(DRILL ADAPTOR) 20,000 Hz
HORSEPOWER	1.7 HP
WEIGHT	19 POUNDS
COOLANT	THROUGH FLUID DRILL ADAPTORS
FEED	POSITIVE RANGE (0.00025 TO 0.008 IPR)
SPEED	150 TO 3000 RPM
DRILL SIZE	UP TO 3/8 INCH DIAMETER
NOSEPIECE	DRILL BUSHING ADAPTED FOR HOLD-DOWN SCREWS
SPINDLE AND CHUCK CONCENTRICITY	0.001 INCH (MAXIMUM)
EOUIPMENT RELIABILITY	COMMERCIAL EOUIPMENT NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING; WITH APPROPRIATE PREVENTIVE MAINTENANCE, IT SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS.	0.50-INCH (STROKE LIMITATION)
ACCESSORIES FOR COMPOSITE DRILLING.	WATER AND PARTICLE DISPOSAL

2566-116W

Figure 4-14 Portable Rotary Ultrasonic Drill Specification spindle speed and feed control. An ultrasonic resonator, coupled directly to the drill spindle, receives ultrasonic power through two brushes from a 150-watt/20,000-Hz power supply. The ultrasonic resonance is transferred to the core drill through a combination adaptor/fluid drill holder. Drill speed can be varied by changing gears; feed can be held constant for all diameters up to 3/8 inch maximum diameter. The drill bushing has slots for hold-down screws which secure the bushing to the drill template. The drills are diamond-sintered core drills; their weight must be kept to a minimum. Countersinking can also be combined with ultrasonic drilling by the addition of a countersink depth control and use of a combination drill/countersink. The application of ultrasonic energy results in a 100 percent increase in the number of holes drilled in boron/epoxy. The equipment specification is given in Figure 4-14.

4.6.2 Stationary Drilling Machines

The Branson UMT-3 machine has an ultrasonic machining head (with both manual and automatic feed) mounted to a cast iron base with a compound work table. The UMT-3 drive system was modified for use with a 3/4-horsepower motor with a speed range of 0-10,000 rpm. Speed is changed by a variable autotransformer that is calibrated for rpm output with a strobe instrument (Strobatac Type 1531-AB). The ultrasonic power supply for the UMT-3 drilling machine gives a maximum output power of 250 watts to the drill spindle resonator at a frequency of 20 Khz (converted from 60 Hz electrical energy). The output from the power supply is wired directly to the resonator's piezoelectric transducer.

A UMT-5 machine (Figure 4-15) is also available which is similar to the UMT-3 unit but with increased power and rapid tool advance. The power supply provides 600 watts to the drill spindle resonator at a frequency of 20 kHz. This provides 0.0007 to 0.001 inch peak amplitude at the spindle end. The drill machine has an infinite feed range with speeds to 6000 rpm. The spindle is fitted with a specially designed micrometer-adjustable countersink depth control. The drill machine tools are water-cooled. Tools used are all-diamond types -- either sintered or plated.

Specifications for both types of machines are given in Figure 4-16.

4.7 PORTABLE DRILLING EQUIPMENT

4.7.1 Spacematic Drill

The Model 62 Spacematic drill (Figure 4-17) is an air-operated, hydraulically controlled portable tool that clamps to the work surface by means of an expanding collet which picks up the previous hole drilled or a template. It drills and countersinks in one operation to a depth accuracy of 0.002 inch. Close spindle concentricity combined with the use of

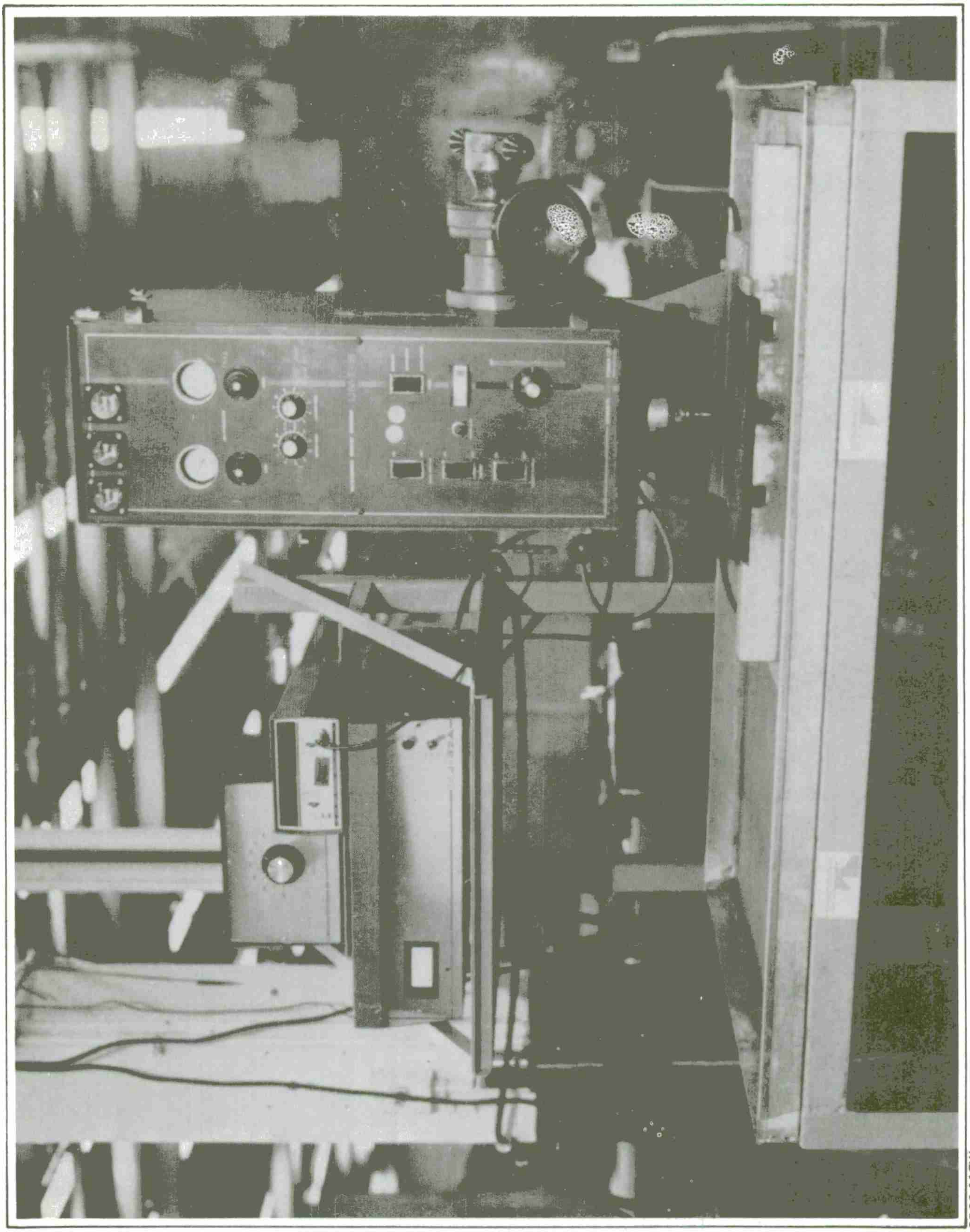


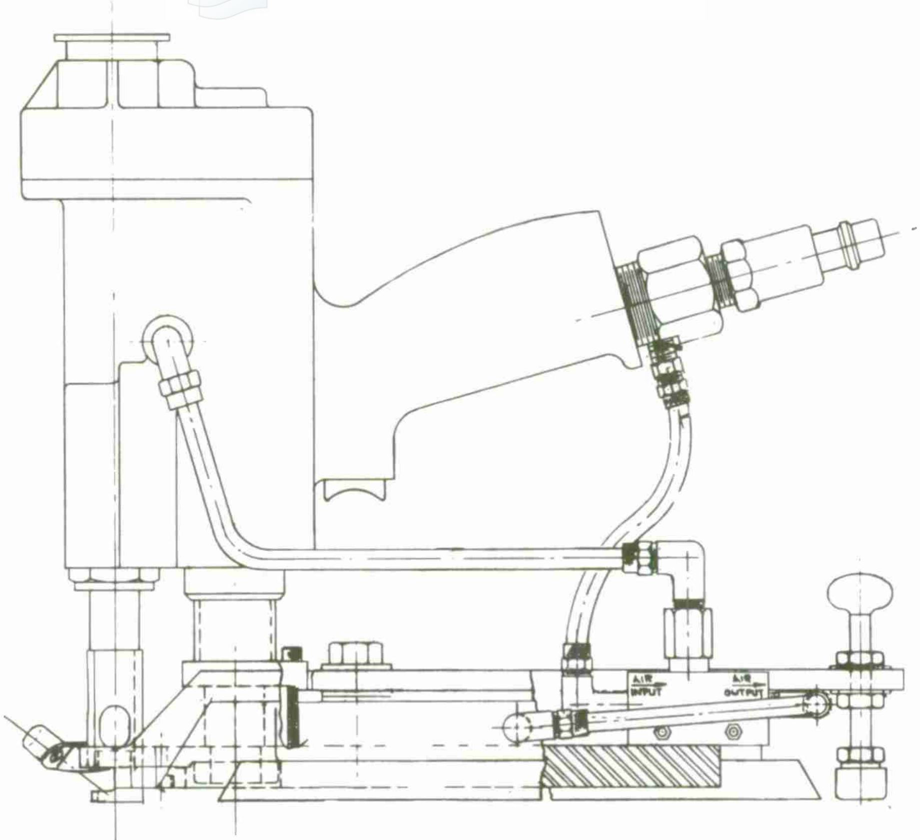
Figure 4-15 Branson UMT-5 Ultrasonic Drilling Machine

2566-117W

MANUFACTURER	BRANSON SONIC POWER CO., DANBURY, CONN.
MODEL	UMT-5 DRILL SPINDLE RESONATES AT 20 KHz, IS DRIVEN BY J32A POWER SUPPLY OF 600 WATTS
HORSEPOWER	1 HP
WEIGHT	45 LBS
COOLANT	THROUGH-SPINDLE (GRUMMAN DESIGN), SPINDLE INTERNALLY PORTED FOR DRILL COUNTERSINK (GAC DESIGN)
FEED	VARIABLE FEED, AIR-ASSISTED
SPEEDS	VARIABLE TO 10,000 RPM
DRILL SIZE	OPTIMUM DRILL WEIGHT FOR RESONATING IS 35 GRAMS-THIN WALL CORE DRILLS TO 4 INCHES HAVE BEEN MADE
NOSEPIECE	THREADED SPINDLE ADAPTED FOR CORE DRILLS
SPINDLE CONCENTRICITY	0.005 INCH (GRUMMAN-MODIFIED) 0.001 INCH WITH TEST FITTING
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE DRILLING AND WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	LIMITED ONLY BY DRILL CONFIGURATION
ACCESSORIES FOR COMPOSITE MACHINING	WATER AND PARTICLE DISPOSAL

2566-118W

Figure 4-16 Stationary Ultrasonic Drilling Equipment Specification



2566-119W

Figure 4-17 Modified Spacematic Drill for Composites

TYPE	AIR-OPERATED, HYDRAULICALLY CONTROLLED PORTABLE TOOL THAT CLAMPS TO WORK SURFACE.
MANUFACTURER	DEUTSCH FASTENER CORP. ARCADIA, CALIFORNIA
MODEL	62
HORSEPOWER	0.75 HP UNDER FULL LOAD
AIR CONSUMPTION	28 CFM AT 90 TO 100 PSI
WEIGHT	6 POUNDS (WITHOUT VACUUM ATTACHMENT)
COOLANT	OUTSIDE APPLICATION REQUIRED
FEED	PNEUMATIC WITH HYDRAULIC CONTROL; ADJUSTMENTS FROM 0.001 IPR TO 0.012 IPR.
SPEEDS	400, 1000, 1800, 2800, 6000 RPM
DRILL SIZE	3/16 DRILL, 3/8 COUNTERSINK
SPINDLE CONCENTRICITY	0.0005 TIR
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS	0.50 INCH
ACCESSORIES FOR COMPOSITE DRILLING	VACUUM ATTACHMENT FOR MOUNTING COOLANT SPRAY AND DUST REMOVAL

2566-120W

Figure 4-18 Spacematic Drill Specification

short, rigid drill/countersinks produces holes of high dimensional and surface quality. Grumman has designed and modified existing units by providing vacuum pads to permit power feeding without the use of a pull-up expanding collet. The collet mechanism can broach a hole in composites when activated. Equipment specifications are given in Figure 4-18.

4.7.2 Gardner-Denver Drill (MM-8 Series)

This portable air-feed drill (Figure 4-19) which is available with high-speed capability, is air-powered and has many features and components that allow adaptation to varied applications. The drill may be mounted by bracketing it to, or into, a jig plate. Attachment using drill bushings and hold-down screws is also possible. Varying feeds, six speed choices, rapid advance, dwell, and automatic control are some of the many features available. The equipment is nominally rated to 5/16 inch capacity. Quality, high-production holes can be obtained with this unit. Equipment specifications are given in Figure 4-20.

4.7.3 Portable Hone

The portable hone is a Grumman-designed fixture utilizing a Cleco Model 11DPV-15, variable-speed drill motor (Figure 4-21) as the power source. Hones are commercially purchased and are modified for attachment purposes. Locating the fixture is done by positioning a tapered cone, projecting from the bottom of the fixture, into the countersunk hole. Vertical alignment is provided by three adjustable feet. The fixture spindle is spring-loaded. Honing is accomplished by utilizing a slow oscillating hand feed while rotation takes place. A speed of 500 rpm has been found satisfactory for boron composities. The hone diameter is adjustable and finished hole sizes to +0.0005/-0.0000 inch can be attained. Holes should be left 0.0005 to 0.0010 inch under-sized prior to honing. Coolant is supplied from an outside source into the fixture base. Freon and water have been used for boron and graphite composites, respectively. This fixture works well where low curvatures are encountered. Equipment specifications are given in Figure 4-22.

4.7.4 Manual Drill Motors

Air-driven drill motors, such as the Cleco unit shown in Figure 4-23, are generally preferred over elective motors because of their lighter weight, ability to stall repeatedly without motor burnout, and elimination of hazardous electrical shocks. They provide a wide range of variable speeds and can apply up to 300 pounds of controlled force to the drill point. Equipment specifications are given in Figure 4-24.

4.8 STATIONARY DRILLING EQUIPMENT

The stationary Rockwell/Delta drill press shown in Figure 4-25 provides variable speeds by a pulley arrangement and manual feed by rack-and-pinion action. A 1-1/2-HP motor drives the spindle with a 1/2-inch-diameter capacity check. This type of drill press is a standard piece of equipment found in most shops. Equipment specifications are given in Figure 4-26.

4.9 ROUTING EQUIPMENT

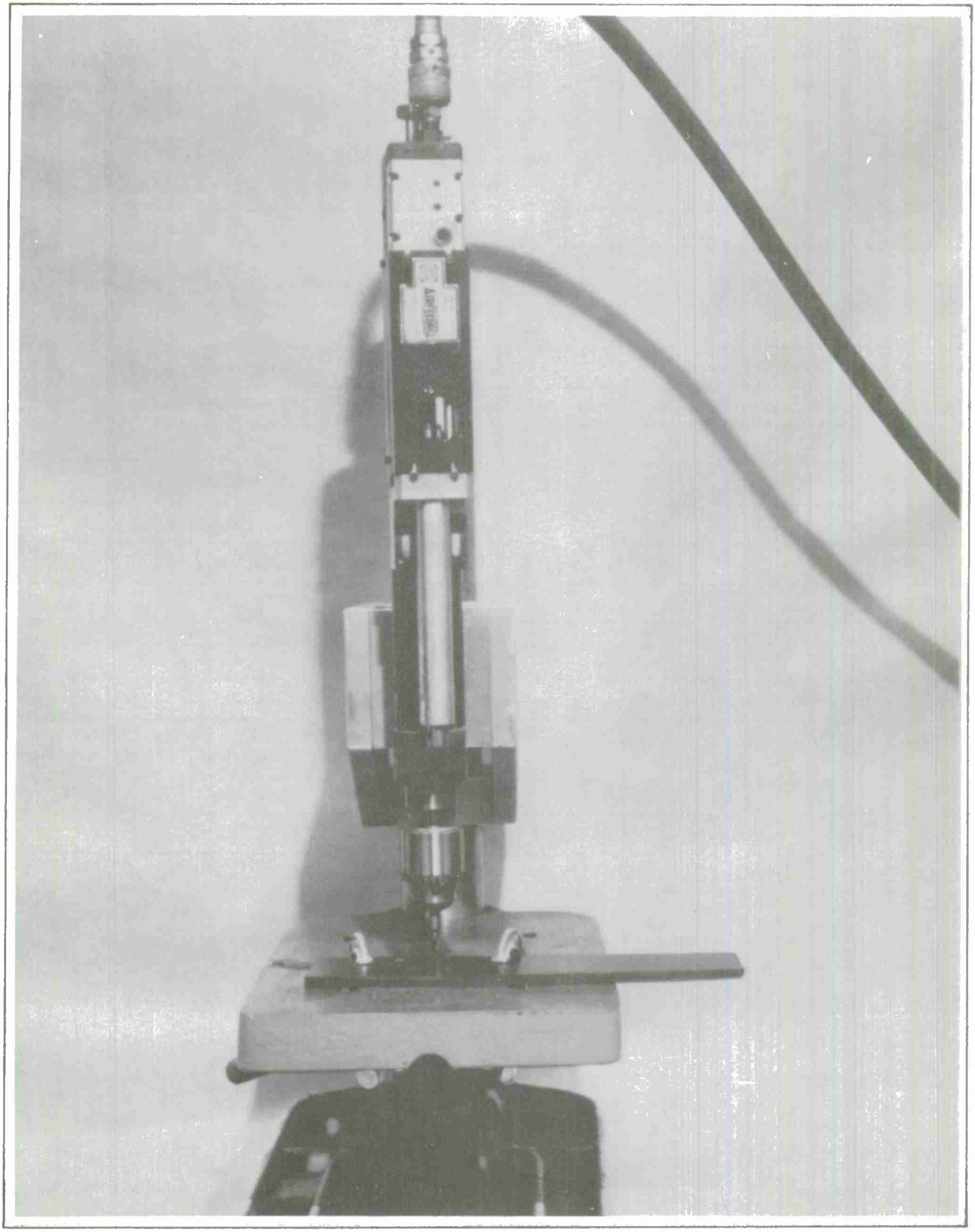
4.9.1 Portable Routers

The Buckeye (Figure 4-27) and Dotco routers are standard, aircraft industry types driven by air. These very versatile routers, used mainly with guiding tools, are capable of routing, trimming and beveling the complete range of cured composite materials except boron/epoxy and boron/epoxy hybrids. The edge in most cases does not require post-processing providing the correct router bit is used (see Figure 4-28).

4.9.2 Stationary Routers

The Marwin Profiler and the Onsrud Router (Figure 4-29) are stationary machines with constant or variable speeds, capable of routing, trimming and beveling the complete range of cured materials, except boron/epoxy and boron/epoxy hybrids. When using the Marwin Profiler, the workpiece is clamped to the table and the profile cut using a guide rim against a template. The feed is manual through a mechanical advantage. A template is always used with the Marwin Router which is manually fed. In most cases, the edge does not require post-processing providing the correct router-bit is used. Equipment specifications are given in Figure 4-30 and 4-31.

The stationary Roto-Recipro router (Figure 4-32) is ideal equipment for routing, trimming and beveling cured boron/epoxy and boron/epoxy hybrids (Figure 4-33). When the Buckeye router is mounted on the Roto-Recipro machine, it provides high torque and minimum feed (surface feet per minute) for the router bit. The reciprocating motion of the router bit provides even wear to the router and also gives a better finish as the number of strokes per minute increase. A finish cut can be obtained with diamond router bits (the finer the diamond grit, the better the finish).



2566-121W

Figure 4-19 Gardner-Denver Portable Drill

TYPE	AIRFEED DRILL
MANUFACTURER	GARDNER-DENVER COMPANY, PNEUTRONICS DIVISION, GRAND HAVEN, MICHIGAN 49417
MODEL	MM-8 SERIES
HORSEPOWER	0.3 HP REGARDLESS OF SPEED
AIR CONSUMPTION	18 CFM AT LOAD, 20 AT FREE SPEED
WEIGHT	13 POUNDS
COOLANT	OUTSIDE SOURCE REQUIRED
FEED	POSITIVE AIRFEED
SPEED	800, 1500, 2900, 5600, 10,500, 21,000 RPM
DRILL SIZE	UP TO 5/16 INCH DIAMETER
MOUNTING	MOUNT IN, OR BRACKET TO, JIG OR DRILL BUSHING TIP FOR HOLD DOWN SCREWS
SPINDLE AND CHUCK CONCENTRICITY	0.001 INCH AT SPINDLE
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE CUTTING	COOLANT SPRAY AND DUST REMOVAL

2566-122W

Figure 4-20 Gardner-Denver Portable Drill Specification

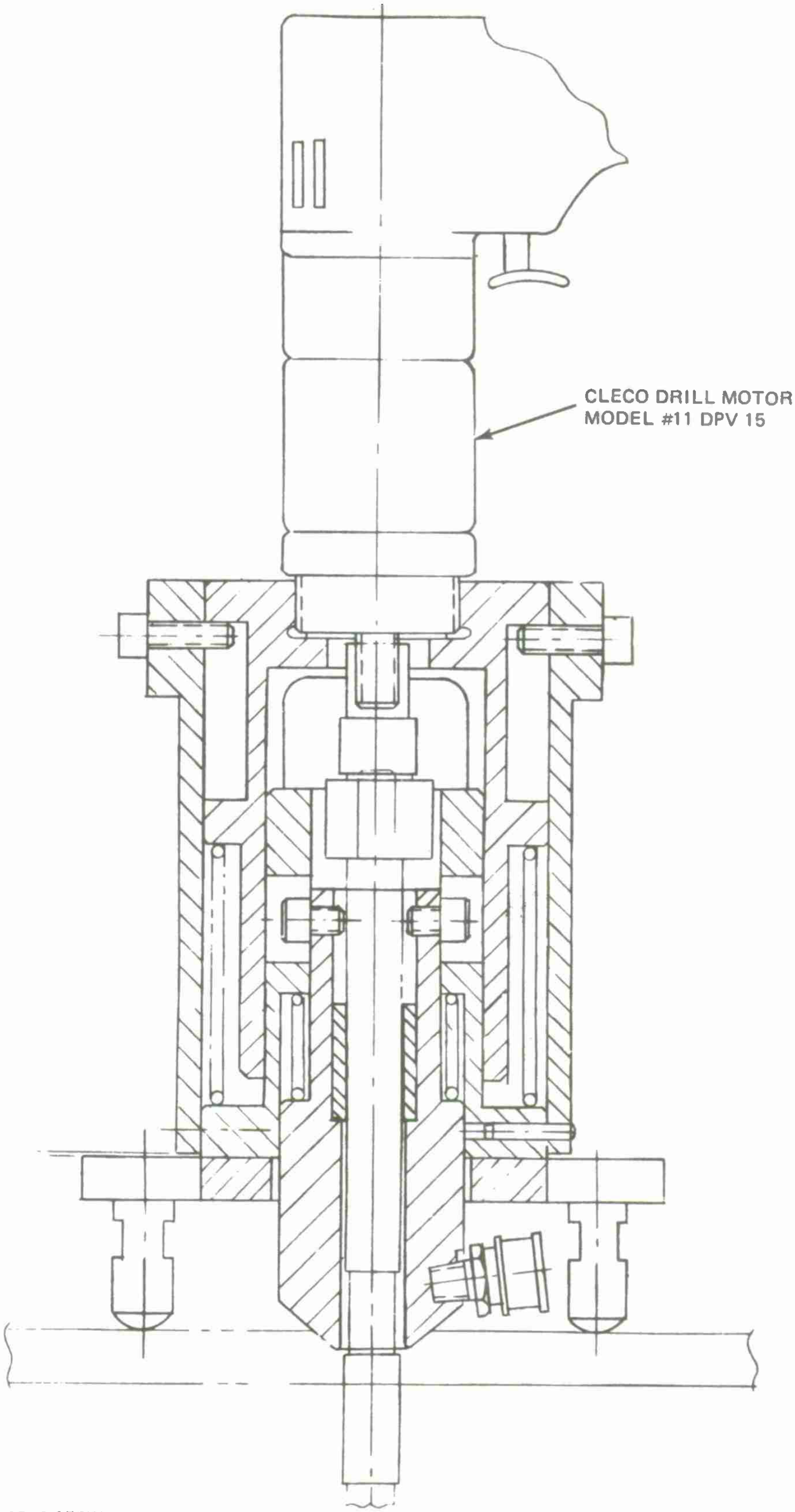


Figure 4-21 Portable Honing Fixture

TYPE	PORTABLE HONING FIXTURE
MANUFACTURER	GRUMMAN AEROSPACE CORPORATION
MODEL	ST4761 (HONING FIXTURE) WITH CLECO 11DPV15 VARIABLE SPEED DRILL MOTOR (POWER SOURCE).
AIR CONSUMPTION	8 TO 15 CFM
HORSEPOWER	0.45 HP
COOLANT	TBI FREON APPLIED BY SPRAY MIST THROUGH FIXTURE BASE.
FEED	HANDFEED, 0.37 INCH (MAX) STROKE
SPEED	500 RPM
HONE SIZE	0.190 TO 0.502 INCH
NOSEPIECE	FIXTURE BASE LOCATING CONE POSITIONS IN HOLE COUNTERSINK.
NOSEPIECE CONCENTRICITY	0.001 INCH (MAXIMUM)
EQUIPMENT RELIABILITY	EQUIPMENT DESIGNED SPECIFICALLY FOR BORON HONING. WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.62 INCH
ACCESSORIES FOR COMPOSITE HONING	COOLANT SPRAY

2566-123W

Figure 4-22 Portable Hone Fixture Specification

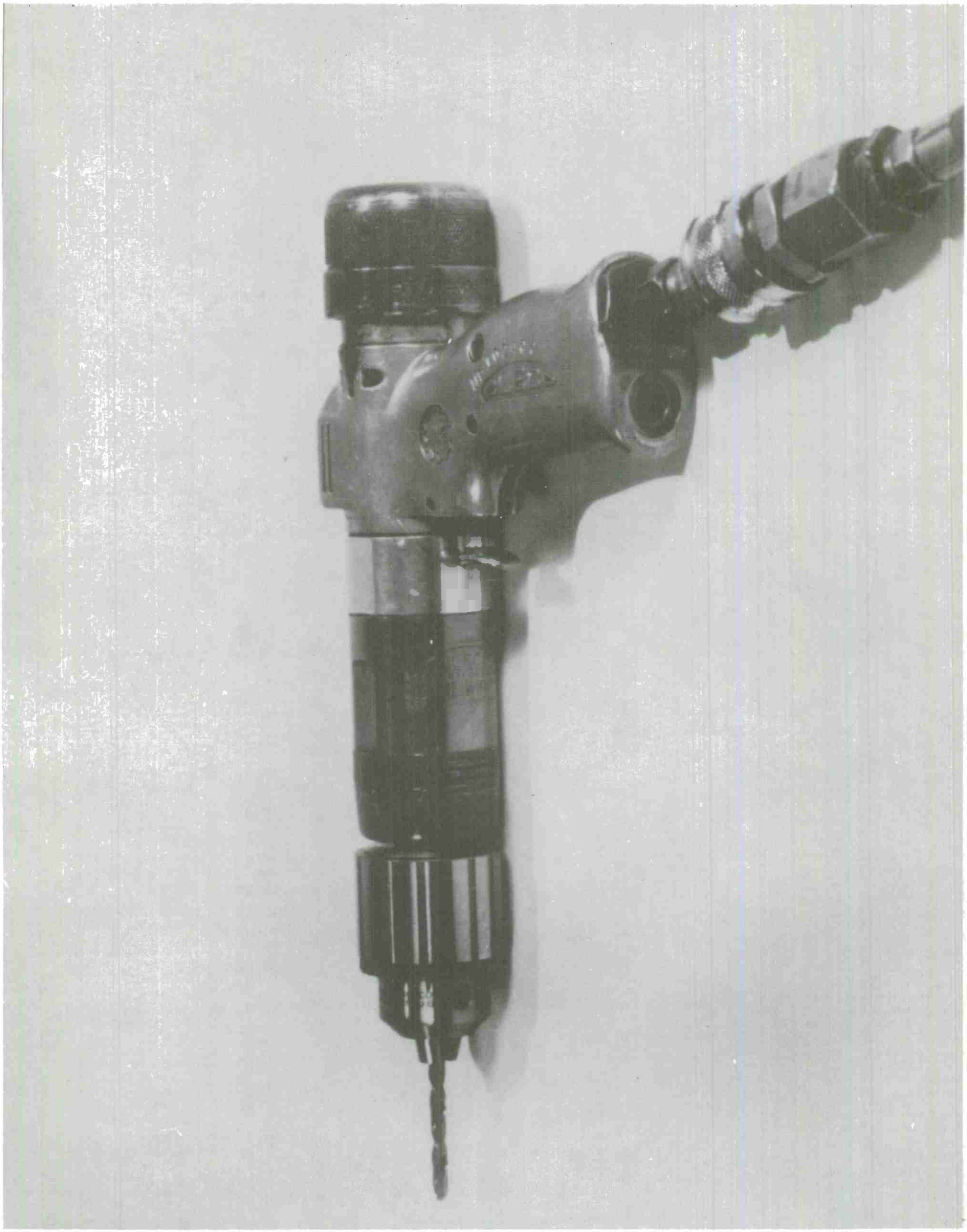


Figure 4-23 Cleco Air-Driven Drilling Motor

2566-124W

TYPE	AIR-OPERATED, HAND-HELD
MANUFACTURER	CLECO/OR ZEPHYR
MODEL	11 DPV-15 (CLECO)
HORSEPOWER	0.8
AIR CONSUMPTION	20 CFM
WEIGHT	3.9 LBS
COOLANT	OUTSIDE APPLICATION REQUIRED
FEED	HAND
SPEEDS	VARIABLE 450 THRU 1250 RPM
DRILL SIZE	UP TO 3/8 IN. DIA
SPINDLE CONCENTRICITY	0.008 TIR
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS	0.50 INCH
ACCESSORIES FOR COMPOSITE DRILLING	COOLANT SPRAY AND DUST REMOVAL

2566-125W

Figure 4-24 Cleco Hand Drilling Unit Specification

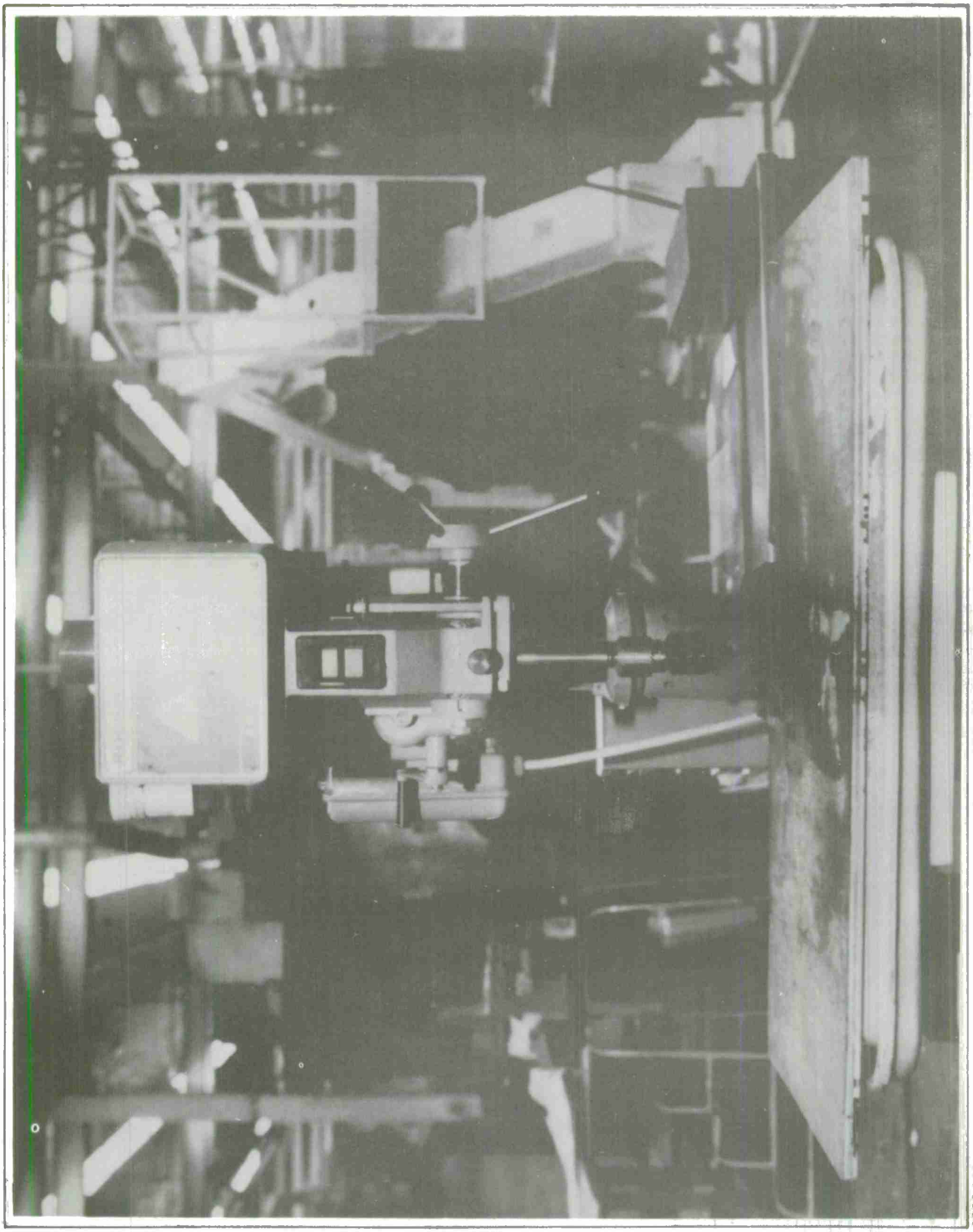


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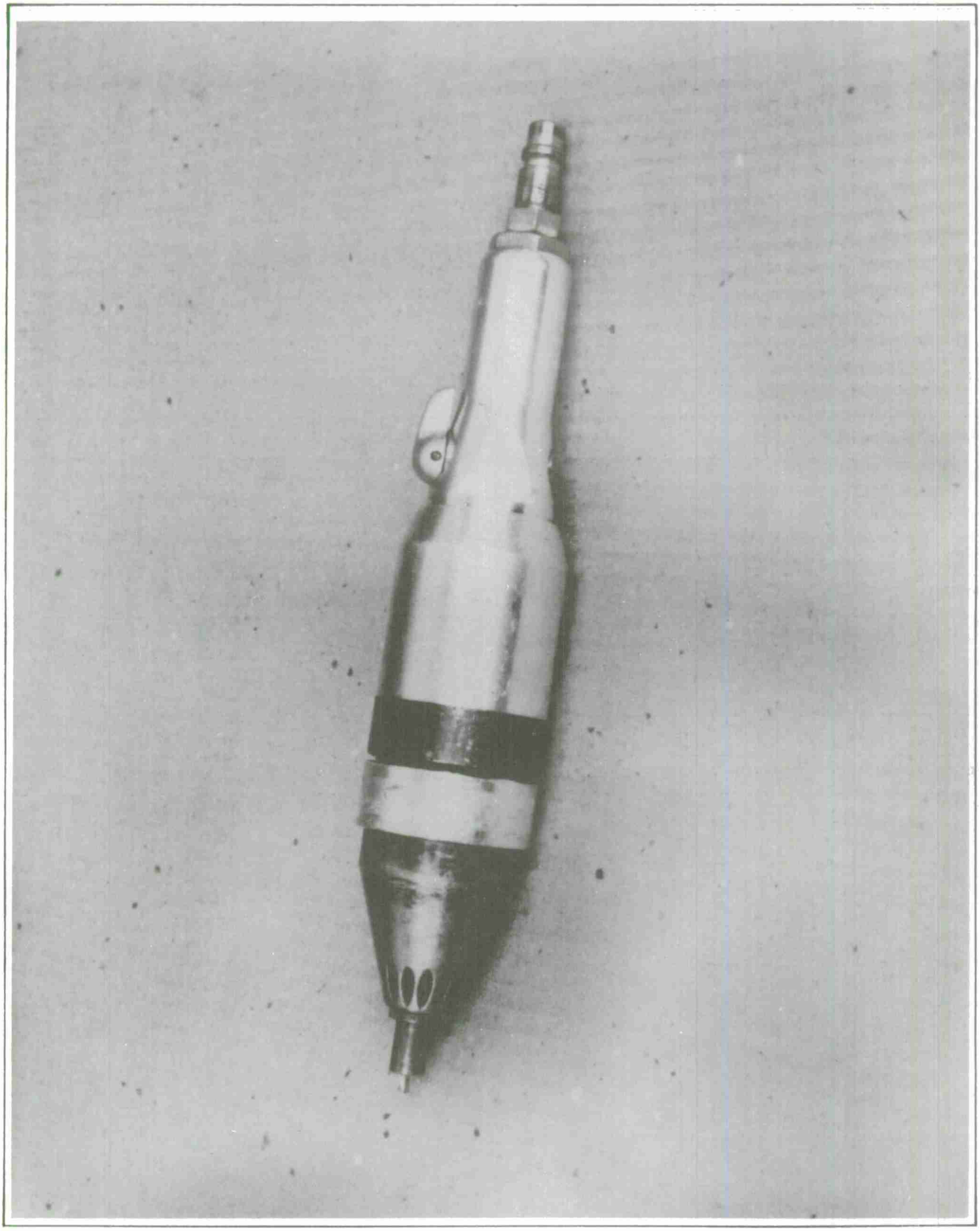
Figure 4-25 Rockwell/Delta Stationary Drill Press

TYPE	AIR-OPERATED
MANUFACTURER	DELTA MFG DIV OF ROCKWELL INT
MODEL	70-6X0
HORSEPOWER	1 1/2
COOLANT	OUTSIDE APPLICATION REQUIRED
FEED	HAND
SPEEDS	VARIABLE 375 - 4200 RPM
DRILL SIZE	UP TO 0.50 IN. DIA
SPINDLE CONCENTRICITY	0.001 TIR
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT AND NOT SIGNIFICANTLY AFFECTED BY COMPOSITE CUTTING AND WITH APPROPRIATE PREVENTATIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS	0.50 INCH
ACCESSORIES FOR COMPOSITE DRILLING	COOLANT SPRAY AND DUST REMOVAL

2566-127W

Figure 4-26 Rockwell/Delta Stationary Drill Press Specification



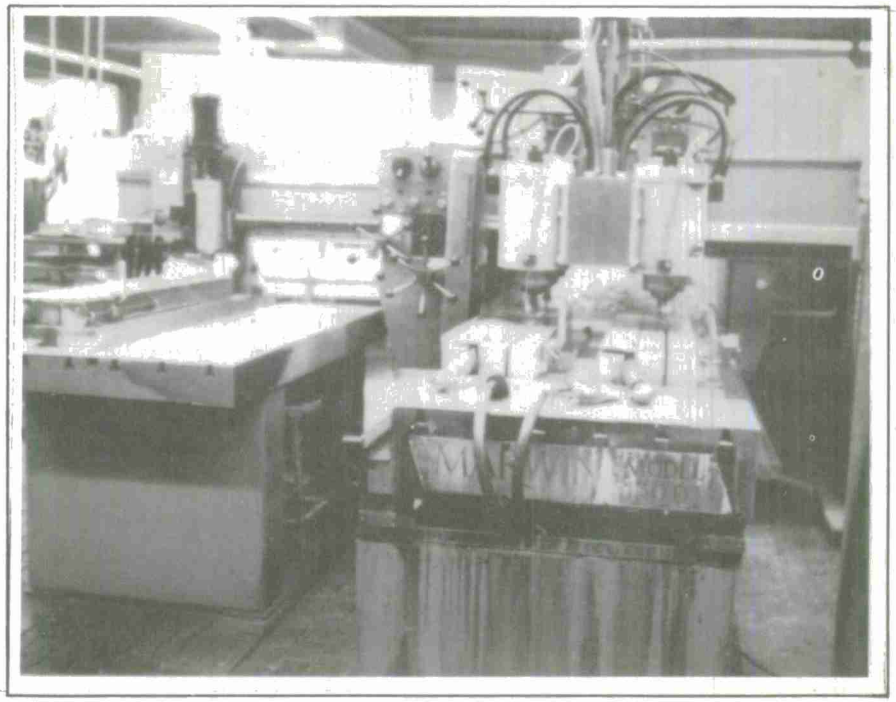
2566-128W

Figure 4-27 Portable Buckeye Router

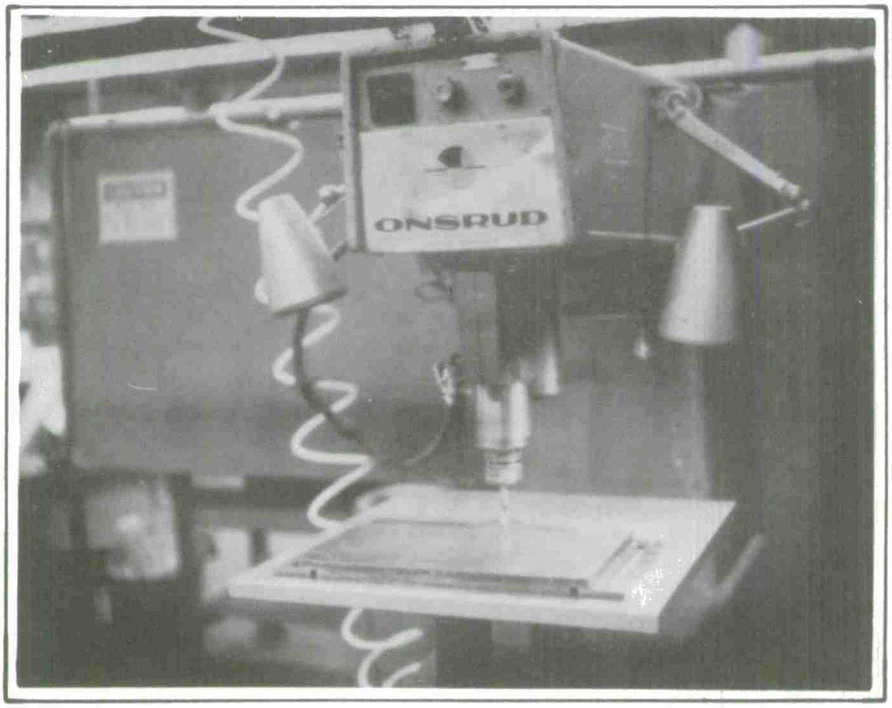
TYPE	PORTABLE AIR DRIVEN (STANDARD) AIRCRAFT TYPE)
MANUFACTURER	BUCKEYE-WESTERN, INC.
MODEL	BWR-191
CHUCK	1/4 INCH DIAMETER
HORSEPOWER	0.9 HP
SPEED	16,000 RPM
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT; NOT SIGNIFICANTLY AFFECTED BY COMPOSITE MACHINING; WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE MACHINING	DUST EXHAUST AND COOLANT SPRAY.

2566-129W

Figure 4-28 Portable Buckeye Router Specification



A. Marwin



B. Onsrud

2566-177W

Figure 4-29 Stationary Routers

MANUFACTURER	MARWIN LIMITED
MODEL	30D
CHUCK	3/8 INCH DIAMETER
SPEED	10,800 RPM (MAXIMUM)
FEED	HAND-DRIVEN MECHANICAL ADVANTAGE
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT; NOT SIGNIFICANTLY AFFECTED BY COMPOSITE MACHINING; APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE MACHINING.	DUST EXHAUST AND COOLANT SPRAY

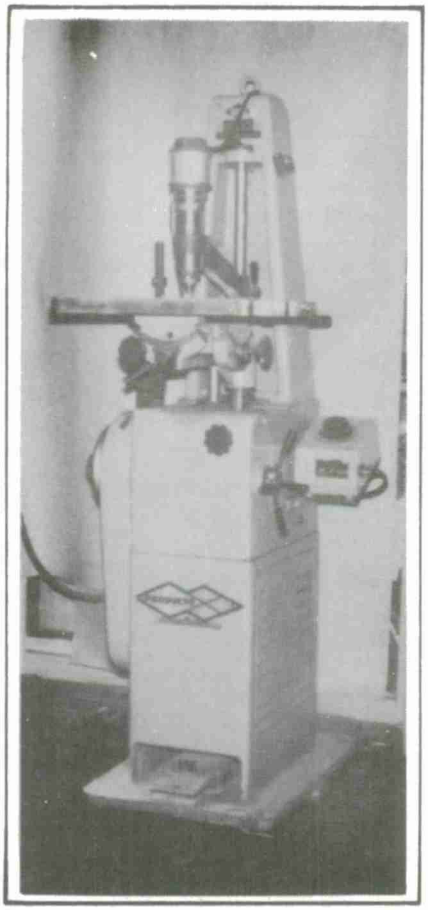
2566-123W

Figure 4-30 Stationary Marwin Profiler Specification

MANUFACTURER	ONSRUD MACHINE WORKS
MODEL	A-1024
CHUCK	1/4 INCH DIAMETER
SPEED	20,000 RPM
FEED	HAND
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT; NOT SIGNIFICANTLY AFFECTED BY COMPOSITE MACHINING; WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE MACHINING.	DUST EXHAUST AND COOLANT SPRAY.

2566-131W

Figure 4-31 Stationary Onsrud Router Specification



2566-133W

Figure 4-32 Stationary Roto-Recipro Router

MANUFACTURER	THE PRODUCTO MACHINE CO.
MODEL	4F
CHUCK	1/4 INCH DIAMETER
SPEED	0-350 STROKES/MINUTE 16,000 RPM WITH ROUTER MOTOR
FEED	HAND
EQUIPMENT RELIABILITY	COMMERCIAL EQUIPMENT; NOT SIGNIFICANTLY AFFECTED BY COMPOSITE MACHINING; WITH APPROPRIATE PREVENTIVE MAINTENANCE SHOULD GIVE NORMAL SERVICE LIFE.
COMPOSITE MATERIAL THICKNESS LIMITATIONS	0.50 INCH
ACCESSORIES FOR COMPOSITE MACHINING	DUST EXHAUST AND COOLANT SPRAY.

2566-132W

Figure 4-33 Stationary Roto-Recipro Router Specification

Section 5

CUTTING TOOLS

The selection of appropriate cutting tools for cutting, drilling, and machining of composites is mandatory for efficient production. Improper selection increases cutting tool acquisition and replacement costs, and reduces cutting rates and part quality. The following subsections should be used as a guide to select both cutting tool materials and configurations.

5.1 TOOL MATERIALS

Selection of the optimum cutting tool material has a major influence on productivity. This subsection discusses both conventional tool materials (high-speed steel and carbides) and diamond materials.

5.1.1 Conventional Tool Materials

Although high-speed steel provides the lowest cost cutting tools (purchase price), it has severe limitations for application to reinforced epoxy materials because of short tool life and poor cut quality. However, high-speed steel should be considered for cutting and drilling of Kevlar/epoxy.

Carbides offer the advantages of both higher hot hardness and increased abrasion resistance which particularly makes carbide a very attractive cutting tool material over high-speed steel. The general grade of carbide is usually a C2 or C-13. (C-13 is more abrasive-resistant but is difficult to purchase). Carbide materials would be generally recommended for all applications which do not contain boron/epoxy. It should be noted that, in the case of drilling, either solid carbide or carbide-tipped drills can be used, but solid carbides have approximately double the tool life.

5.1.2 Diamond Cutting Tools

Diamond cutting tools are utilized in a metal matrix form for cutting, machining, and drilling. Application is usually to boron/epoxy laminates or hybrids containing boron/epoxy. Since diamond cutting tools are sensitive to heat generation, the use of coolant is recommended in most applications to extend tool life. These cutting tools can be utilized in either conventional or rotary ultrasonic drilling equipment. In general, when drilling is done conventionally, high wear and tool breakage occur. The application of ultrasonic excitation to core drilling has been found to reduce these problems and yield higher cutting rates.

In selecting diamond tools, grit size, concentration and types of metal matrix must be considered. The grit size to be used is a function of the final finish required. For example, a grit size of 40 may be considered as coarse, 60 as standard and 100 or greater as fine. Fine grit sizes are subject to loading-up during the cutting operation. Grit sizes greater than 200 are available for extra-fine finishes. These diamond tools are generally fabricated by plating or sintering.

Diamond-plated tools are made by coating diamond abrasive grit to a formed tool surface by electrodeposition. Grit and tool blanks are placed in a plating solution in which a metallic coating, generally nickel, is deposited on the tool blank. The plated material anchors the diamond abrasive to the cutting tool surface. A single layer of highly concentrated diamonds results. The diamonds secured by this plating process are usually highly exposed, providing lower temperature operation and freer cutting. Rapid stock removal is obtained. Because of the limited depth of diamonds and plating wear, however, shorter tool life is experienced. Plated tools can be salvaged by replating.

Sintered diamond tools represent another alternative. These tools are made by sintering a mixture of diamond grit and bonding material to the desired configuration. Hard, abrasive-resistant metallic bonds are recommended for composites. The impregnated section is sintered to a steel tool blank. Although these tools are not as free-cutting as plated tools and require use of coolants, they withstand erosion better and have longer wear life because of their multi-layer construction. Sintered tools can refurbish themselves by exposing new diamond edges and therefore cut freer than plated tools after a few holes.

In the non-ultrasonic mode, metal-matrix diamond tools have a tendency to become congested with coolant sludge when honing boron-graphite/epoxy. Once the matrix is congested, the hones seize, twist and, in some cases, break. Cleaning with Freon is required to maintain normal operation.

Drilling of composite/metallic laminates has met with reasonable success in the ultrasonic mode. Aluminum elements do not present a problem. Because titanium causes high wear and requires use of slow rates, sheet thicknesses under 0.06 inch only (Reference 7) can be drilled.

An important point in using diamond core-drills is that a few test holes should be drilled first to confirm the hole size before proceeding with production drilling. Although diamond core drills are purchased to a diametrical tolerance of plus or minus 0.002 inch, the drill diameters often exceed this tolerance. Normal drilled hole drawing tolerance is plus 0.003 inch.

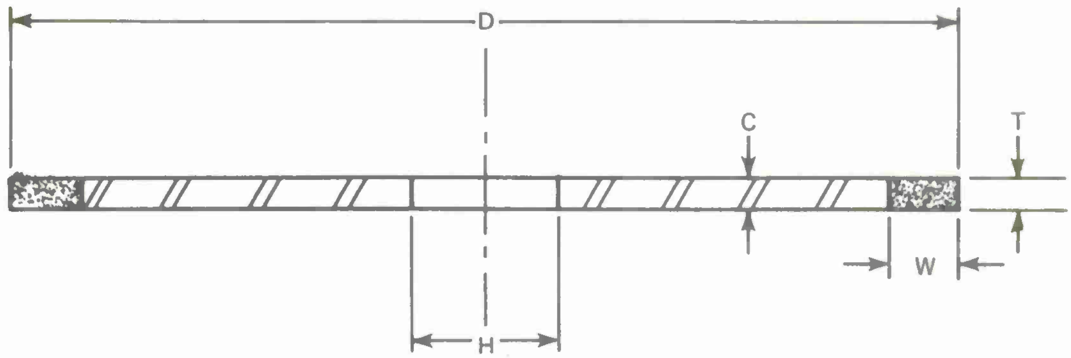
A new technology evolving within diamond cutting tools is that of the diamond-compacted, inserted-tooth cutting tools. These cutting tools are intended to be competitive with carbides, offering better abrasion resistance and dimensional stability. However, at this time, there are reliability problems with the compacted diamond attachments and sufficient testing has yet to be performed that will substantiate feasibility.

5.1.3 Other Cutting Tool Materials

Cutting tool materials other than high-speed steels, carbides and diamonds have also been evaluated in this and other programs. Due to either poor cutting characteristics and/or high tool wear, silicon carbide, aluminum oxide, and Borazon materials are not recommended for composite cutting or drilling. Preliminary tests did not show promise.

5.2 CUTTING TOOL CONFIGURATIONS

Cutting tool configurations for each of the recommended machining conditions given in Section 3 can be found in Figures 5-1 through 5-30. These cutting tools represent the latest state-of-the-art and will undoubtedly be subject to refinement as additional production experience is gained.



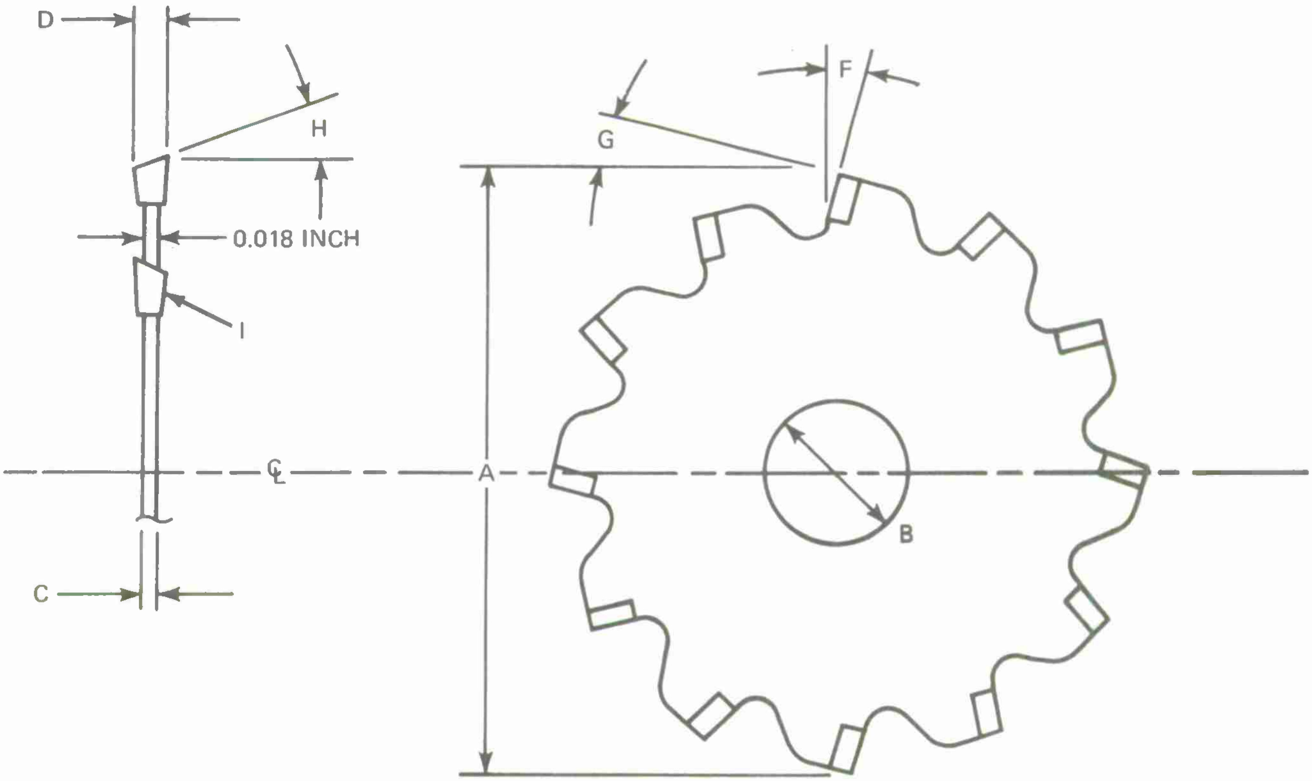
NOTES:

1. ALT. MANUFACTURERS – CUTWELL, LUNZER
2. SLOTTED BLADE TO IMPROVE COOLING

D	T	H	W	GRIT	C	SPEC	MANUFACTURER
8	3/32	5/8	1/16	60	1/16	R-805	SAMPLE MARSHALL
3	3/32	3/4	1/16	60	1/16	R-805	SAMPLE MARSHALL

2199-043B

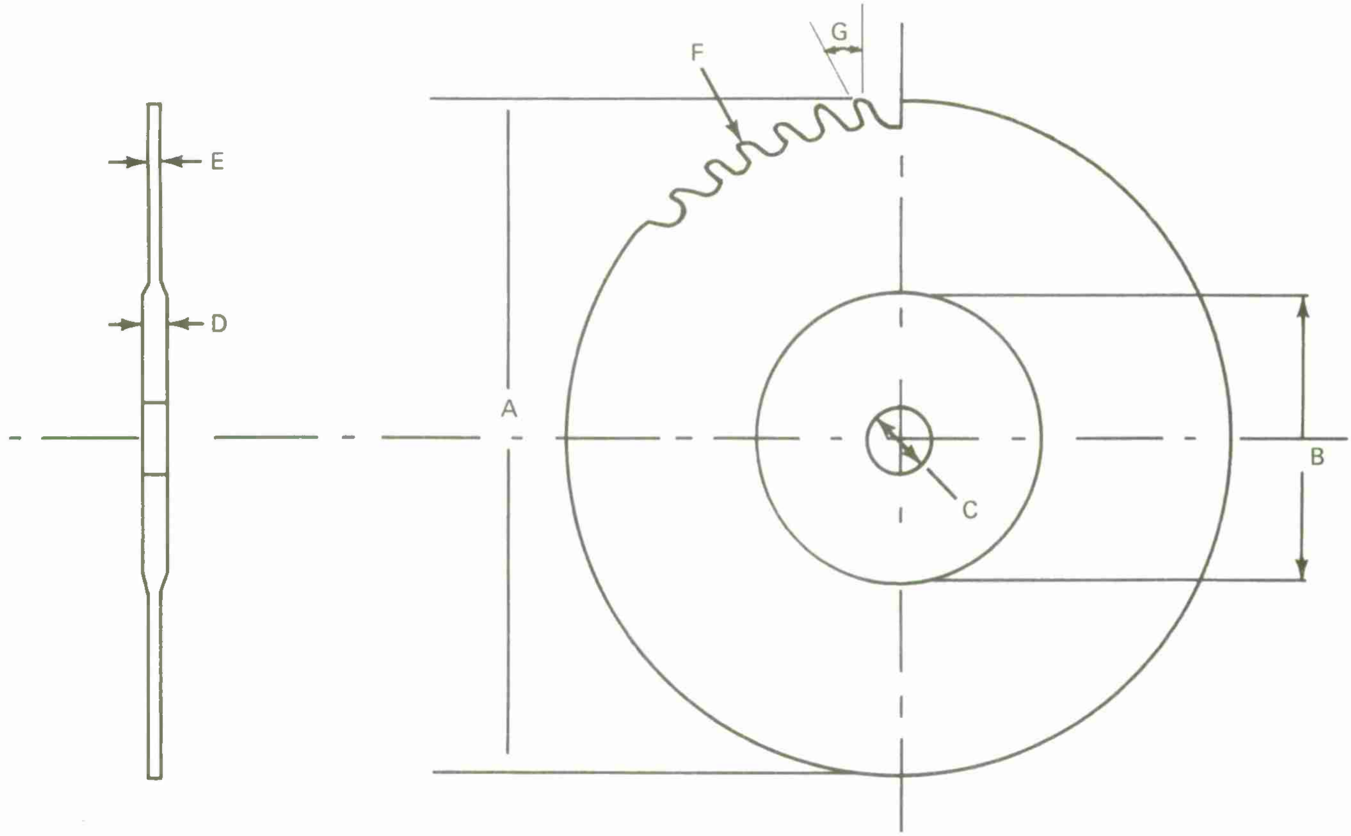
Figure 5-1 Diamond-Plated Cutoff Wheel



A	B	C	D	E - NO TEETH	F - NEG HOOK	G – RE RELIEF	H - ALT FACE BEVEL	I - DISH BACK	MANUFAC-TURER
3.0	3/4	0.09	0.125	12	15°	20°	20°	4°,4	ZEILLER & NAGEL

2566-134W

Figure 5-2 Carbide-Tipped Radial Saw Blade

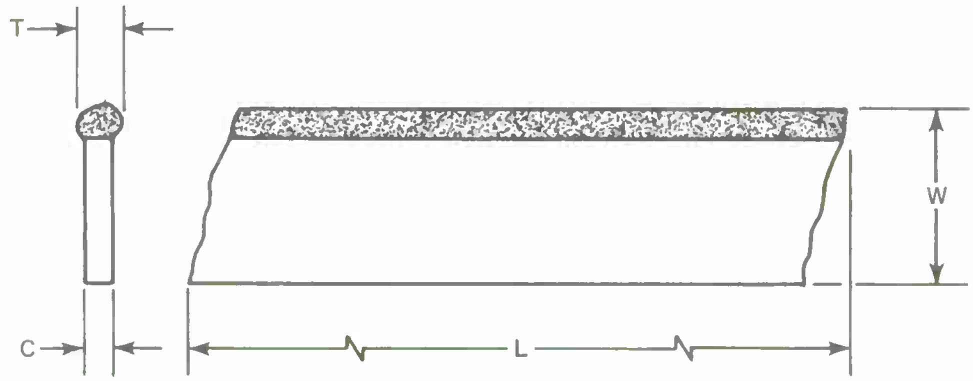


NOTE: 1 – STRAIGHT BACK TEETH

A	B	C	D	E	F NO. TEETH	G HOOK	MANUFACTURER
8.0	3.25	5/8	0.055	0.065	126-130	+5°	SIMONDS-STYLE 4-MS

2566-135W

Figure 5-3 HSS Circular Saw Blade for Kevlar/Epoxy



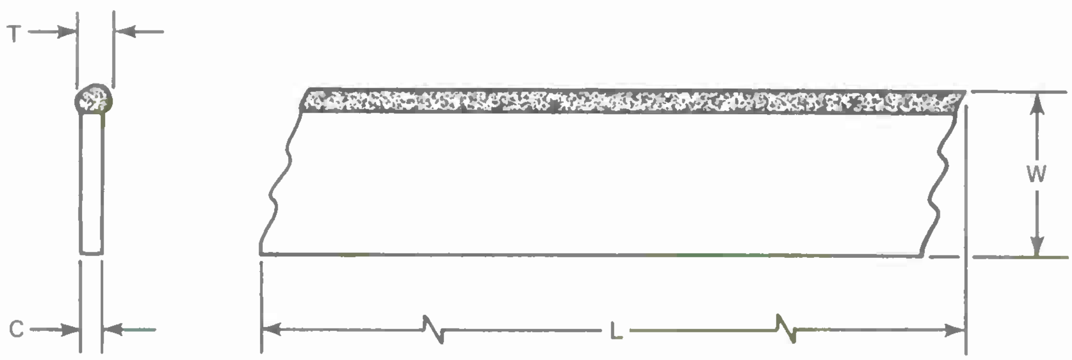
L	T	W	GRIT	C	SPEC	MANUFACTURER
120"	0.047	1/2	MED	0.025	BS4-IM	REMINGTON

NOTE:

1 – CONTINUOUS EDGE

2566-136W

Figure 5-4 Tungsten Carbide-Coated Bandsaw Blade



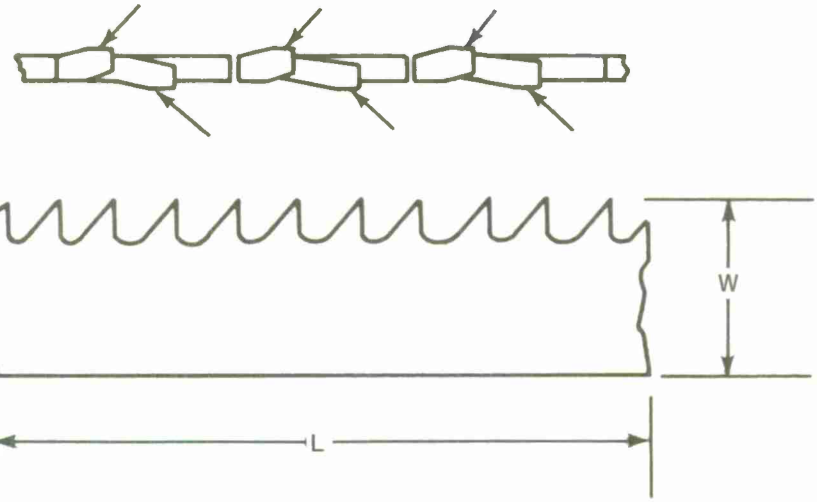
NOTE:

1-ALT MANUFACTURERS - CUTWELL, LUNZER

L	T	W	GRIT	SPEC	MANUFACTURER
120"	0.050	1/4	60		SAMPLE MARSHALL

2566-137W

Figure 5-5 Diamond-Plated Bandsaw Blade



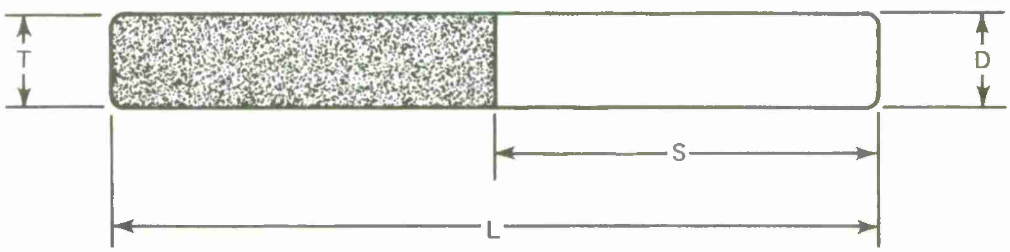
NOTE:

1. LAP EDGES OF TEETH, INDICATED BY ARROWS – 0.005–0.010"

P	W	L	TYPE	SET
18	1/4	114"	PRECISION	RAKER

2199-048B

Figure 5-6 Modified Carbon Steel Bandsaw Blade



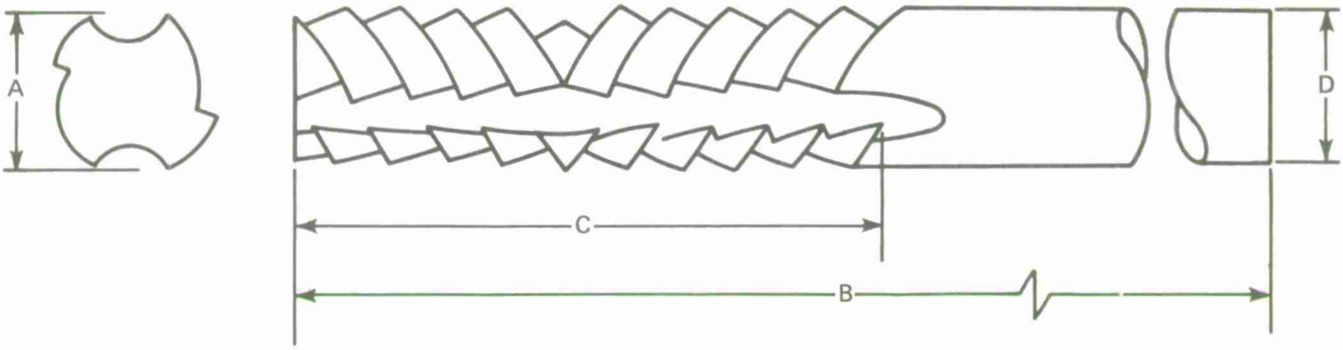
NOTE:

1. ALT MANUFACTURERS - CUTWELL, LUNZER

D	L	S	GRIT	T	SPEC	MANUFACTURER
0.250	2.0	1.0	40/50	0.250	R-810	SAMPLE MARSHALL

2566-138W

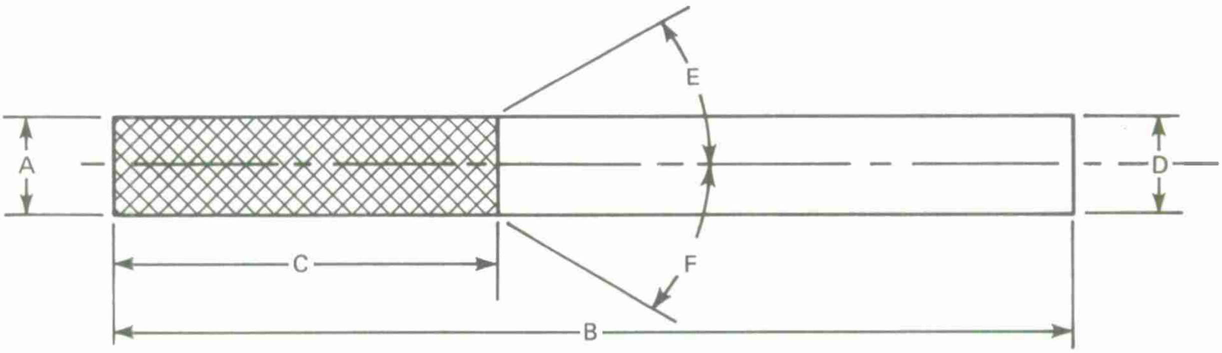
Figure 5-7 Diamond-Grit Router Bit



A	B	C	D	CODE	MANUFACTURER
0.250	2.50	0.75	0.250	PA1-2630	PEN ASSOCIATES

2566-139W

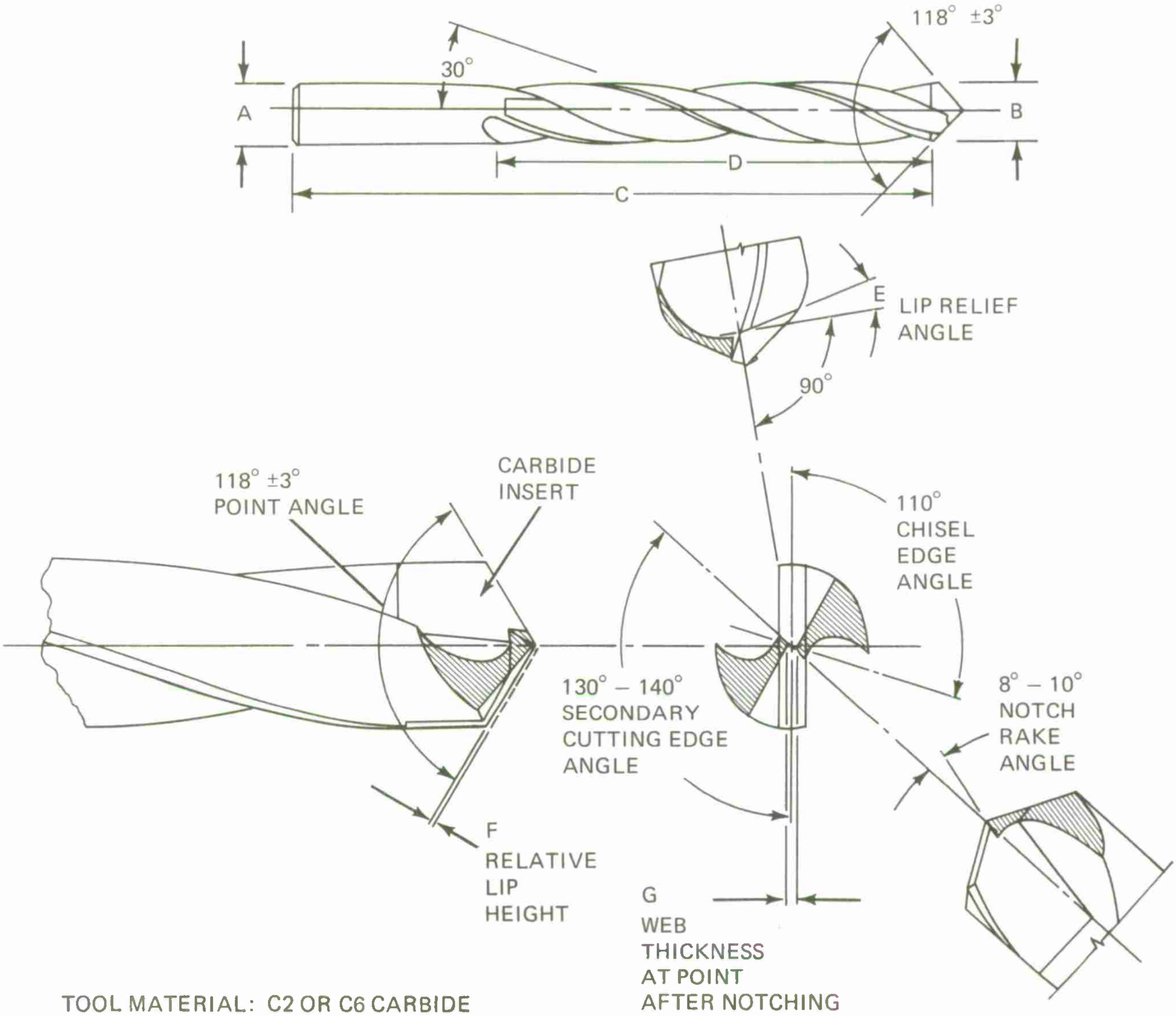
Figure 5-8 Carbide Opposed-Helix Router Bit



A	B	C	D	E HELIX <	NO. FLUTES	NO. CHIP BRKS	TANGENT HOOK	F CHIP BRK <
0.375	2.50	1.00	0.375	30°	16	6	5°	30°
0.250	2.50	1.00	0.250	30°	12	6	5°	30°

2566-140W

Figure 5-9 Carbide Diamond-Cut Router Bit



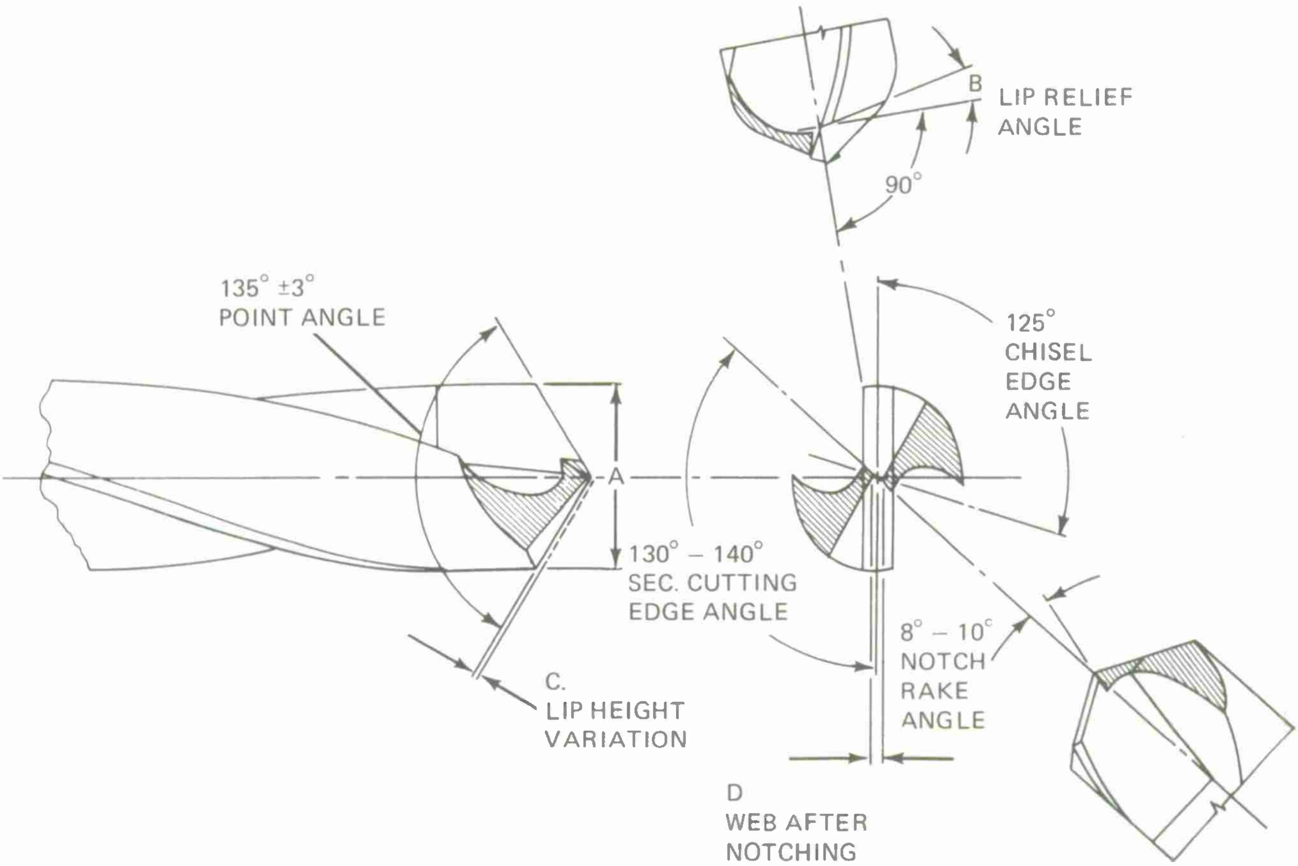
TOOL MATERIAL: C2 OR C6 CARBIDE

A*	B*	C*	D*	E	F	G	GRUMMAN CODE NO.
1/4	.2500	4.00	2.75	10° – 16°	.003	.007/.010	CT 3483-2709-148

*DIMENSIONS AND TOLERANCES NOT SPECIFIED TO BE PER USAS B94.11-1967

2566-141W

Figure 5-10 Carbide-Tipped Twist Drill



NOTES:

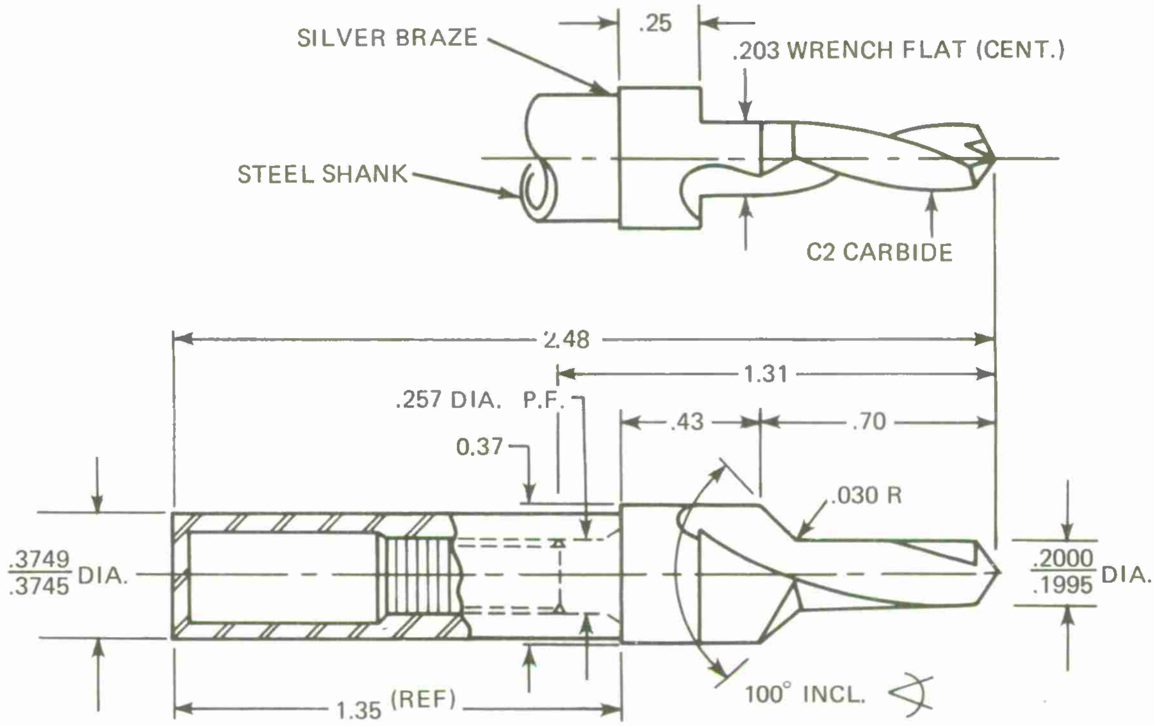
CT GEOMETRIC FEATURE	VALUE	TOL.
SPLIT WEB CENTRALITY	.003	TIV
ALIGNMENT OF SPLIT	.002	TIV
HELIX ANGLE, DEG	20	±1
WEB TAPER, IN/IN.	.032	REF
DRILL BK TAPER, IN/IN.	.0005 / .00010	
MARGIN WIDTH, IN.	.015	±.010 -.005

A	B	C	C
.2500	14 $^{+3°}_{-0°}$	.001	.005 .010

2566-142W

Figure 5-11 Solid Carbide Twist Drill

NOTE:
FOR USE ON GRAPHITE/EPOXY

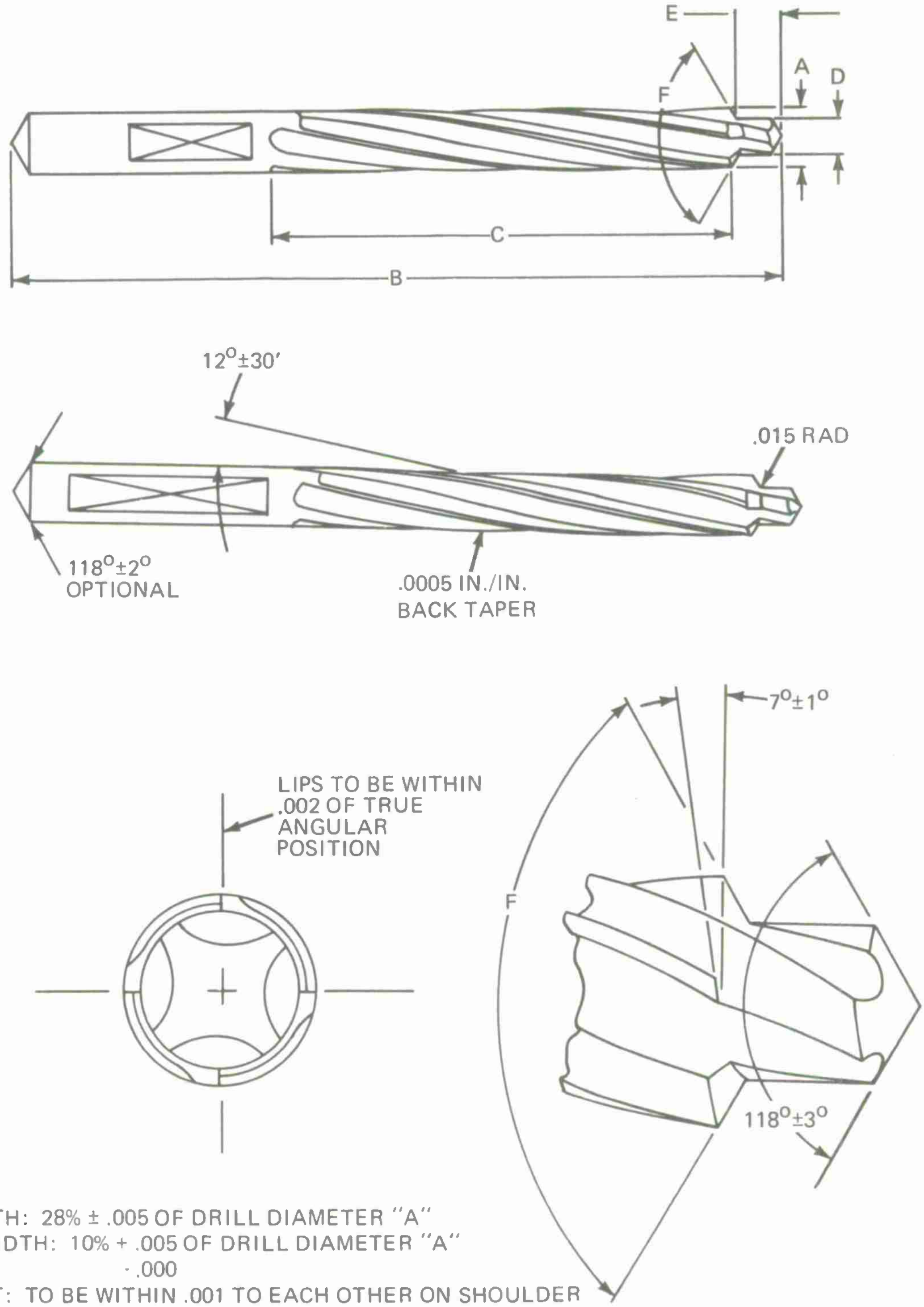


GEOMETRIC FEATURE

a) HELIX ANGLE 20° ± 1°
b) WEB AT POINT .050 ± .005 IN.
c) WEB TAPER .032 IN./IN.
d) C'SINK RELIEF = 4° ± 1°
e) MARGIN WIDTH .015 $^{+.010}_{-.005}$ IN.
f) DRILL POINT 135° ± 3°
g) NOTCH RAKE ANGLE 0° AXIAL ± 2°
h) POINT GEOMETRY PER GAC MFG. STD CD 2700-D11. EXCEPT POINT IS MODIFIED TO 135°
i) DRILL BACK TAPER $\frac{.0005}{.0010}$ IN/IN
j) IDENT. NO. CSZ114105
CSZ114104 SAME AS ABOVE EXCEPT DRILL DIA'S $\frac{.1910}{.1905}$

2566-143W

Figure 5-12 Solid Carbide Combination Drill/Countersink



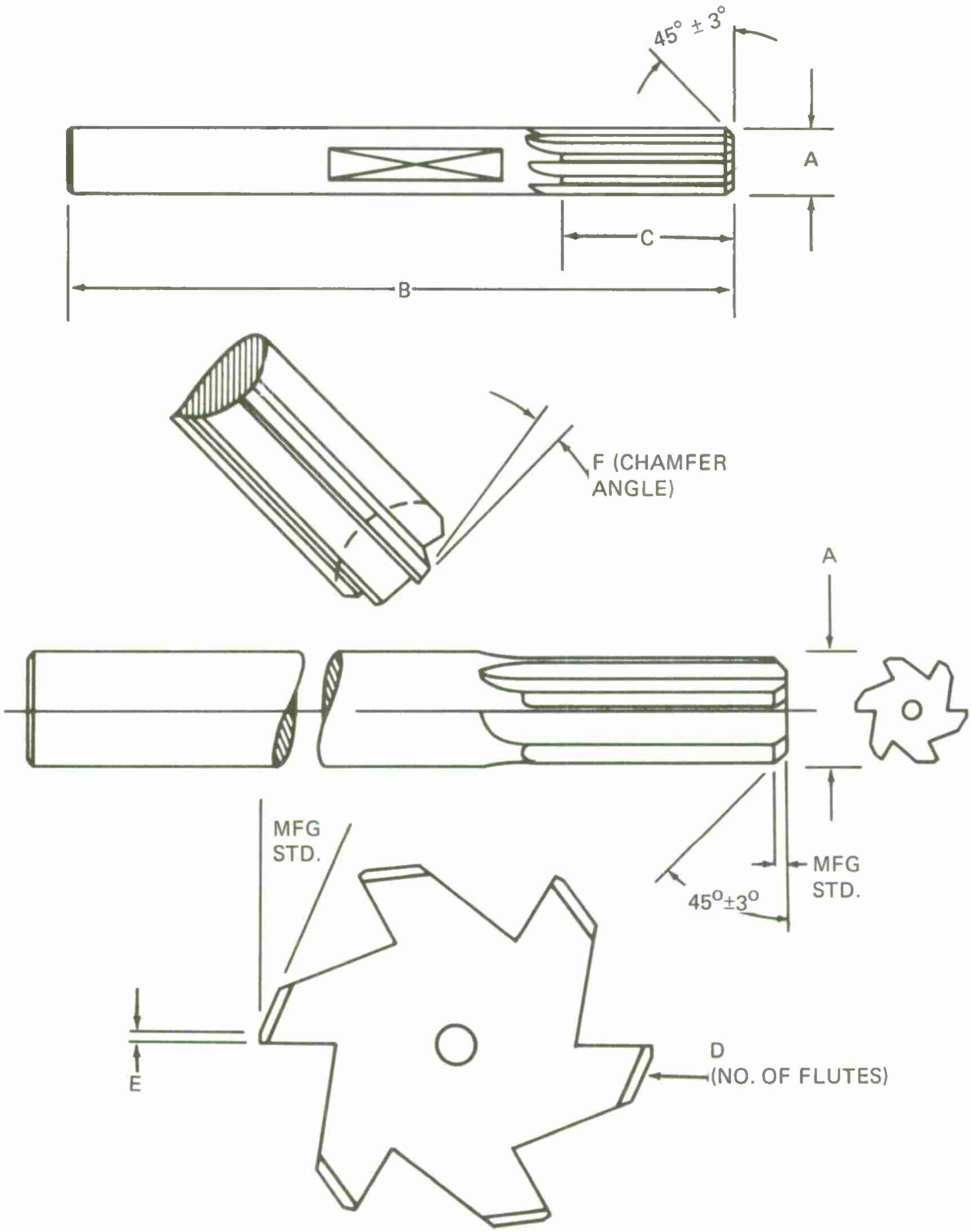
NOTES:

1. LAND WIDTH: 28% ± .005 OF DRILL DIAMETER "A"
2. MARGIN WIDTH: 10% + .005 OF DRILL DIAMETER "A"
   - .000
3. LIP HEIGHT: TO BE WITHIN .001 TO EACH OTHER ON SHOULDER

A	B	C	D	E	F	NO FLUTES
.2505	4.0	2.0	.234	.25	118°	4

2566-144W

Figure 5-13 HSS (Cobalt) Piloted Core Drill

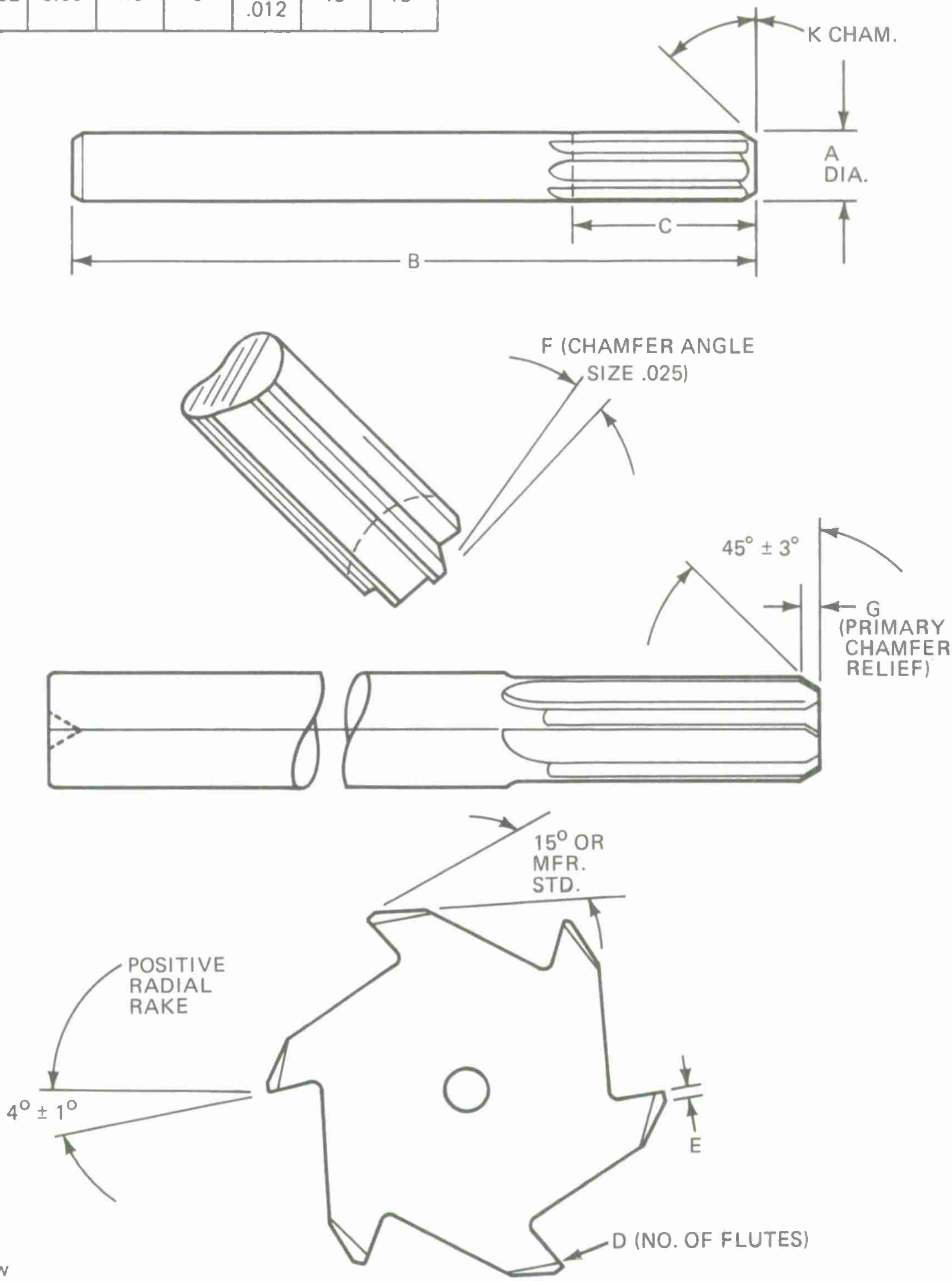


A	B	C	D	E	F	RAD. RAKE
.2500	6.00	1.5	6	.006 / .012	13°	0°

2566-145W

Figure 5-14 HSS (M-2) Reamer

A	B	C	D	E	F	G
.2502	6.00	1.5	6	.005 / .012	45°	13°



2566-146W

Figure 5-15 Solid Carbide (C-6) Reamer

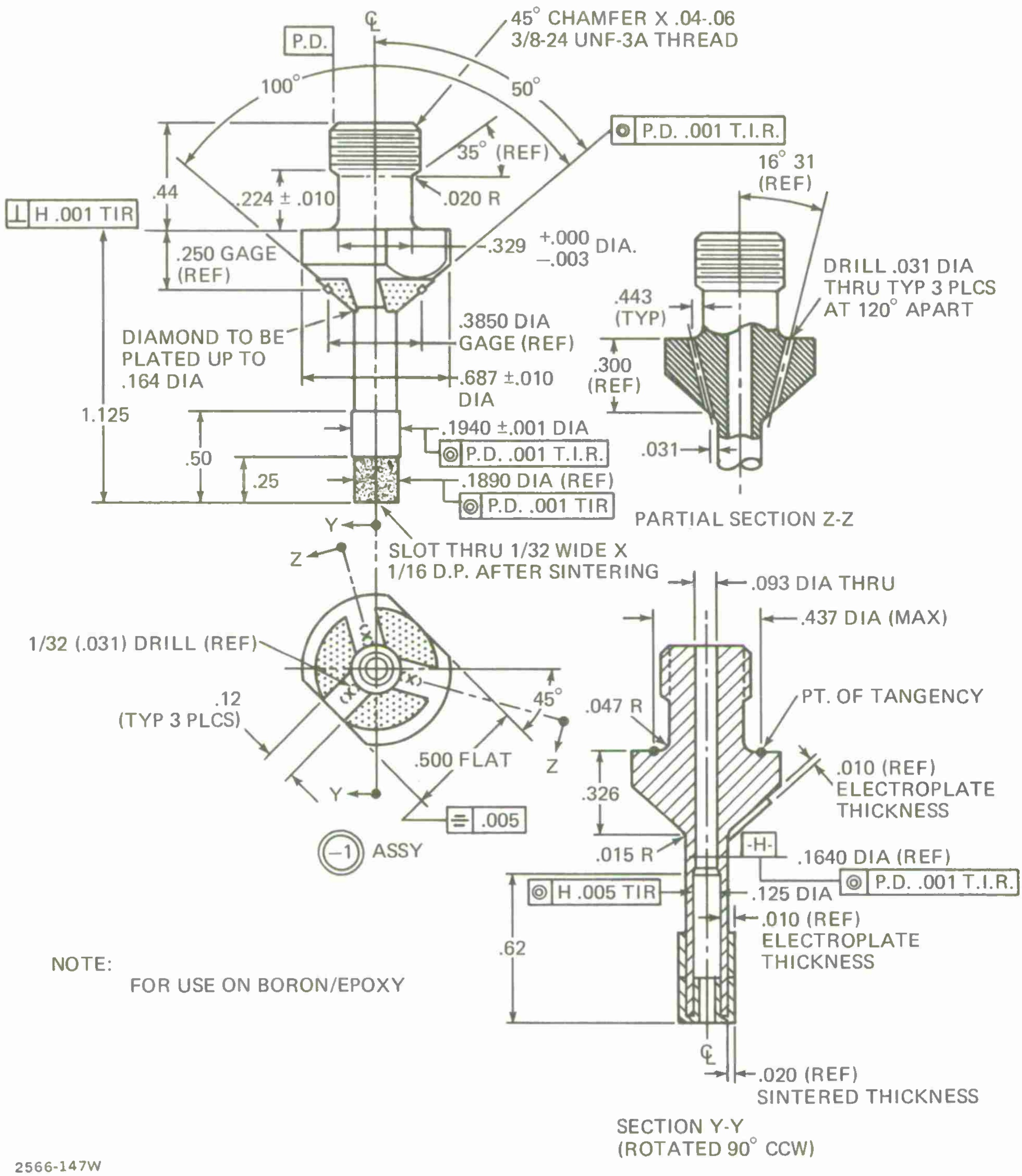
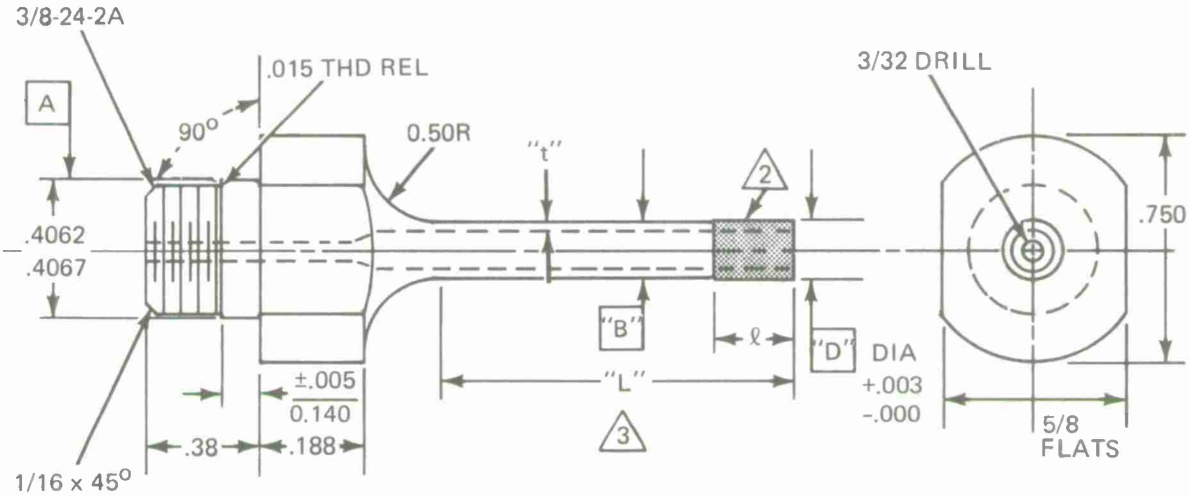


Figure 5-16 Diamond-Impregnated (Sintered)/Plated Drill/Countersink



NOTES:

1 – MAX. ECCENTRICITY TO BE .001 T.I.R. FOR DIAS A, B, & D.

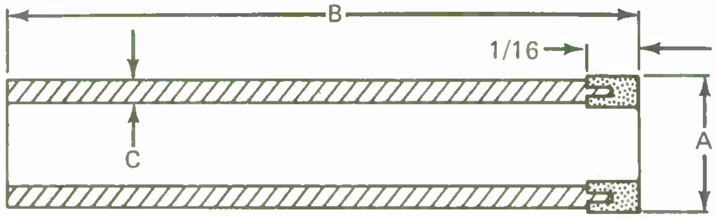
2 – GRIT 80-100, CONC-100, APPROX KNOOP HARDNESS OF 4500 Kg/mm^2
HOLD "D" DIA TO LOW SIDE OF TOLERANCE (-.000)

3 – "L" LENGTH DEPENDS ON RESONANCE AND MIN MATL THICKNESS TO BE DRILLED – RESONANCE 20 KHz

D	L	ℓ	T	MANUFACTURER
0.247	1.0	3/16	0.020	CUTWELL OR LUNZER

2566-148W

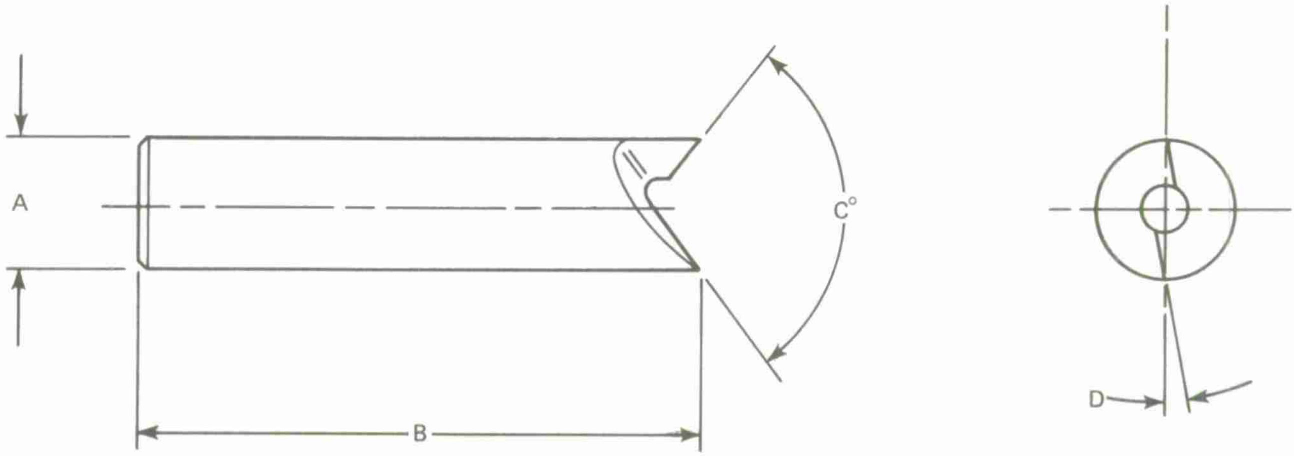
Figure 5-17 Diamond-Impregnated (Sintered) Core Drill for Ultrasonic UMT-3 or UMT-5 Unit



A	B	C	GRIT	MANUFACTURER
.200	2-1/4	~ .041	80 - 100	SAMPLE MARSHALL, LUNZER AND ABRASIVE TECH

2566-149W

Figure 5-18 Diamond-Plated Core Drill (Non-Ultransonic)

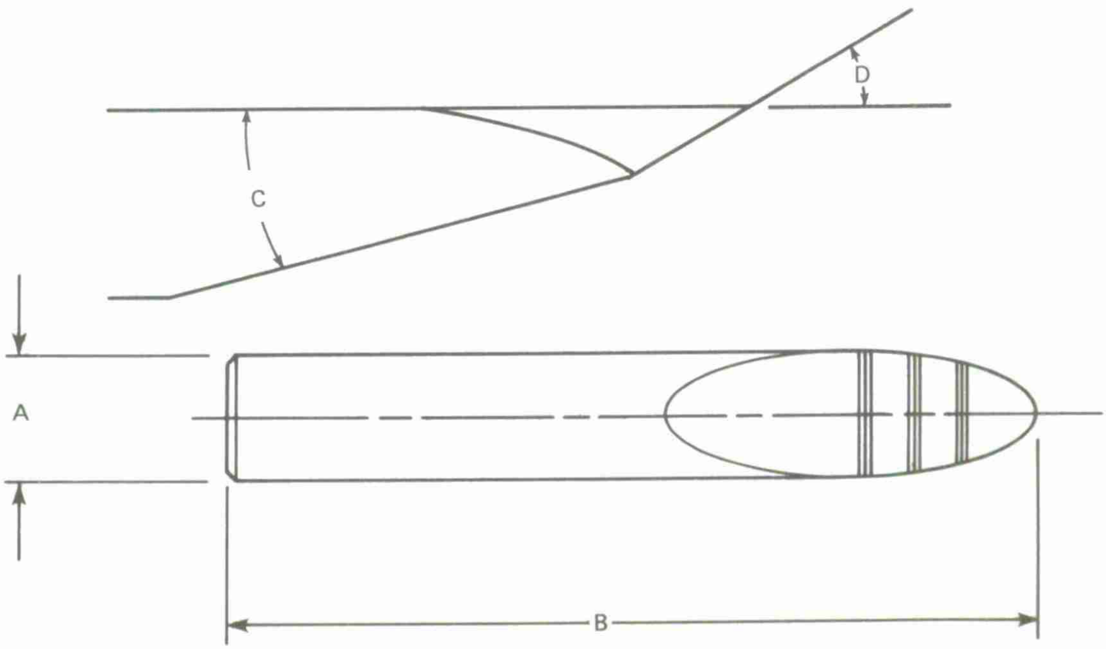


NOTE: USED ON KEVLAR/EPOXY.

A	B	C	D	MANUFACTURER
.250	2.25	110°	5°	JANCY ENGINEERING CO. DAVENPORT, IOWA

2566-150W

Figure 5-19 HSS Jancy Counterbore Drill



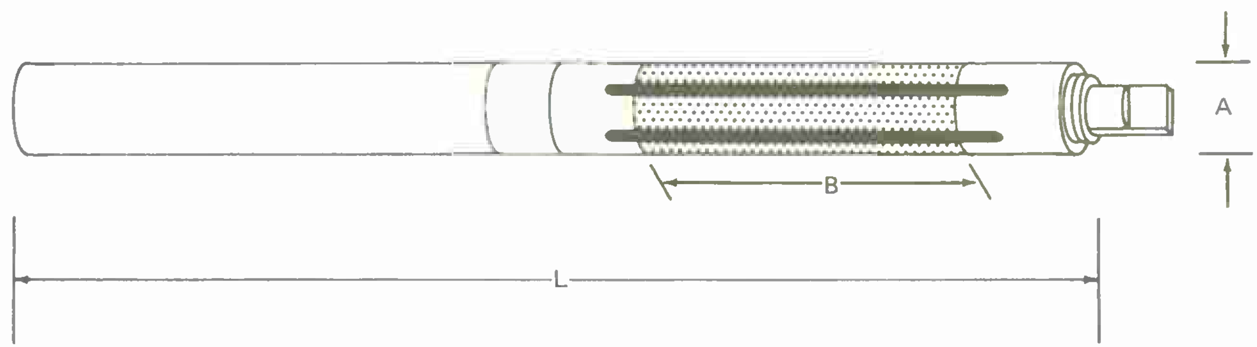
NOTE:

FOR LIMITED USE ON KEVLAR/EPOXY
HOLE SIZES LESS THAN 3/16

A	B	C	D	MANUFACTURER
.250	2.5	26°	45°	PEN ASSOCIATES

2566-151W

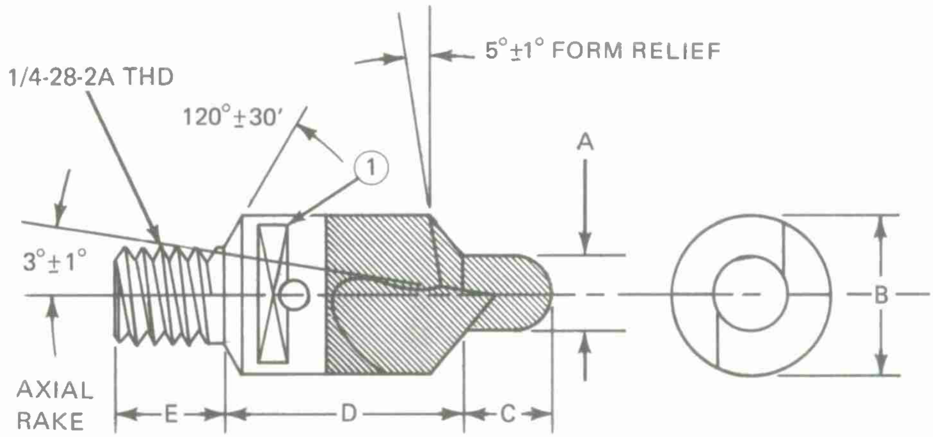
Figure 5-20 Carbide Slant Drill



A	B	L	GRIT	MANUFACTURER
0.250	1/2	6.5	220	SAMPLE MARSHALL

2566-152W

Figure 5-21 Diamond-Impregnated Hone (Adjustable)

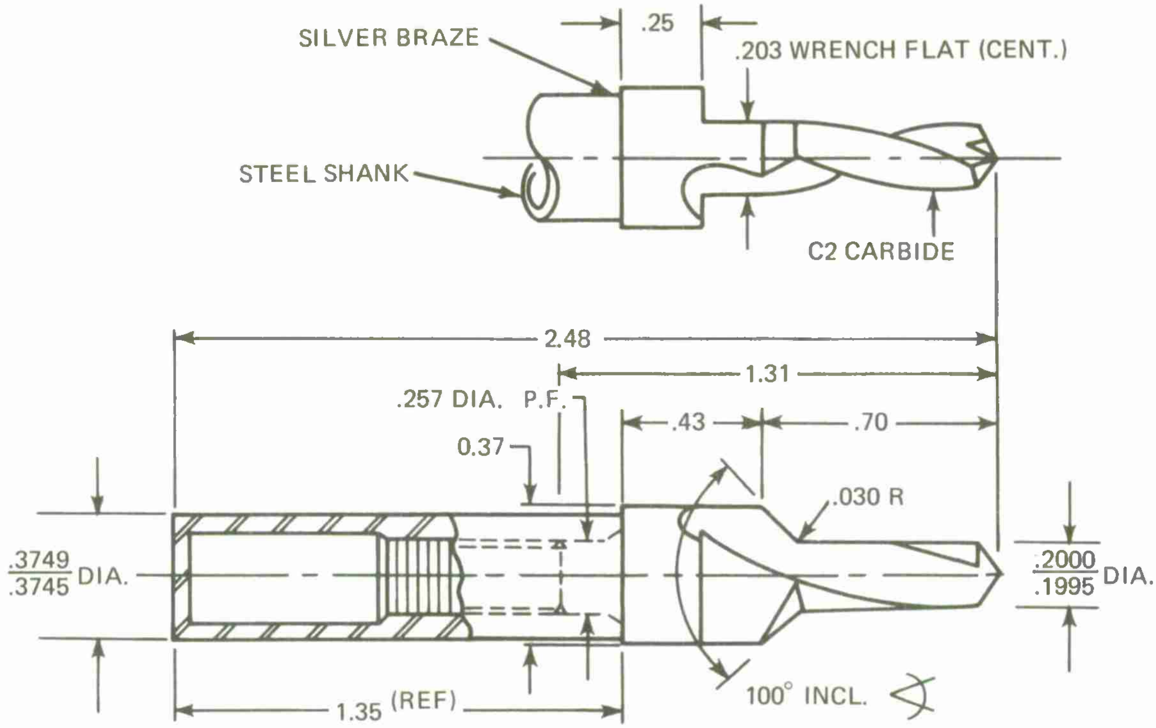


A	B	C	D	E
.1875	7/16	.190	.719	.312

2566-153W

Figure 5-22 Carbide-Tipped Two-Fluted Countersink (Piloted, Steel Threaded Shank)

NOTE:
FOR USE ON GRAPHITE/EPOXY



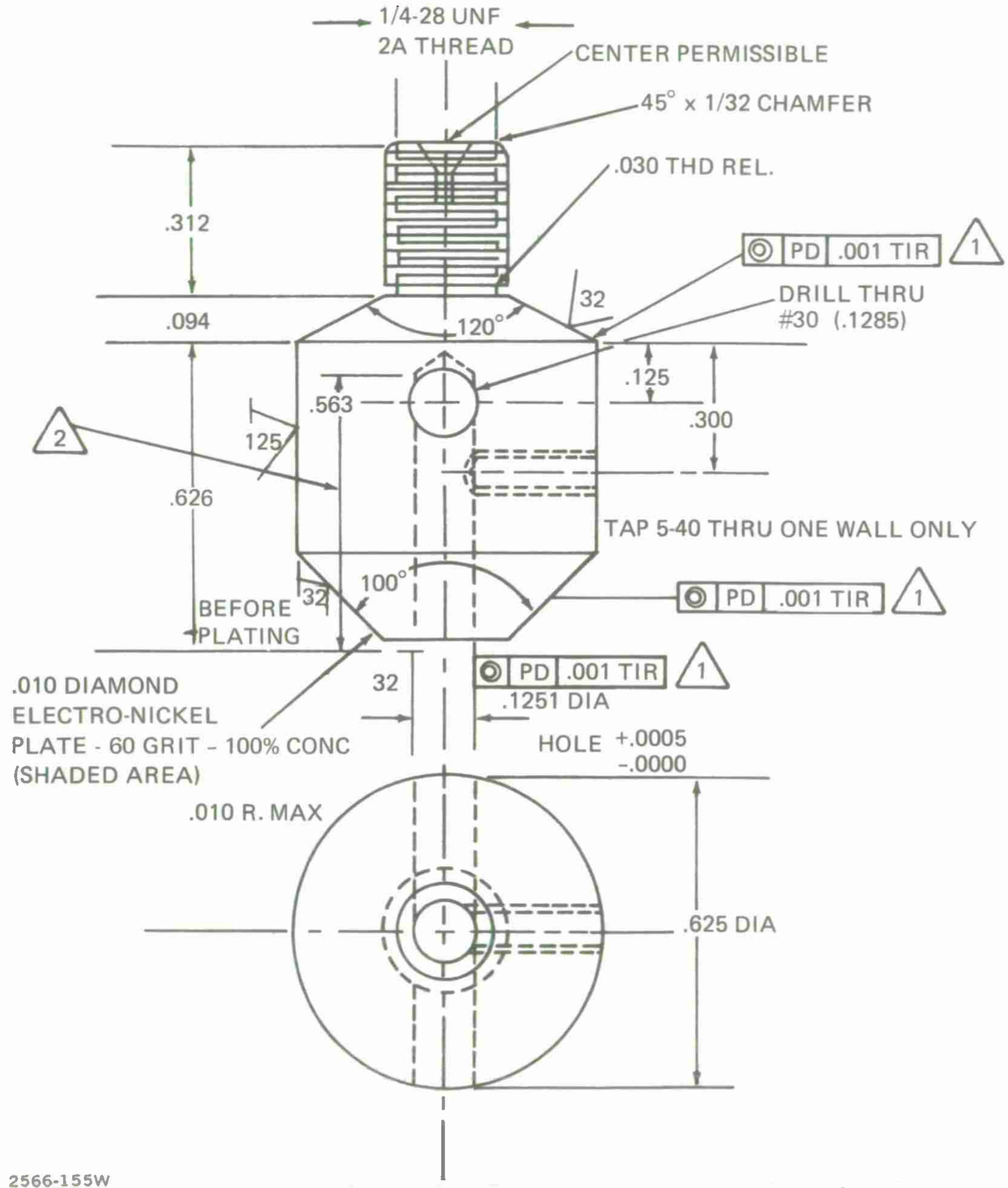
GEOMETRIC FEATURE

a) HELIX ANGLE 20° ± 1°
b) WEB AT POINT .050 ± .005 IN.
c) WEB TAPER .032 IN./IN.
d) C'SINK RELIEF = 18° ± 2°
e) MARGIN WIDTH .015 $^{+.010}_{-.005}$ IN.
f) DRILL POINT 135° ± 3°
g) NOTCH RAKE ANGLE 5° AXIAL ± 1°
h) POINT GEOMETRY PER GAC MFG. STD CD 2700-D11. EXCEPT POINT IS MODIFIED TO 135°

2566-154W

IDENT. NO. CSZ 114105

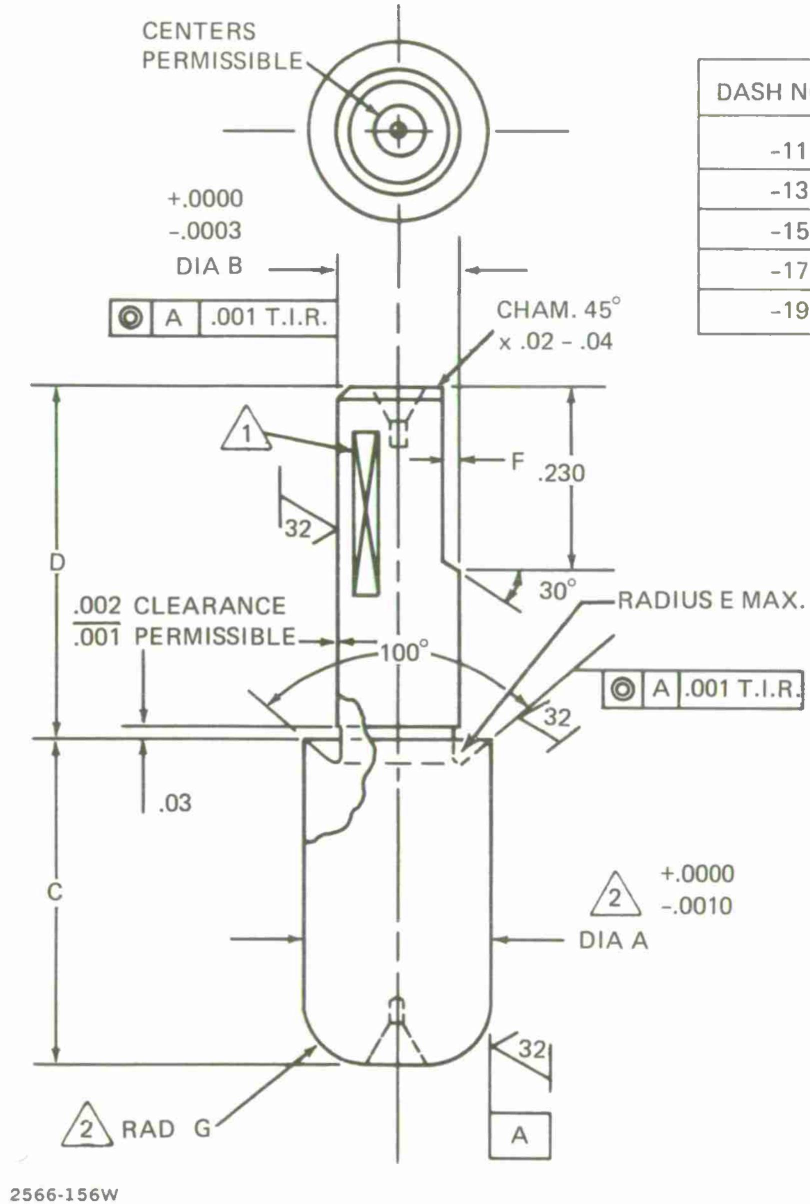
Figure 5-23 Carbide Combination Drill/Modified Countersink



NOTES:

1. MAX ECCENTRICITY TO BE .001 TIR FOR SURFACES INDICATED
2. VIBRO-ENGRAVE OR ETCH TOOL NO. WHERE SHOWN
3. MATL A151-4130

Figure 5-24 Diamond-Plated Countersink, (100°), Finishing Tool, Inserted Pilot and Threaded



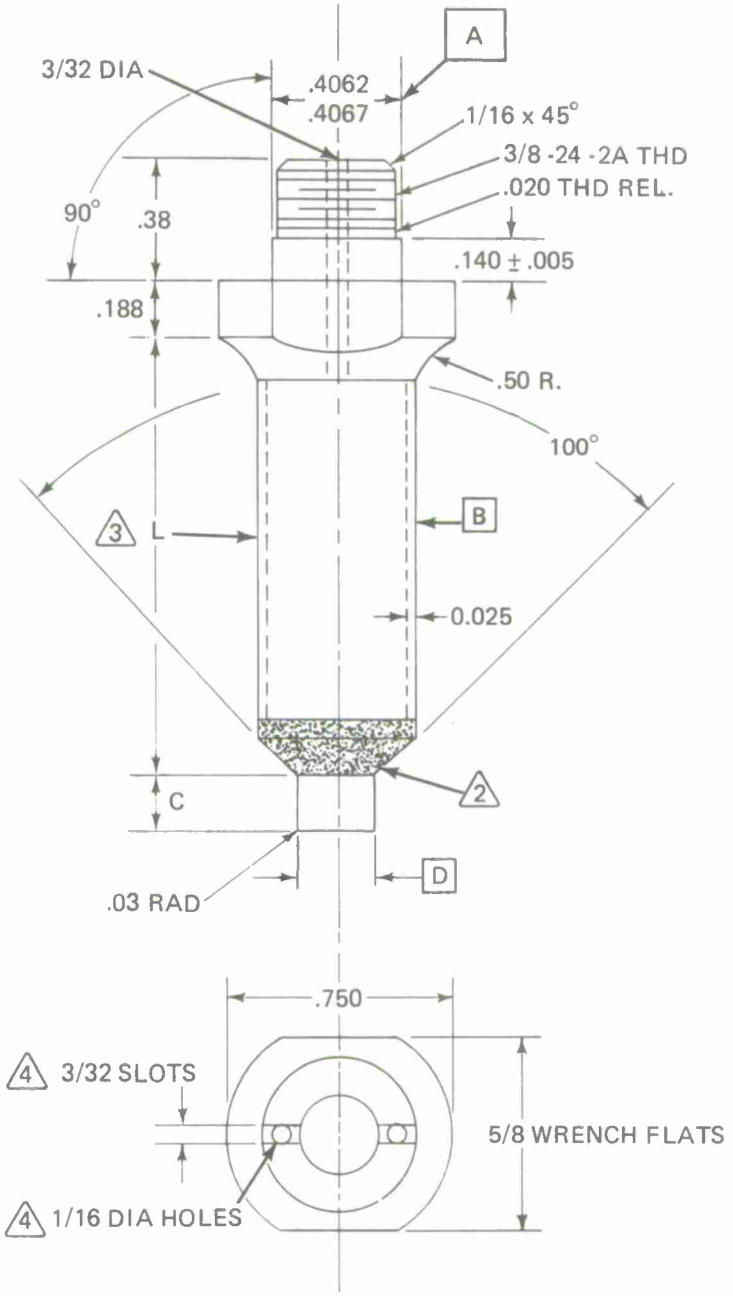
DASH NO.	DIA A	DIA B	C	D	RAD E	F	RAD G
-11	.164	.1250	.38	.44	.005	.025	.09
-13	.203	.1250	.38	.44	.005	.025	.09
-15	.250	.1250	.50	.44	.005	.025	.09
-17	.260	.1250	.50	.44	.005	.025	.09
-19	.266	.1250	.50	.44	.005	.025	.09

NOTES:

1. ACID ETCH TOOL NO. WHERE SHOWN.

2. HARDEN TO 35-42, THEN HARD CHROMIUM PLATE DIA A & RAD G TO .003-.005 DEPTH & BAKE @ 300/400°F FOR 3-4 HOURS TO AVOID HYDROGEN EMBRITTLEMENT. .003-.005 DEPTH OF CHROME PLATE MUST BE MAINTAINED AFTER GRINDING A DIA. MATL A151-4340

Figure 5-25 Pilot for Diamond Countersink



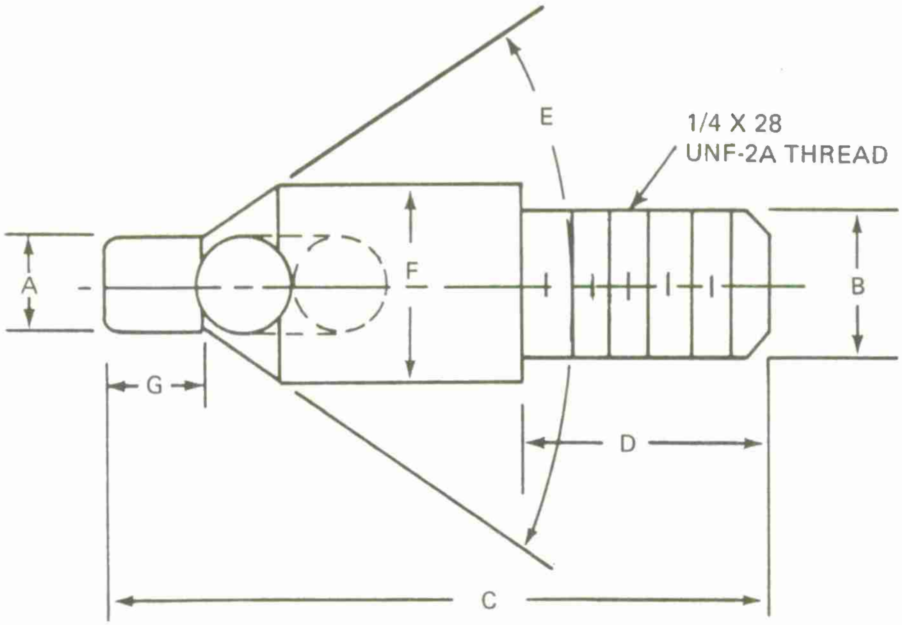
B	C	D	L	MANUFACTURER
0.510	0.38	0.250	0.63	CUT WELL OR LUNZER

NOTES

1. MAX ECCENTRICITY TO BE .001 T.I.R. FOR DIA'S A, B & D
2. DIAMOND GRIT – CONC 100, IMPREGNATED (SINTERED) APPROX KNOOP HARDNESS OF 4500 Kg/mm^2, ALT DIAMOND ELECTRO-NICKEL PLATE
3. L – LENGTH DEPENDS ON RESONANCE AND ACCESSIBILITY – RESONANCE IS 20 kHz
4. SLOTS AND COOLANT HOLES, 2 PLCS FOR LESS THAN 1/2 IN. DIA AND 3 PLCS FOR GREATER THAN 1/2 IN. DIA

2566-157W

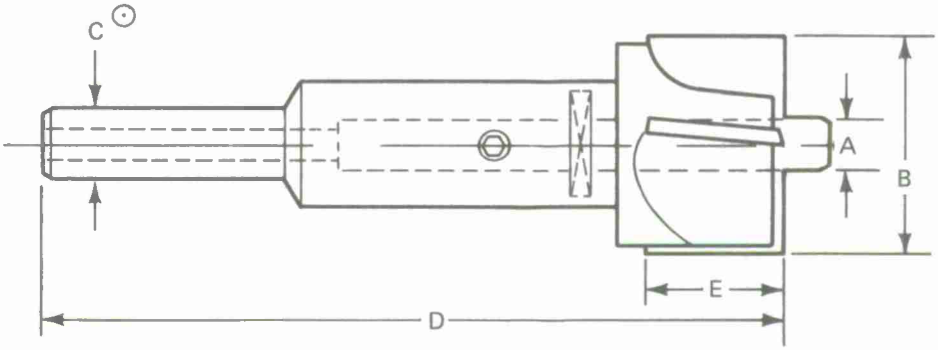
Figure 5-26 Diamond-Impregnated Countersink (100°), Ultrasonic for UMT-3 or UMT-5 Unit



A	B	C	D	E	F	G	MANUFACTURER
0.250	1/4-28 UNF	2.0	.312	100°	0.437	0.250	WELDON

2566-158W

Figure 5-27 HSS (Weldon) Countersink

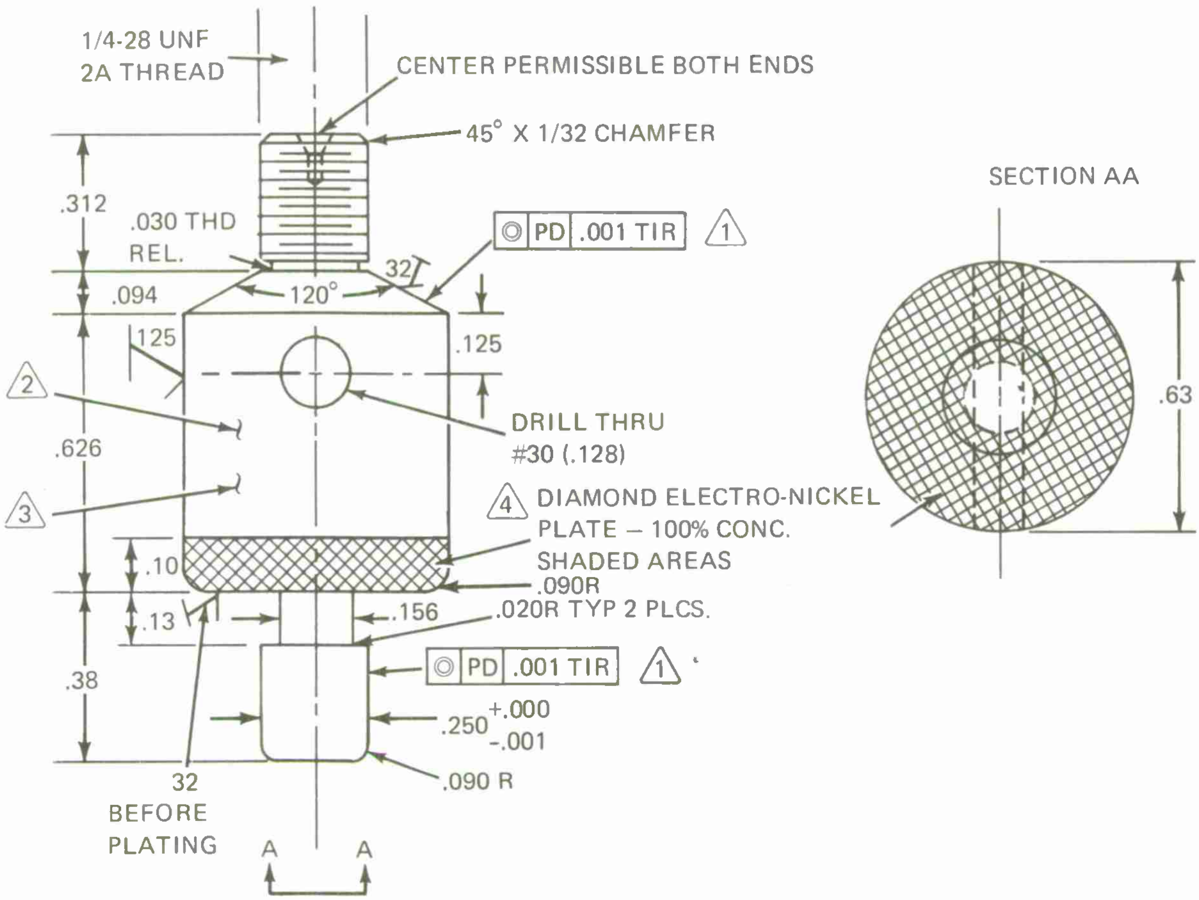


AXIAL RAKE - 5°
RADIAL RAKE - 5°
NO. OF FLUTES - 3

2566-159W

A	B	C	D	E
.250	.625	.250	2.75	.75

Figure 5-28 Carbide-Tipped, Three-Fluted Counterbore, Reduced Shank and Removable Pilot

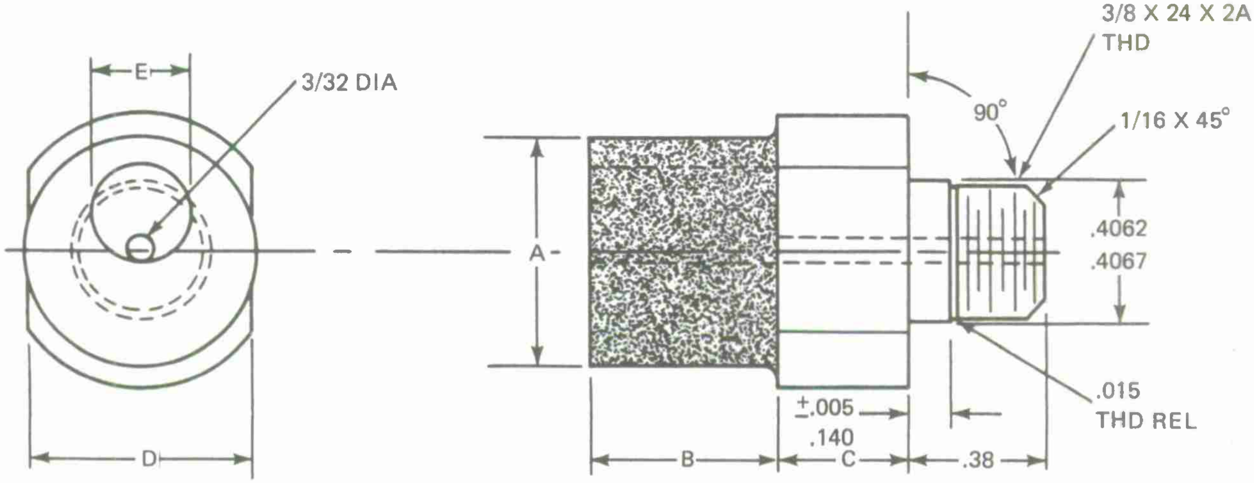


NOTES:

1. MAX ECCENTRICITY TO BE .001 T.I.R. FOR SURFACES INDICATED
2. VIBRO-ENGRAVE OR ETCH TOOL NO. WHERE SHOWN
3. H/T TO RC 50/53 – AIR HARDEN AND DRAW AT 900° F. MAT'L A-6
4. DIAMOND 40 GRIT FOR ROUGH COUNTERBORE, 80-100 GRIT FOR FINISHING

2566-160W

Figure 5-29 Diamond-Plated Counterbore, Piloted and Threaded



A	B	C	D	E	GRIT	MANUFACTURER
0.625	0.53	0.200	0.625	0.250	60-80	CUT WELL OR LUNZER

2566-161W

Figure 5-30 Diamond-Impregnated (Sintered) Counterbore

Section 6

CUTTING FLUIDS

6.1 GENERAL

The primary function of cutting fluids during cutting, machining or drilling of composites is to act as a coolant. Cutting composites with diamond tools generates heat. Since diamond tools are sensitive to the amount of heat generated, it is important to utilize a coolant. On the other hand, tool life of carbide drills used on graphite/epoxy is not increased by applying coolants. A secondary function of the cutting fluid is to minimize dust generation and/or flush away residue. Where metal/composite combinations are encountered, the cutting fluid may be required to cool the epoxy matrix and prevent thermal damage.

6.2 CUTTING FLUID TYPES

Water and water-soluble oils are probably the most common coolants used. The use of water alone is generally limited to diamond core drilling. Because some cutting fluids leave a compound residue, Freon is an acceptable alternative, particularly if required for an assembly drilling situation. Freon TB-1, Isopar-M and Hangsterfers HE-2 coolants have been tested and found to be a compatible with epoxy matrix composites.

6.3 APPLICATION RECOMMENDATIONS

The general forms of application are spray mist or flooding. The advantages of using spray mist are that spray mist is easily applied and a collection system is not required. Another form of cooling is forced fluid such as that encountered when pushing the coolant through diamond core drills. In this application, fluid chucks or special spindle fluid coupling adaptors can be used.

It is generally recommended that coolants be used with all forms of diamond cutting tools. It is also necessary to utilize a coolant for all diamond drilling applications if tool life is to be maximized.

The use of coolants, however, will not serve as a panacea for all operations. For example, drilling tests conducted on graphite/epoxy with both carbide-tipped drills and solid carbide drills at 6000 rpm and 0.001 ipr (actual feed) showed a slight decrease in tool life (about 15 percent). For this reason, the coolant recommendations outlined in Section 3 should be followed.

Section 7

QUALITY CONTROL AND NON-DESTRUCTIVE EVALUATION TECHNIQUES

7.1 PROCESS DAMAGE/INSPECTION CRITERIA

Flaws in composite materials can easily be generated by cutting, machining and drilling operations. These flaws may cause the part to be totally rejected or returned to manufacturing for costly repair. The types of damage that can occur are:

- Delamination - separation of the laminates
- Breakout - splintering of the material, usually at the drill exit surface or bottom surface of the cut
- Microcrack - intra-laminate cracks, usually 0.080 to 0.400 inch (maximum) in length
- Fiber/resin pullout - tearing out of resin or fiber from drilled, cut or machined surfaces
- Shreading - fraying of the top, middle or bottom surface leaving material unsightly and difficult to inspect for flaws.

Recent structural tests have shown that flaws such as delaminations as large as 1/2 x 1/2 inch can be tolerated in certain composite designs. Should design requirements be such that smaller flaws cannot be tolerated, several nondestructive evaluation methods may be used to find them.

Figure 7-1 shows the types of flaws that can occur in four different composite materials and the suggested NDE methods for evaluating these flaws.

Figure 7-2 shows the severity of flaws that can occur as a result of certain operations. The depth of the flaw is measured from the hole or part edge to the furthest distance the delamination or crack has progressed. Additional information on the speeds and feeds that cause these flaws can be found in Appendix A. The NDE methods used for detecting the flaws are listed below. A brief description of the methods and their limitations are contained in Figure 7-3. It is recommended that designs be formulated so that small microcracks, resin/fiber pull-out and minor breakout flaws need not be required as part of the inspection procedure; this would eliminate boroscope and dye-penetrant requirements.

		PHASE I				PHASE II	PHASE III				PHASE IV			
		CUTTING				DRILLING	MACHINING				NONDESTRUCTIVE EVALUATION METHOD			
MATERIAL	DAMAGE	RADIAL SAW	BAND SAW	WATER JET	HAND RADIAL SAW	DRILLING	HAND ROUTE	COUNTER SINK	HAND TRIM	COUNTER BORE	TRACER FLUOROSCOPY	DYE PENETRANT	FIBER OPTICS/ BOROSCOPE	VIDEO SCAN
GRAPHITE/EPOXY KEVLAR/EPOXY	DE-LAMINATION			X	X		X	X	X		X			X
	BREAKOUT		X								X			X
	MICRO CRACKS						X				X	X	X	
	FIBER/RESIN PULLOUT													
	SHREDDING			X	X		X	X		X				X
FIBERGLASS/ EPOXY	DE-LAMINATION							X		X	X			X
	BREAKOUT													
	MICRO CRACKS													
	FIBER/RESIN PULLOUT													
	SHREDDING													
GRAPHITE & FIBERGLASS/ EPOXY	DE-LAMINATION		X	X	X		X			X	X			X
	BREAKOUT		X								X			
	MICRO-CRACKS		X								X	X	X	
	FIBER/RESIN PULLOUT		X	X							X		X	
	SHREDDING			X										X
GRAPHITE/EPOXY	DE-LAMINATION			X		X	X				X			X
	BREAKOUT	X	X			X	X				X			X
	MICRO-CRACKS		X								X	X	X	
	FIBER/RESIN PULLOUT	X				X					X		X	
	SHREDDING													
GRAPHITE/EPOXY & BORON/ EPOXY	DE-LAMINATION		X	X		X					X			X
	BREAKOUT	X				X					X			X
	MICRO-CRACKS			X							X	X	X	
	FIBER/RESIN PULLOUT	X	X	X		X					X		X	
	SHREDDING													
BORON/EPOXY	DE-LAMINATION			X							X			X
	BREAKOUT	X	X								X			
	MICRO-CRACKS													
	FIBER/RESIN PULLOUT	X									X		X	
	SHREDDING													
KEVLAR/ EPOXY	DE-LAMINATION		X		X	X		X	X		X			X
	BREAKOUT					X					X			
	MICRO-CRACKS													
	FIBER/RESIN PULLOUT													
	SHREDDING				X	X		X						X

2199-060B

Figure 7-1 Induced Flaws and NDE Detection Methods

OPERATION	TYPE AND DEPTH OF FLAW (INCH)				
	DELAMI-NATION	BREAKOUT	MICRO-CRACKS	PULLOUT FIBER/RESIN	SHREADING
CUTTING					
RADIAL SAW	NONE	MINOR	NONE	0.001 – 003	NONE
BANDSAW	0.0 – 0.080	0 – 0.120	0.0 – 0.60	0.001 –.003	BOTTOM PLIES
WATER-JET	0 – 0.300	MINOR	MINOR	MINOR	BOTTOM PLIES
HAND RADIAL SAW	0.0 – 0.125	NONE	MINOR	MINOR	NONE
MACHINING					
HAND ROUTING	0.0 – 0.030	MINOR	MINOR	MINOR	TOP AND BOTTOM PLIES; PROBLEM WITH KEVLAR
ROUTING	0.0 – 0.070	MINOR	TRANSVERSE CRACKS	MINOR	TOP AND BOTTOM PLIES
HAND TRIMMING	0.0 – 0.090	MINOR	TRANSVERSE CRACKS	MINOR	MINOR
COUNTERBORING	0.0 – 0.040	NONE	NONE	NONE	NONE; KEVLAR POSSIBLE
COUNTERSINKING	MINOR 0.005	NONE	NONE	NONE	TOP PLY WITH KEVLAR
DRILLING	0.0 – 0.270	MAJOR PROBLEM	MINOR	0.001 –.003	NONE

2199-061B

Figure 7-2 Severity of Flaws From Machining Operations

NDE METHOD	MATERIALS REQUIRED	TYPE OF FLAWS FOUND	LIMITATIONS
VISUAL	BOROSCOPE, FLASHLIGHT, MIRROR, 10X HAND LENS	SURFACE DELAMINATIONS, RESIN/FIBER PULLOUT, BREAKOUT, MICROCRACKS, SHREADING	EVALUATION SUBJECTIVE: CONFUSE TOOL MARKS WITH FLAWS; TIME-CONSUMING
TRACER FLUOROS-COPY	TRACER (DI-IODOBUTANE) X-RAY GENERATION SOURCE, TV CAMERA, VIDEO DISPLAY, SAFETY PROCEDURES	DELAMINATIONS, BREAK-OUT	FIND CRACKS AND DELAMINATIONS 0.010 AND LARGER. SURFACE FRAYING CAN GIVE FALSE POSITIVES
DYE PENETRANT	WATER-WASHABLE PENE-TRANT, SELF-DRYING DEVELOPER, SOLVENT, BLACKLIGHT	MICROCRACKS, DELAMI-NATIONS, FIBER/RESIN PULLOUT	VERY SENSITIVE; USE FOR SMALL CRACKS, TOOL MARKS AND KEVLAR INTERFERE; INTERPRETATION SUBJECTIVE, TIME-CONSUMING

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Figure 7-3 NDE Methods For Finding Flaws In Composite Edges

7.2 QUALITY INSPECTION PROCESS PROCEDURE - TRACER FLUOROSCOPY

This section describes an automated inspection procedure for detecting flaws produced during cutting, machining or drilling of composites.

7.2.1 Introduction

This procedure outlines the requirements for detecting flaws such as cracks or delaminations occurring in composite materials as a result of cutting, machining or drilling operations. The instructions herein apply to composites such as graphite/epoxy, fiberglass/epoxy, graphite/epoxy plus boron/epoxy and other hybrids. The flaws caused by cutting, machining and drilling operations originate at composite edges or holes and consequently lend themselves to tracer fluoroscopy evaluation. The concept may be integrated into an automated inspection system.

7.2.2 Related Documents

- MIL-STD-453 - Inspection, Radiographic
- XXXX-XX - Related process specification for certification of radiographers
- XXXX-XX - Applicable operator manuals for video scanning and display systems
- XXXX-XX - Applicable processing specification stating defect allowable criteria.

7.2.3 Implementation

7.2.3.1 Requirements

7.2.3.1.1 Work Areas - Work areas wherein tracer fluoroscopy is to be performed shall adhere to the premises, equipment and safety requirements of MIL-STD-453.

7.2.3.1.2 Personnel - Personnel performing tracer fluoroscopy shall be certified for radiographic inspection per applicable military or company specifications. Personnel shall also be instructed in the care, use and handling of tracer material as well as following the safety recommendations of the material supplier.

7.2.3.1.3 Materials and Equipment

Test samples of the same composite material and thickness as that being tested shall be prepared by drilling and/or cutting. Flaws such as delaminations shall be placed into the composites so they emanate from the hole or cut composite edge. The size of the test sample flaws shall be such that they can be detected by the tracer fluoroscopy system with a degree of confidence required by design considerations.

X-Ray Source - A portable x-ray unit with a beryllium window is recommended. Voltage output requirements should range from 10 to 110 KV and 5 MA with stepless KV and MA.

T.V. Camera -

Fluoroscopy Screens -

Video Tape System - a video tape system, capable of operating off a video display is recommended if a permanent record of flaws detected is required.

Tracer Material - the tracer material recommended is 1, 4 diiodobutane (DIB), chemical formula, $I(CH_2)_4I$, specific gravity 2.3.

Miscellaneous - rubber gloves, aspirator, cotton swabs, lead identification tape, wiping cloths.

7.2.3.2 Testing Procedure

7.2.3.2.1 Application of Tracer Material

- Tracer solution shall be applied with a cotton swab or similar applicator and shall adequately wet the composite edge or hole so that sufficient liquid is present to penetrate the flawed area.
- Tracer solution which runs down the side of the composite from the edge or hole shall be wiped dry immediately so as not to cause false positive indications.
- When applying the tracer, personnel shall wear rubber gloves, work in a well ventilated area, wear an aspirator especially if considerable DIB is used.
- Tracer material will be effective within two minutes and retain most of its absorption characteristics up to six hours. No evidence of tracer is usually seen after 24 hours and the material evaporates within 48 hours.

7.2.3.2.2 Mark Area

- Each hole or edge shall be marked and identified with lead tape or other effective radiographic marking procedure so as to maintain adequate traceability to the part and materials.
- Acceptable parts which have satisfactorily met the applicable inspection requirements shall be marked in a manner and location harmless to the part and which shall preclude removal, smearing or obliteration by subsequent handling.

7.2.3.2.3 Fluoroscopic Inspection

- Arrange work piece, X-ray generation source, fluoroscopic screen, TV camera and video output display.

- If fluoroscopy is being undertaken in an exposed area, shielding of the X-ray source and subsequent radiation scatter monitoring must be accomplished. Subsequent radiation leakage checks should be made with appropriate Geiger counters.
- Calibrate system by applying DIB Tracer onto standard and establishing correct voltage of the system to adequately observe the flaw in the standard. Note voltage and distance settings for the standard.
- Set image enhancement controls to give best contrast and edge enhancement of the flawed area. Note settings of video display system and remove composite standard.
- Place composite structure into fixture for automated system, or into fluoroscopy unit for manual inspection. Check setting from standard and proceed to inspect composite. Note flaws from video monitor.
- Record video monitor data onto video tape machine should permanent records of the flaws be needed.
- Calibrate the system with the composite standard after each appropriate production run.

Section 8

SAFETY

Composite materials are composed of small-diameter fibers in an epoxy matrix. When subjected to cutting, drilling, or machining operation, composite materials can produce dust or slivers. Safety and health requirements for composites to avoid potential hazards are described below.

8.1 INHALATION HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application - Curing, Laser Cutting, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Local Exhaust Ventilation Enclosures, Barriers, Wet Machining Methods, Limited Exposure Time, Respirators, Medical Surveillance, Periodic Exposure Testing, Training, Vacuum Facility for Waste Collection.

8.2 SKIN CONTACT HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Local Exhaust Ventilation Enclosures, Barriers, Wet Machining Methods, Special Washing Facilities, Emergency Showers, Gloves, Sleeves, Aprons or Smocks, Barrier Creams, Medical Surveillance, Training.

8.3 INGESTION HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Eating, Drinking, and Smoking away from Work Station, Good Personal Hygiene.

8.4 SIGHT HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application - Curing, Laser Cutting, Radio Frequency Curing, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Sight Protection Devices, Emergency Eye Wash Facility, Medical Surveillance, Shielding, Periodic Exposure Testing, Interlocked Facilities.

8.5 BURN HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application, Laser Cutting, Radio Frequency Curing.

Control Measures: Enclosures, Barriers, Emergency Showers, Gloves, Sleeves, Aprons or Smocks, Barrier Creams, Medical Surveillance, Training, Shielding, Interlocked Facilities.

8.6 FIRE HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material - Mixing - Application - Curing, Laser Cutting, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Wet Collection Systems for Exhaust Systems, Special Storage and Dispensing, Training, Emergency Fire Procedures, Automatic and Manual Fire Equipment, Specially Designed Facilities.

8.7 HEARING HAZARDS

Typical Operations: Sanding, Routing, Grinding, Drilling, Sawing, Polishing.

Control Measures: Acoustically Treated Facilities, Special Tools and Equipment, Limited Exposure Time, Personal Protective Equipment, Audiometric Testing, Periodic Exposure Monitoring.

8.8 WASTE HAZARDS

Typical Operations: General Cleaning, Chemical Treatment, Material Application, Laser Cutting, Sanding, Routing, Grinding, Drilling, Sawing, and Polishing.

Control Measures: Segregation, Special Containers, and Labeling.

8.9 RADIATION HAZARDS

Typical Operations: Radiographic or Fluoroscopic Inspection

Control Measures: Limited-Access Area, Personal Dosimeters, Medical Surveillance and Interlocked Facilities

Section 9

COST ANALYSES

9.1 GENERAL

Reliable cost analyses require several key ingredients including good machining parameters, the relationship of tool life to these machining parameters, and valid cost equations which describe the process. This section defines the required equations and gives illustrative examples of application. It should also be pointed out that accurate prediction of tool life data requires an extensive data base which obviously could not be generated within the scope of one program. The tool life data presented within this manual should, therefore, be treated as initial data points for subsequent expansion and trend development.

9.2 COST EQUATIONS

Equations that can be used to calculate recurring costs for various material removal processes are described. These equations represent derivations from the standard cost equations developed by the Machinability Data Center.

9.2.1 Radial Sawing and Bandsawing

$$C = M\left[\underbrace{\frac{L}{V_1}}_{\text{FEED TIME}} + \underbrace{\frac{Lh\ Tw\ Td}{T_M}}_{\text{DULL TOOL REPLACEMENT TIME}}\right] + \frac{Lh\ Tw}{T_M}\left[\underbrace{\frac{Cp}{(K_1+1)}}_{\text{TOOL DEPRECIATION COST}} + \underbrace{C_R}_{\text{TOOL RE-CONDITIONING COST}}\right]$$

9.2.2 Laser Cutting

$$C = M\left[\underbrace{\frac{L}{V_1}}_{\text{FEED TIME}}\right] \underbrace{\frac{1}{E}}_{\text{UTILIZATION RATE}} + \underbrace{\frac{L}{V}\left[\dot{m}\ Cg\right]}_{\text{ASSIST GAS COST}}$$

9.2.3 Water Jet Cutting

$$C = M \underbrace{\left[\frac{L}{V_1}\right]}_{\text{FEED TIME}} \underbrace{\frac{1}{E}}_{\text{UTILIZATION RATE}}$$

9.2.4 Reciprocating Mechanical Cutting

$$C = M \underbrace{\left[\frac{L}{V_1}\right]}_{\text{FEED TIME}} \underbrace{\frac{1}{E}}_{\text{UTILIZATION RATE}} + \frac{L}{T_t} \left[\underbrace{\frac{Cp}{(K_1 + 1)}}_{\text{TOOL DEPRECIATION COST}} + \underbrace{C_R}_{\text{TOOL RECONDITION COST}}\right]$$

9.2.5 Blanking

$$C = M \left[\underbrace{t_L}_{\text{LOAD UNLOAD COST}} + \underbrace{\frac{to}{N_L}}_{\text{SETUP COST}}\right] + \underbrace{\frac{Cp}{K_4}}_{\text{TOOL DEPRECIATION COST}}$$

9.2.6 Drilling

$$C = M \left[\underbrace{\frac{D(L+e)}{3.82 f_r V}}_{\text{FEED COST}} + \underbrace{\frac{LD t_d}{3.82 f_r T_L}}_{\text{DULL TOOL REPLACEMENT COST}}\right] + \frac{LD}{3.82 f_r T_L} \left[\underbrace{\frac{Cp}{(K_1 + 1)}}_{\text{TOOL DEPRECIATION COSTS}} + \underbrace{C_R}_{\text{RECONDITION COST}}\right]$$

9.2.7 Routing, Trimming and Beveling

$$C = M \left[\underbrace{\frac{L}{V_1}}_{\text{FEED TIME}} + \underbrace{\frac{Lh\,Tw\,td}{T_M}}_{\text{DULL TOOL REPLACEMENT TIME}}\right] + \frac{Lh\,Tw}{T_M} \left[\underbrace{\frac{Cp}{(K_1 + 1)}}_{\text{TOOL DEPRECIATION COST}} + \underbrace{C_R}_{\text{TOOL RECONDITIONING COST}}\right]$$

A listing of symbols for cost equations is given in Figure 9-1.

SYMBOL	DEFINITION
C	COST FOR MACHINING ONE WORKPIECE; $/WORKPIECE
C_g	COST OF LASER ASSIST GAS; $/POUND
C_p	PURCHASE COST OF TOOL OR CUTTER; $/CUTTER
C_R	TOOL RECONDITIONING COST; $
D	DIA. OF WORK IN TURNING OF TOOL IN MILLING, DRILLING, REAMING, TAPPING; INCHES
e	EXTRA TRAVEL AT FEEDRATE (f_r OR f_t) INCLUDING APPROACH, OVERTRAVEL, AND ALL POSITIONING MOVES; INCHES.
E	UTILIZATION RATE; PERCENT/100
f_r	FEED PER REVOLUTION; IN./REV.
h	MATERIAL THICKNESS; INCHES
K_1	NO. OF TIMES TOOL, OR DRILL, OR REAMER IS RESHARPENED BEFORE BEING DISCARDED
K_4	TOTAL NUMBER OF PARTS TO BE MADE ON TOOL
L	LENGTH OF WORKPIECE IN TURNING AND MILLING OR SUM OF LENGTH OF ALL HOLES OF SAME DIAMETER IN DRILLING, REAMING, TAPPING; INCHES.
$\dot{m}$	LASER ASSIST GAS FLOW RATE; POUNDS/MINUTE
M	LABOR + OVERHEAD COST ON LATHE, MILLING MACHINE OR DRILLING MACHINE; $/MIN.
M_F	LABOR + OVERHEAD FOR TOOL FABRICATION; $/MIN.
N_L	NO. OF WORKPIECES IN LOT
t_d	TIME TO REPLACE DULL CUTTER IN TOOL CHANGER STORAGE UNIT; MIN.
t_L	TIME TO LOAD AND UNLOAD WORKPIECE; MIN.
t_o	TIME TO SETUP MACHINE TOOL FOR OPERATION; MIN.
t_s	TIME TO RESHARPEN LATHE TOOL, MILLING CUTTER, DRILL, REAMER OR TAP; MIN./TOOL
T_L	TOOL LIFE IN CIRCUMFERENTIAL TRAVEL; FEET
T_M	TOOL LIFE MEASURED IN MAXIMUM TOOL WIDTH OR DIAMETRAL WEAR; INCHES
T_W	TOOL WEAR RATE FOR CROSS SECTIONAL AREA CUT; IN/IN^2
T_t	TOOL LIFE MEASURED IN INCHES TRAVEL OF WORK OR TOOL TO DULL A DRILL, REAMER, TAP OR ONE MILLING CUTTER TOOTH; IN.
V	CUTTING SPEED; FT/MIN.
V_1	FEED; INCHES/MINUTE

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Figure 9-1 Symbols for Cost Equations

9.3 CUTTING TOOL COST

Representative costs of selected cutting tools are presented in Figures 9-2 and 9-3.

9.4 USE OF COST EQUATIONS

The establishment of parametric process data, as presented in the previous sections, allows for the comparative analyses of various approaches. To illustrate how this data can be utilized, a series of manufacturing problems are presented within which a series of alternatives are exercised.

9.4.1 Problem No. 1:

To cut a contour pattern in graphite/epoxy prepreg for single-ply quantities, and multiple-ply quantities of 6 and 12. The trimmed periphery is specified at 200 inches.

Alternatives:

- Manual trimming with knife
- N/C water-jet trimming (55 ksi)
- N/C laser trimming (250 and 500 watts)
- N/C reciprocating cutter (Gerber System 90)

Assumptions:

- Maximum cutting speed is 600 ipm (due to machine dynamics)
- Average cutting speed is 2/3 of maximum
- Set-up time is not included for various alternatives
- Manual trimming cannot be accomplished in stack-ply quantities

Solution:

Manual trimming costs were based on actual average trimming costs for a horizontal stabilizer. Feedrates for water-jet, laser, and reciprocating cutting were obtained from Section 2.0. Based upon these feedrates, total cutting time was established and burdened at \$25 per hour for labor and \$25 per hour for equipment. Maintenance and supply costs of \$3.00, \$0.60, and \$0.36-per hour were used for water-jet, laser and reciprocating cutting, respectively. Inert cutting gas consumption and cutter wear were included as miscellaneous costs. For the illustrative problem, comparative trimming costs are shown in Figure 9-4 based upon a 30-percent machine duty cycle.

PROCESS	TOOL DESCRIPTION	COST, $
RADIAL SAW (STATIONARY)	• 60-GRIT, DIAMOND-PLATED, 8-INCH-DIAMETER X 3/32-INCH-THICK (WITH OR WITHOUT SIDES GROUND)	98.60
	• MEDIUM-GRIT TUNGSTEN CARBIDE, 6.5-INCH-DIAMETER	33.50
	• HSS, 126 STRAIGHT-BACKED TEETH, 8-INCH-DIAMETER	34.15
RADIAL SAW (PORTABLE)	• 60-GRIT, DIAMOND-PLATED, 3-INCH-DIAMETER X 3/32-INCH-THICK	40.00 (1)
	• 40-GRIT, DIAMOND-PLATED, 3-INCH-DIAMETER X 3/32-INCH-THICK	40.00 (2)
BANDSAW	• MEDIUM-GRIT, TUNGSTEN CARBIDE, 1/2-IN. X 13.5-FT. LONG	61.58 (2)
	• 60-80-GRIT DIAMOND-PLATED, 1/4 OR 1/2-INCH-WIDE	28.00/FT.
ROUTING	• CARBIDE, 1/4-INCH-DIAMETER, DIAMOND CUT	5.30 (3)

NOTES: (1) UNIT COST FOR 15-PIECE QUANTITIES
(2) UNIT COST FOR 36-PIECE QUANTITIES
(3) UNIT COST FOR 500-PIECE QUANTITIES

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Figure 9-2 Purchase Cost Of Cutting Tools

TYPE OF TOOL	MATERIAL	SIZE, IN.	PURCHASE COST, $	RECONDITIONING COST	AVERAGE NUMBER OF RESHARPENINGS
TWIST DRILL	HSS	1/8	0.59	30%	NONE
		3/16	0.59	TO	NONE
		1/4	0.80	40%	NONE
DR/CSK (WINSLOW)		3/16	16.00	OF	NONE
PILOT C'SINK		7/16	2.80	ORIGINAL	NONE
REAMER		3/16	3.00	COST	NONE
		1/8	5.58		1-2
TWIST DRILL	CARBIDE-TIPPED	3/16	8.98	MAX. 50%	1-2
		1/4	9.03	OF	1-2
REAMER		1/2	17.15	ORIGINAL	1-2
		1/4	11.59	COST	1
TWIST DRILL	SOLID CARBIDE	1/8 (.1285)	7.34	MAX. 50%	2
		3/16 (.190)	10.65	OF	2
		1/4	12.22	ORIGINAL	2
DR/C'SINK DRIVMATIC (WINSLOW)		3/16	35.00	COST	2
PILOT C'SINK,		7/16	14.03		2
REAMER		3/16	30.00		1
U/S CORE DRILL	METAL MATRIX (SINTERED)	3/16	55.00		4
		1/4	60.00	MAX.	4
		1/2	75.00		4
U/S DRILL/C'SINK	METAL MATRIX/ PLATED	3/16 (.190)	65.00	OF	4
		1/4	75.00		4
		1/2	90.00	50% OF	4
U/S C'SINK, DIAMOND		5/8	35.00		4
STD. DIAM. CORE DR.		3/16	30.00	ORIGINAL	4
		1/4	35.00		4
		1/2	45.00	COST	4

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NOTE: PRICES ARE AVERAGE AND VARY WITH LOT SIZE, MARKET CONDITIONS, ETC.

Figure 9-3 Cutting Tool Cost Summary

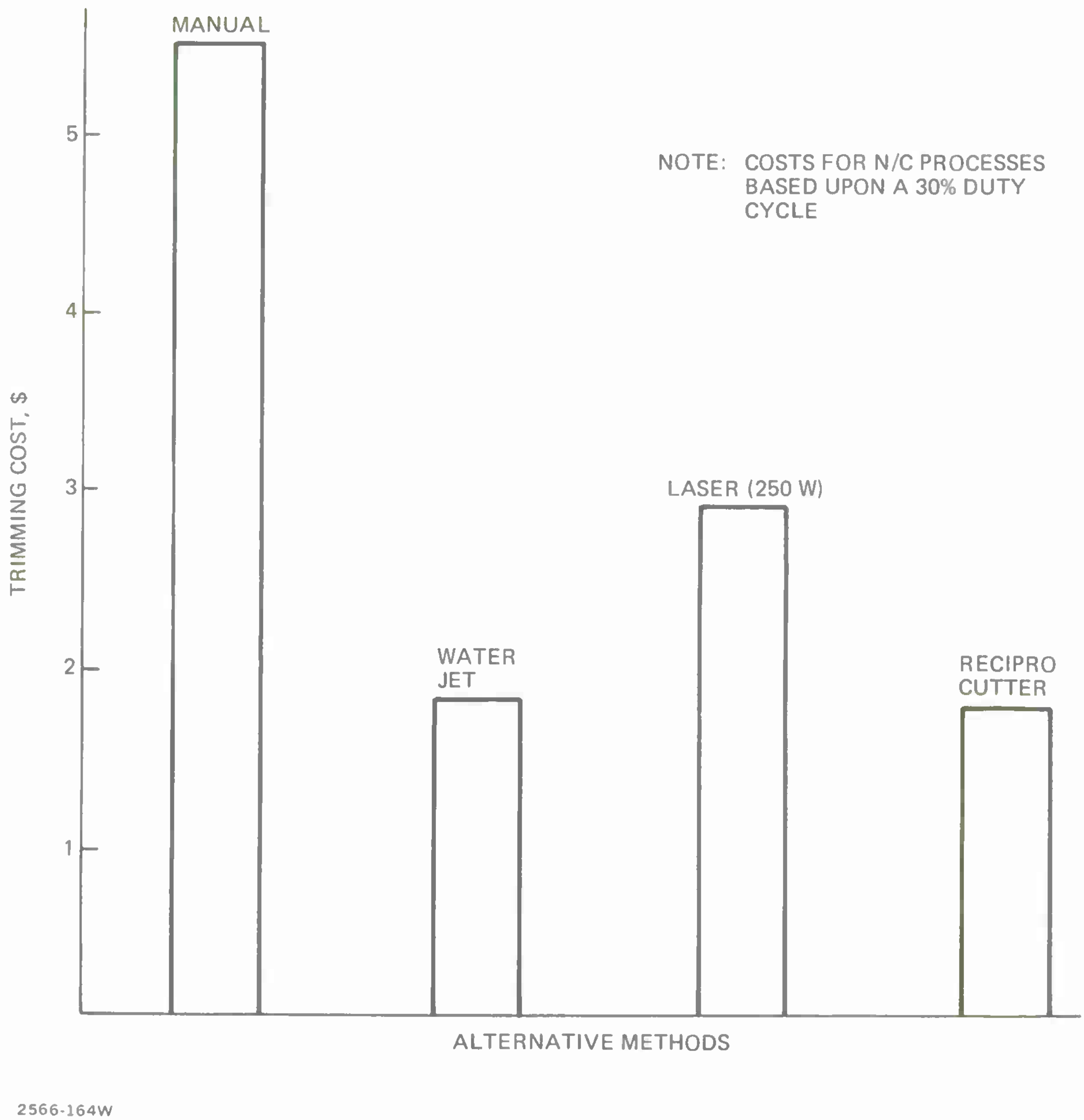

Figure 9-4 Comparative Costs for Trimming 200 Inches of Uncured Graphite/Epoxy Periphery

Another consideration in selecting a programmable process over a manual one is equipment utilization. For the selected trimming problem, all three programmable systems are shown to be more cost-effective than manual trimming at utilization rates of at least 15 percent (see Figure 9-5).

9.4.2 Problem No. 2:

To trim a contour pattern in a 0.125-inch-thick graphite/epoxy part with a total perimeter length of cut of 120 inches. The part is relatively flat (beam or rib edge) and requires crack-free edges.

Alternatives:

- Manual routing
- Rough bandsaw trim within 0.12 inch and rout net
- Water-jet cut
- Water-jet cut within 0.12 inch and then rout to net trim
- Portable-saw net over 90 percent of perimeter and final 10-percent hand rout
- Machine rout

Assumptions:

- Maximum carbide router tool life per cut is 0.0015-inch diametral wear
- Three cutting positions per router bit before changing
- Maximum bandsaw wear life is 0.008 inch
- Maximum radial saw diametral wear life is 0.015 inch
- Setup times for manual and machine operations are 1.2 and 3.0 minutes, respectively

Solution:

Typical cutting rates and tool wear rates for each approach were selected from Section 3.0. Based on part geometry and cut description, set-up and handling times were obtained using the Advanced Composite Cost Estimating Manual as a guideline. Costs were compiled and plotted in Figure 9-6. It should be noted that amortized equipment costs are not included in Figure 9-6.

If water-jet cutting were capable of producing a crack-free edge, it would appear to be very attractive; but such is not the case based upon current technology for graphite/epoxy. Therefore, a post-processing treatment, such as router trimming, must be added and unfavorable costs result. The most effective means of trimming appears to be routing, with machine routing (not including amortized equipment cost) having an advantage over manual routing due to slightly increased tool life. Also interesting to note is the comparison of

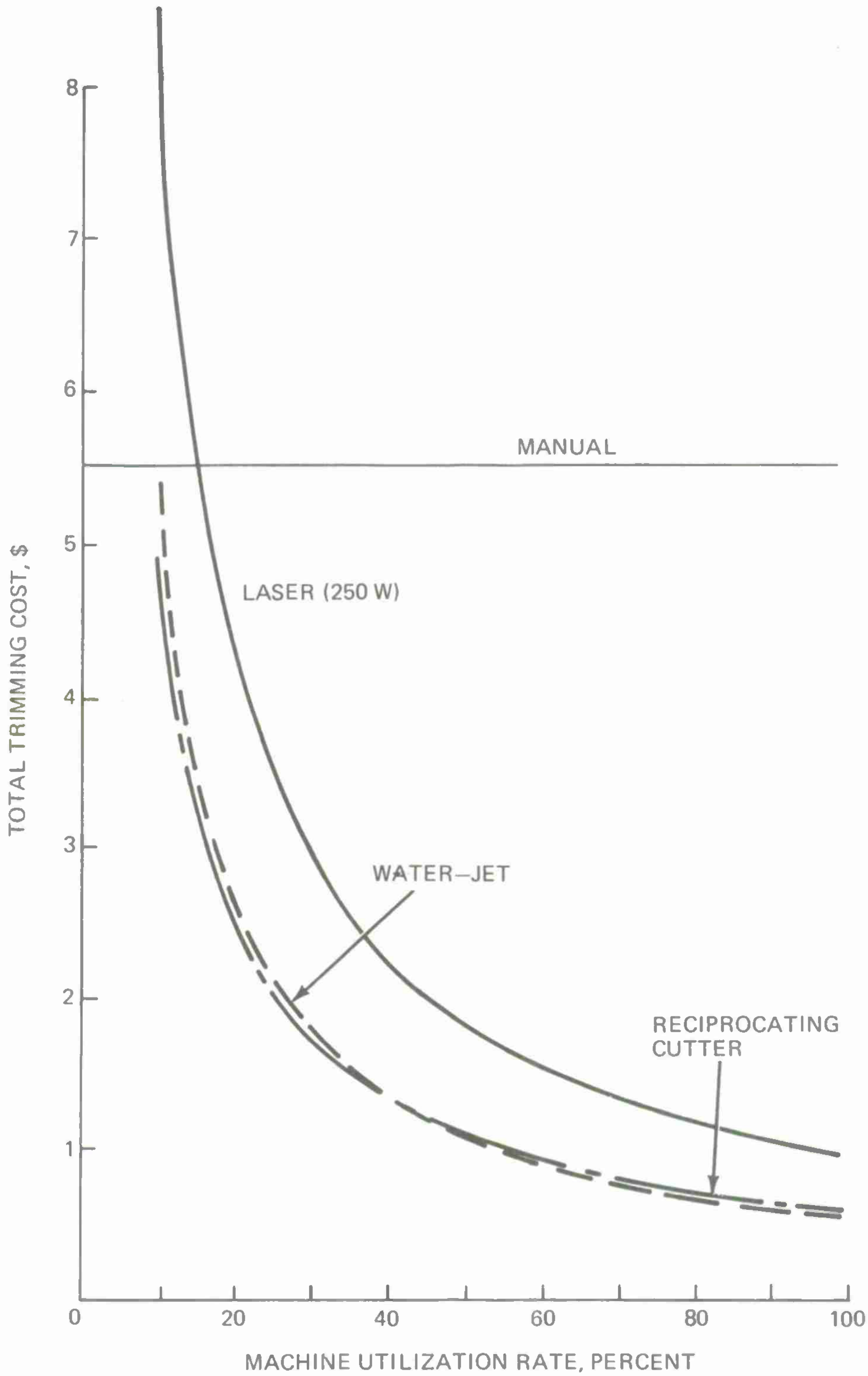

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Figure 9-5 Cost Comparison for Trimming a Single-Ply Graphite/Epoxy Prepreg with 200-Inch Periphery

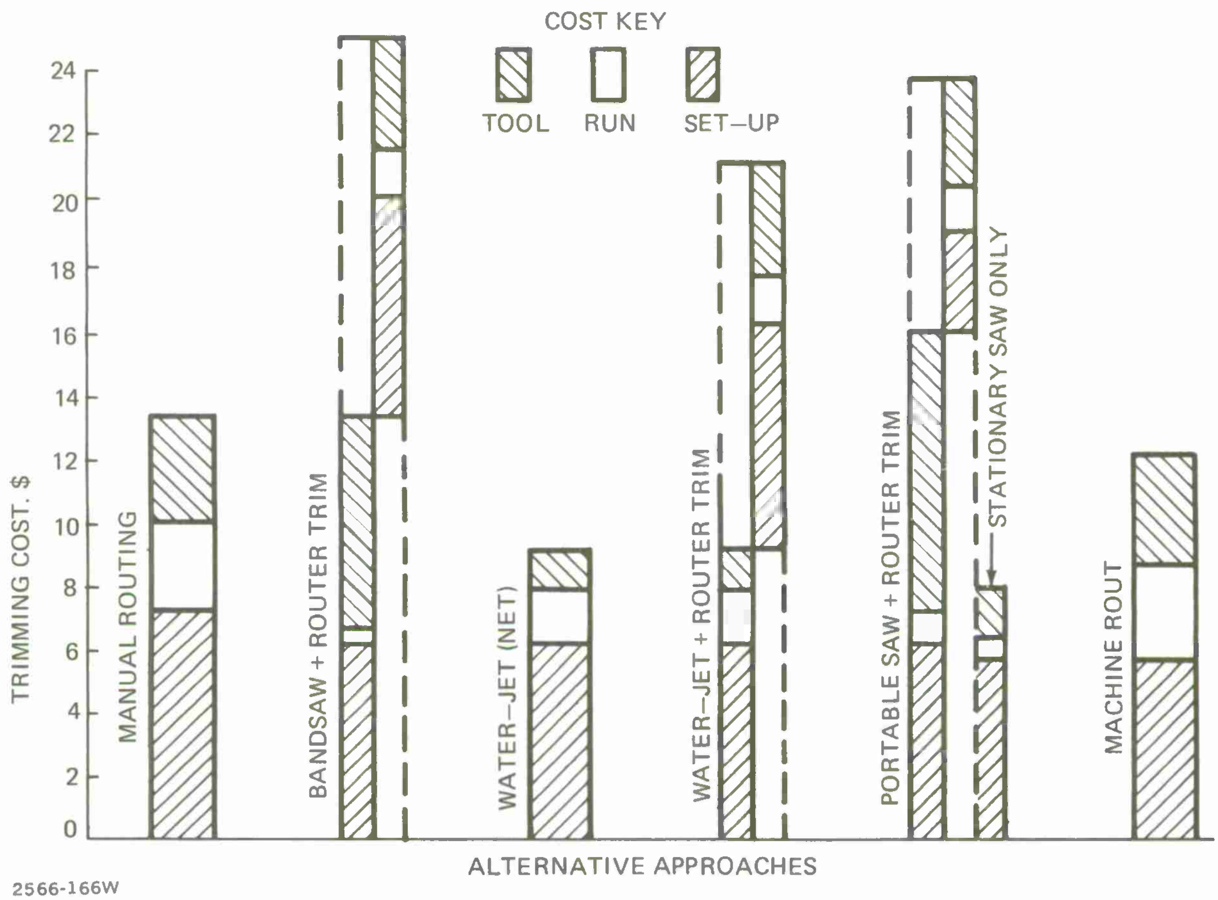

Figure 9-6 Comparative Costs for Trimming a 120-inch Periphery in 1/8-Inch-Thick Graphite/Epoxy

portable radial saw costs with that of stationary sawing. From this example, stationary radial sawing is one-half the cost of portable sawing due to lower cutting tool costs. Where stationary radial sawing can be utilized for the complete trimming operation, it is very attractive in terms of cost compared to any other approach. Bandsawing followed by router trimming is the most expensive approach of those considered.

9.4.3 Problem No. 3:

To drill and countersink 0.190-inch-diameter holes in 0.15-inch-thick graphite/epoxy laminates.

Alternatives:

- Manual drilling with HSS drill and countersink
- Manual drilling with carbide drills and countersinks
- Portable drilling with a carbide combination drill/countersink tool at 0.001 ipr feed and 6000 rpm speed
- Portable drilling with a carbide combination drill/countersink tool at 0.001 ipr feed and 21,000 rpm speed
- Portable drilling with a megadiamond combination drill countersink tool (assume 1000 hole life), at 0.001 ipr and 4,000 rpm

For each case compute the unit cost per hole.

Solution:

Summarized costs for each of the manufacturing alternatives are plotted in Figure 9-7. From the summary data it can be seen that off-hand drilling with high-speed steel (HSS) cutting tools is the most costly due to two reasons: hand operation which requires three separate operations and high cutting tool consumption. Simply by switching from HSS cutting tools to solid carbide, unit drilling costs are cut almost in half with the same three operations. Portable drilling equipment affords the advantage of combination drill-countersinking with the same tool and thereby eliminating two operations. It has also been shown, that under similar drilling conditions, a more rigid machining platform (i.e., portable drill equipment) yields 3 to 6 times drill life. Therefore, the third alternative (same conditions used for B-1 horizontal stabilizer) yields an additional 75 percent reduction in cost. High-speed drilling (21,000 rpm) developed within the current program demonstrated its ability to not only penetrate over three times faster but also double tool life. As a result, this high-speed operation reduces costs another 50 percent.

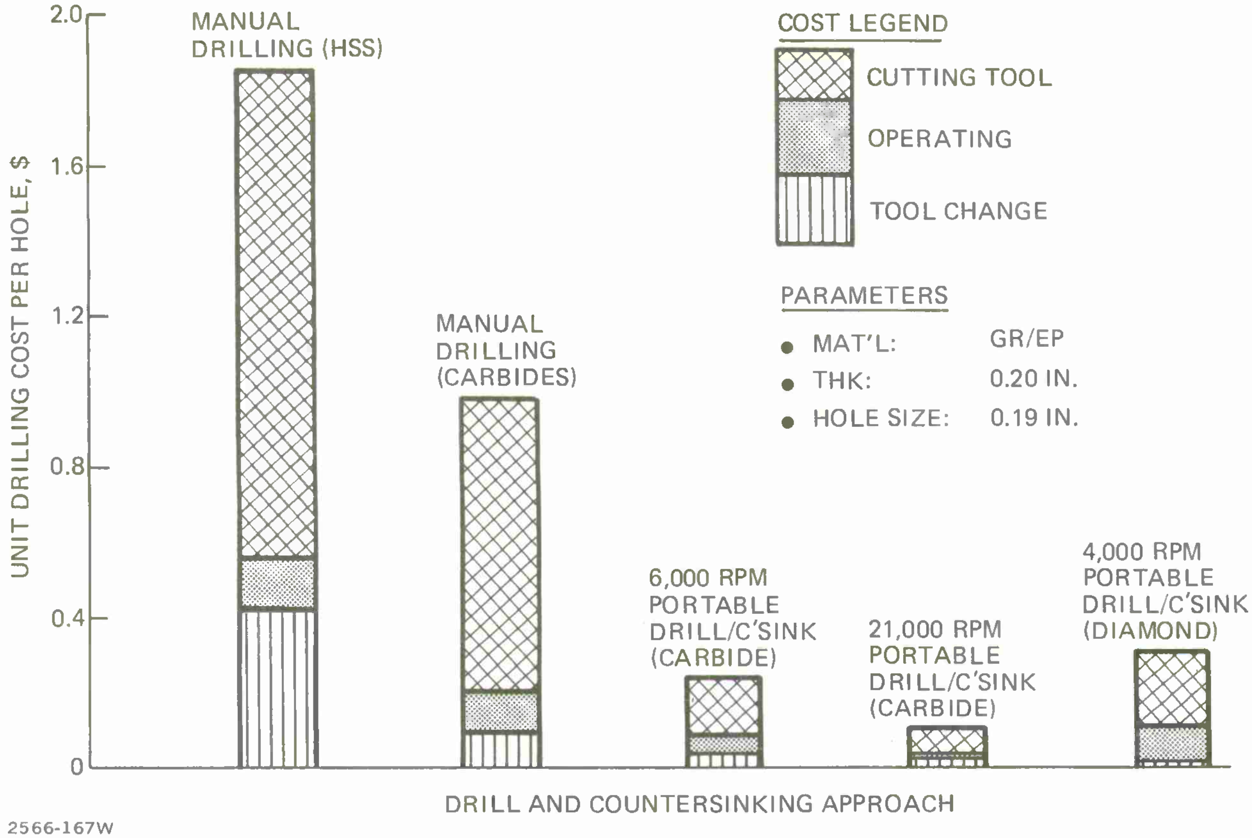

Figure 9-7 Comparative Drilling Costs for Graphite/Epoxy

Another approach to lowering drilling costs was to develop new, long-lasting tools such as compacted diamond inserts. Initial testing indicated that cutting-tool change costs could be halved with this approach, but initial data indicate that the cutting tools must be run at lower speeds (4000 rpm), therefore sacrificing penetration rate. This penetration rate constraint must be overcome before these cutting tools can become viable. Currently, these cutting tools are being fabricated at experimental rates and cost 250 dollars each. It would be reasonable to expect that this cost could be halved with production quantities; unit cutting tool cost per hole would then be competitive. In addition, the reliability of these new cutting tools has yet to be demonstrated and much work appears needed before further evaluation would be warranted.

9.4.4. Problem No. 4:

To drill 0.190-inch-diameter holes in 0.375-inch-thick boron/epoxy laminates.

Alternatives:

- Portable drilling using diamond core drills
- Ultrasonic portable drilling using diamond core drills

For each case compute the unit cost per hole.

Solution:

The same basic method used previously to develop drilling cost is again used. Comparative costs are shown in Figure 9-8. As can be seen, ultrasonically assisted portable drilling reduces unit costs by 70 percent due to increased feed capabilities (twice as great) and decreased wear (88 percent longer life) for an equivalent circumferential distance traveled.

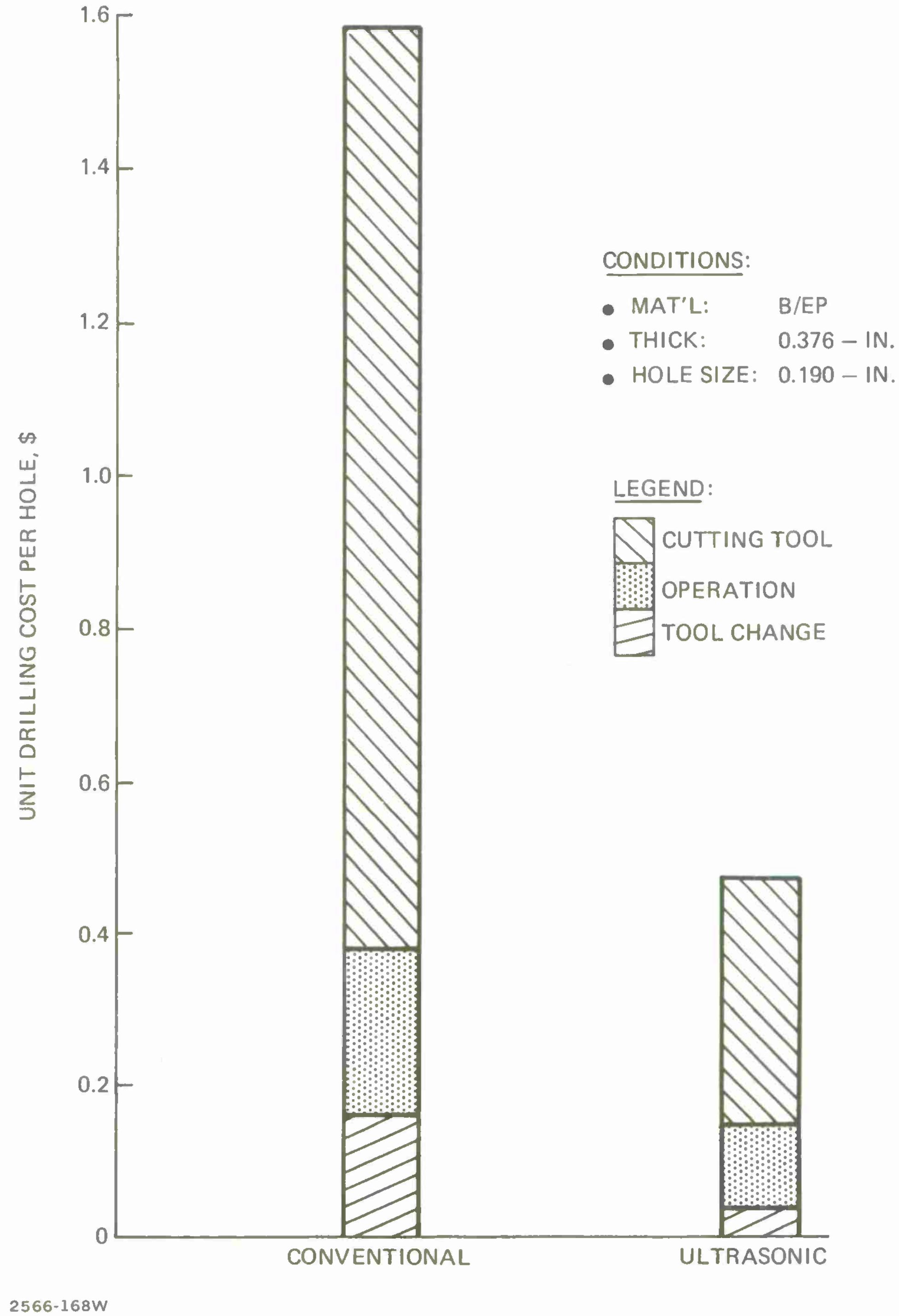

Figure 9-8 Cost Comparison – Conventional Vs. Ultrasonic Drilling

APPENDIX A

MATERIAL	THICKNESS, IN.	BLADE TYPE(1)	SPEED, sfm	FEED, ipm	COOLANT(3)	FLAWS FOUND BEFORE MOISTURE CONDITIONING			FLAWS FOUND AFTER MOISTURE CONDITIONING			
						VISUAL	TRACER	PENETRANT	VISUAL	TRACER	PENETRANT	MINOR
GR/EP + B/EP	0.500	DIAMOND PLATED 60 GRIT	7154(2)	14	MIST	MINOR BREAKOUT	NONE	MINOR POROSITY	NO CHANGE	NONE	NO CHANGE	NONE
GR/EP	0.310		7154(2)	44	MIST	MINOR BREAKOUT	NONE	NONE	NO CHANGE	NONE	NONE	NONE
GR/EP	0.310		7154	102	MIST	MINOR PULLOUT	NONE	MINOR POROSITY	NO CHANGE	NONE	NO CHANGE	NONE
B/EP	0.125		7154	102	MIST	POROSITY	NONE	PORSITY	NO CHANGE	NONE	NO CHANGE	NONE
FG/EP	0.125		7154	24	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
FG/EP	0.125		7154	69	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + B/EP	0.508		7154	14	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP	0.250		7154	32	MIST	NONE	NONE	NONE	NONE	NONE	NONE	NONE

NOTES:
(1) SIDES GROUND
(2) BLADE EXTENDED 2.125 INCHES ABOVE WORK PIECE
(3) HANGSTERFERS – HE2 (20:1) WATER MIX

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Figure A-1 Moisture Conditioning Test of Stationary Radially (Sawed Specimens)

MATERIAL	THICKNESS, IN.	BLADE TYPE(1)	SPEED, sfm	FEED, ipm	COOLANT(2)	FLAWS FOUND BEFORE MOISTURE CONDITIONING			FLAWS FOUND AFTER MOISTURE CONDITIONING			
						VISUAL	TRACER	PENETRANT	VISUAL	TRACER	PENETRANT	MICRO
GR/EP + B/EP	0.1185	DIAMOND PLATED 60 GRIT	2000	31	MIST	NONE	NONE	MINOR POROSITY	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.485		2000	28	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + B/EP	0.485		4000	34	DRY	NONE	NONE	MINOR POROSITY	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.091		4000	34	DRY	MINOR CRACKS	NONE	NONE	NO CHANGE	NONE	NONE	YES (NIL)
GR/EP + KEV/EP	0.280	TUNGSTEN CARBIDE COATED MED GRIT	4000	32	DRY	NONE	NONE	KEVLAR INTERFERED	NONE	NONE	NO CHANGE	NONE
GR/EP + B/EP	0.334		4000	13	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + KEV/EP	0.280		2000	21	DRY	NONE	NONE	KEVLAR INTERFERED	NONE	NONE	NO CHANGE	NONE
KEV/EP	0.118	CARBON(1) STEEL 32T	5400	55	DRY	NONE	NONE	NONE	NONE	NONE	NONE	NONE
GR/EP + FG/EP	0.250	TUNGSTEN CARBIDE COATED; MED GRIT	2000	17	DRY	MINOR DELAMIN-ATION	NONE	MINOR DELAMIN-ATION	NO CHANGE	NONE	NO CHANGE	YES (0.010")

NOTES:
(1) PRECISION WAVE SET
(2) HAMSTERFERS – HE-2 (20:1 WATER MIX)

2566-181W

Figure A-2 Moisture Conditioning Tests of Bandsawed Specimens

MATERIAL	THICKNESS, IN.	BLADE TYPE	SPEED, sfm	FEED, ipm	COOLANT(3)	NDT METHOD: RADIOGRAPHY TRACER FLAW FOUND	RADIOGRAPHY TRACER DEPTH, IN.	MICRO-SECTIONING FLAW FOUND	MICRO-SECTIONING DEPTH, IN.	VISUAL FLAW FOUND	PENETRANT FLAW FOUND
GR/EP + B/EP	0.450	DIAMOND PLATED 60 GRIT(1)	7154	14	DRY	NO	NONE	NO	NONE	MINOR BREAKOUT	MINOR POROSITY
GR/EP	0.310		7154	102	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	MINOR POROSITY
GR/EP + B/EP	0.450		7154(2)	14	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP	0.310		7154	44	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP + B/EP	0.508		7154	14	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.310		7154(3)	44	MIST	NO	NONE	NO	NONE	MINOR BREAKOUT	NO
GR/EP	0.500		7154	32	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	NO
GR/EP	0.500		7154	32	MIST	NO	NONE	NO	NONE	NO	NO
B/EP	0.136		7154	69	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
B/EP	0.136		7154	102	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
B/EP	0.136		7154	102	MIST	NO	NONE	NO	NONE	POROSITY	POROSITY
GR/EP	0.310	TUNGSTEN CARBIDE COATED MED GRIT	5790	20	MIST	NO	NONE	NO	NONE	BREAKOUT	NO
GR/EP	0.490	DIAMOND PLATED 60 GRIT(2)	7154	69	MIST	NO	NONE	NO	NONE	MINOR POROSITY	MINOR POROSITY
GR/EP	0.310		7154(3)	44	MIST	NO	NONE	NO	NONE	MINOR POROSITY	MINOR POROSITY
GR/EP	0.500		7154	25	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.310		7154(3)	57	MIST	NO	NONE	NO	NONE	MINOR PULLOUT	NO
FG/EP	0.147		7154	24	MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.147		7154	69	MIST	NO	NONE	NO	NONE	NO	NO

NOTES:
(1) SIDES GROUND
(2) SIDES NOT GROUND
(3) BLADE EXTENDED 2.125 INCHES ABOVE MATERIAL
(4) HANGSTERFERS-HE-2 (20:1 WATER MIX)

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Figure A-3 Stationary Radial Saw Non-Destructive Evaluation

MATERIAL	THICKNESS, IN.	BLADE TYPE	SPEED, fpm	FEED ipm	COOLANT	NDT METHOD: RADIOGRAPHY TRACER		MICROSECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND*
GR/EP	0.065	TUNGSTEN CARBIDE MED GRIT	2000	41	DRY	YES	0.075	YES	0.075	YES	YES
GR/EP	0.065		2000	19	DRY	YES	0.040	YES	0.055	YES	YES
GR/EP	0.270		4000	20	DRY	YES	0.060	YES	0.060	YES	YES
GR/EP	0.270		2000	50	DRY	YES	0.070	YES	0.070	YES	YES
GR/EP + FG/EP	0.057		4000	150	DRY	YES	0.035	YES	0.035	YES	YES
GR/EP + FG/EP	0.057		1000	20	DRY	YES	0.020	YES	0.020	YES	POSSIBLE
GR/EP + FG/EP	0.057		2000	1B	DRY	ND	NONE	YES	0.010	MINOR DE-LAMINATION	YES
GR/EP + FG/EP	0.250		4000	80	DRY	YES	0.020	YES	0.025	YES	YES
GR/EP	0.600	CARBON STEEL 10T RAKER SET 0° RARE	500 & 2000	4.4 & 7.0	DRY	NO	NONE	NO	NONE	NO	NO
KEV/EP	0.11B	CARBDN STEEL 32T PRECISION WAVE SET	5400	55	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP	0.270	DIAMOND PLATED 60 GRIT	3000	55	DRY	YES	0.035	YES	0.035	NO	YES
8/EP	0.136		4000	B6	DRY	ND	NONE	NO	NONE	NO	NO
GR/EP + 8O/EP	0.091		4000	34	DRY	ND	NONE	YES	NEGLIGIBLE	YES	NO
GR/EP + 8O/EP	0.4B5		2000	2B	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + 8O/EP	0.485		4000	34	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + BO/EP	0.490		2000	31	DRY	NO	NONE	NO	NONE	NO	MINOR POROSITY
FG/EP	0.143	TUNGSTEN CARBIDE MED GRIT	4000	B0	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.280		4000	32	DRY	NO	INTER-FERENCE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.280		2000	21	DRY	NO	INTER-FERENCE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.065		2000	25	DRY	NO	INTER-FERENCE	NO	NONE	NO	NO
GR/EP + 8/EP	0.334		4000	14	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.334		4000	12	DRY	ND	NONE	NO	NONE	NO	NO
KEV/EP	0.11B	CARBON STEEL 32T PRECISION WAVE SET	4000	46	DRY	YES	0.250	YES	0.250	YES	YES

NOTES:
(1) HANGSTERFERS-HE-2 (20:1 WATER MIX)
*POSSIBLE SATURATION WITH PENETRANT OIL

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Figure A-4 Bandsaw NDT Evaluation

MATERIAL	THICKNESS, IN.	BLADE TYPE	SPEED, fpm	FEED ipm	COOLANT	NDT METHOD					
						RADIOGRAPHY TRACER		MICROSECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND*
GR/EP	0.267	DIAMOND PLATED 60 GRIT	7496	58	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + FG/EP	0.260		7496	65	DRY	NO	NONE	NO	NONE	NO	NO
B/EP	0.136		7496	86	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.333		7496	43	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.333		7496	43	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP	0.067		7496	132	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.090		7496	118	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.064		7496	98	DRY	YES	0.065	YES	0.065	DE-LAMINATION	YES
GR/EP + FG/EP	0.064		7496	167	DRY	YES	0.125	YES	0.100	DE-LAMINATION	YES
FG/EP	0.147		7496	101	DRY	NO	NONE	NO	NONE	NO	NO
B/EP	0.135		7496	94	DRY	NO	NONE	NO	NONE	NO	NO
GR/EP	0.275		7496	46	DRY	NO	NONE	NO	NONE	NO	NO
KEV/EP	0.112	CARBIDE 12 TEETH ALT OP-POSED FACE ANGLE	7496	96	DRY	(2)		NO	NONE	(2)	(1)
GR/EP + KEV/EP	0.271		7496	29	DRY	(2)		YES	0.060	NO	NO

(1) PENETRANT ABSORBED BY ALL KEVLAR TEST OBSCURED
(2) SPECIMEN TOO BADLY FRAYED

2566-184W

Figure A-5 Hand Radial Saw NDT Evaluation

MATERIAL	THICKNESS, IN.	PRESSURE, KSF	STAND OFF, IN.	NOZZLE DIA, IN.	FEED, ipm	NDT METHOD					
						RADIOGRAPHY TRACER		MICRO-SECTIONING		VISUAL	PENETRANT
						FLAW FOUND	DEPTH, IN.	FLAW FOUND	DEPTH, IN.	FLAW FOUND	FLAW FOUND
GR/EP	0.062	55	3/16	0.008	60	YES	0.075	YES	0.021	CRACK	YES
GR/EP	0.134	60	3/16	0.010	30	YES	0.375	YES	0.390	DELAMINATION	YES
GR/EP	0.275	60	1/8	0.014	6.6	YES	0.110	YES	0.300	CRACK	YES
8/EP	0.058	60	3/16	0.012	120	YES	0.250	YES	0.300	NO	YES
8/EP	0.136	60	1/8	0.010	120	YES	0.285	YES	0.290	DELAMINATION	YES
KEV/EP	0.062	55	1/8	0.006	120	YES	THRU CRACK	YES	THRU CRACK	NO	YES
KEP/EP	0.123	55	1/8	0.010	6.6	NO	NONE	NO	NONE	NO	NO
FG/EP	0.143	60	3/16	0.010	6.0	NO	NONE	NO	NONE	NO	NO
GR/EP + 8/EP	0.095	60	1/8	0.012	14	YES	0.05	YES	0.100	NO	YES
GR/EP + 8/EP	0.154	60	1/8	0.012	4	YES	0.090	YES	0.200	MINOR CRACKS	YES
GR/EP + KEV/EP	0.063	60	1/8	0.010	16	NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.267	60	1/8	0.014	5	YES(1)	0.100	NO	NONE	NO	NO
GR/EPT + FG/EP	0.067	55	1/8	0.012	9	YES	0.075	YES	0.075	NO	YES
GR/EP + FG/EP	0.253	60	1/16	0.012	9	YES	0.125	YES	0.290	NO	YES
GR/EP + 8/EP	0.321	60	1/8	0.014	9	NO	NONE	NO	NONE	NO	NO

(1) CRACK MAY HAVE BEEN CUT OUT DURING SECTIONING

2566-185W

Figure A-6 Water Jet NDT Evaluation (Flow Industries Inc.)

MATERIAL	THICKNESS IN.	COMPANY	PRESSURE, kpsi	STAND OFF IN.	NOZZLE DIA IN.	NDT METHOD			
						FEED RATE ipm	RADIOGRAPHY TRACER		COMMENTS
							FLAW FOUND	DEPTH, IN.	
GR/EP	0.090	ITTRI	81	0.5	0.24	270	YES	0.025 – 0.445	SPORADIC DELAMINATION
GR/EP	0.181	ITTRI	100	0.5	0.40	270	YES	0.300 – 0.110	CONTINUOUS DELAMINATION
GR/EP	0.131	MCCARTNEY	40 TO 50	0.5	0.010	72	YES	0.080 – 0.110	
GR/EP	0.134	FLOW IND	60	3/16	0.010	45	YES	0.130 – 0.300	SPORADIC
GR/EP	0.134		60	3/16	0.010	30	YES	0.025	CONTINUOUS GOOD SPECIMEN
GR/EP	0.134		60	3/16	0.008	30	YES	0.075 – 0.220	SPORADIC
GR/EP	0.134		55	3/16	0.012	30	YES	0.175	SPORADIC
GR/EP	0.063		50	3/16	0.012	30	YES	0.080 – 0.300	
GR/EP	0.134		55	3/16	0.010	30	YES	0.120 – 0.350	
GR/EP	0.134		60	3/16	0.010	60	YES	0.080 – 0.220	
GR/EP	0.134		40	3/16	0.012	30	YES	0.150 – 0.400	
GR/EP	0.063		55	3/16	0.005	120	YES	0.165	
GR/EP	0.063		60	3/16	0.008	120	YES	0.060	
GR/EP	0.063		55	3/16	0.008	120	YES	0.095	
GR/EP	0.063		35	3/16	0.008	120	YES	0.230	
GR/EP	0.063		55	3/16	0.008	30	YES	0.115	
GR/EP	0.063		60	3/16	0.012	30	YES	0.050	
GR/EP	0.063		55	3/16	0.008	45	YES	0.100	
GR/EP	0.063		50	3/16	0.012	120	YES	0.130	
GR/EP	0.063		60	3/16	0.010	120	YES	0.030 – 0.080	
GR/EP	0.063		55	3/16	0.008	60	YES	0.120	
GR/EP	0.134		60	3/16	0.012	60	YES	0.025 – 0.050	

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Figure A-7 Water Jet Evaluation

MATERIAL	THICKNESS, IN.	SPEED, sfm	FEED, ipm	CUTTER TYPE	COOLANT(4)	NDT METHOD: RADIOGRAPHY TRACER FLAW FOUND	RADIOGRAPHY TRACER DEPTH, IN.	MICRO-SECTIONING FLAW FOUND	MICRO-SECTIONING DEPTH, IN.	VISUAL FLAW FOUND	PENETRANT FLAW FOUND
GR/EP	0.132	851	46	CARBIDE DIAMOND CUT	MIST	NO	NONE	NO	NONE	NO	YES
GR/EP	0.132	851	46			NO	NONE	NO	NONE	NO	YES
GR/EP	0.272	851	30			YES	0.030	NO(2)	NONE	YES	YES
GR/EP	0.272	851	30			YES	0.020	NO(2)	NONE	YES	NO
GR/EP	0.132	851	22			NO	NONE	NO	NONE	NO	YES
GR Q	0.132	851	22			NO	NONE	NO	NONE	NO	NO
GR/EP + KEV/EP	0.287	851	14			(1)		NO	NONE	NO	NO
GR/EP + KEV/EP	0.287	851	14			(1)		YES	0.100	NO	NO
FG/EP	0.148	851	27			NO	NONE	NO	NONE	NO	YES
FG/EP	0.148	851	27			NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.266	851	16			NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.266	851	16			YES	0.020	NO	NONE	NO	YES
GR/EP	0.068	851	83			YES	0.050	YES	0.025	DE-LAMINATION	YES
GR/EP	0.068	851	83			YES	0.065	NO(3)	NONE	NO	NO
GR/EP + KEV/EP	0.075	851	60			(1)		NO	NONE	(1)	(1)
GR/EP + KEV/EP	0.075	851	60			(1)		NO	NONE	(1)	(1)
GR/EP + FG/EP	0.065	851	85			YES	0.020	YES	0.035	NO	YES
GR/EP + FG/EP	0.065	851	85			NO	NONE	NO	NONE	NO	NO
GR/EP	0.132	1435	13			YES	0.030	YES	0.050	NO	YES
GR/EP	0.132	1435	13			NO	NONE	NO	NONE	NO	YES MINOR
FG/EP	0.148	1435	18			YES	0.050	YES	0.100	NO	YES
FG/EP	0.148	1435	18			NO	NONE	NO	NONE	NO	NO
GR/EP	0.068	1435	82			NO	NONE	NO	NONE	NO	NO
GR/EP	0.066	1435	82			NO	NONE	NO	NONE	NO	YES
GR/EP	0.272	1435	82			YES	0.050	YES	0.055	OE-LAMINATION	YES DELAM

(1) INTERFERENCE BY KEVLAR
(2) SURFACE FLAW
(3) FLAW CUT BY CUT OFF WHEEL
(4) HANGSTERFERS-HE-2 (20:1 WATER MIX)

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Figure A-8 Hand Routing NDT Evaluation

MATERIAL	THICKNESS, IN.	MACHINE TYPE	SPEED, sfm	FEED ipm	STROKES PER MIN	CUTTER TYPE	COOLANT(3)	NDT METHOD: RADIOGRAPHY TRACER FLAW FOUND	NDT METHOD: RADIOGRAPHY TRACER DEPTH, IN.	NDT METHOD: MICRO-SECTIONING FLAW FOUND	NDT METHOD: MICRO-SECTIONING DEPTH, IN.	NDT METHOD: VISUAL FLAW FOUND	NDT METHOD: PENETRANT FLAW FOUND
GR/EP + KEV/EP	0.064	ONSRUD	1315	44	–	CARBIDE OPPOSED HELIX	DRY	YES	0.065	YES	0.065	DE-LAMINATION	(1)
GR/EP + KEV/EP	0.263	ONSRUD	1315	8	–		DRY	YES	0.020	NO(2)	NONE	TRANSVERSE CRACKS/ DELAM	YES
GR/EP + KEV/EP	0.263	ONSRUD	1315	8	–		DRY	YES	0.035	NO(2)	NONE	TRANSVERSE CRACKS/ DELAM	YES
KEV/EP	0.102	ONSRUD	1315	59	–		DRY	YES	0.050	YES	0.090	YES	NO
KEV/EP	0.102	ONSRUD	1315	59	–		DRY	YES	0.070	YES	0.075	YES	NO
GR/EP	0.086	ONSRUD	723	29	–	CARBIDE DIAMOND CUT	MIST	NO	NONE	NO	NONE	NO	NO
GR/EP	0.287	MARWIN	723	10	–		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + FG/EP	0.063	MARWIN	723	24	–		MIST	NO	NONE	NO	NONE	NO	YES
GR/EP + FG/EP	0.263	MARWIN	723	12	–		MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.144	MARWIN	723	22	–		MIST	NO	NONE	NO	NONE	NO	YES
B/EP	0.136	ROTO-RECIPRO	723	4	60	DIAMOND PLATED 40-50 GRIT	MIST	NO	NONE	NO	NONE	NO	NO
B/EP	0.136	ROTO-RECIPRO	851	4	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.090	ROTO-RECIPRO	851	5	60		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.090	ROTO-RECIPRO	851	5	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.346	ROTO-RECIPRO	851	5	60		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.346	ROTO-RECIPRO	851	5	60		MIST	NO	NONE	YES	0.030	NO	NO
GR/EP + B/EP	0.500	ROTO-RECIPRO	851	3	200		MIST	NO	NONE	NO	NONE	NO	NONE

NOTES:
(1) INTERFERENCE FROM KEVLAR
(2) CRACKS TO SMALL TO MICROSECTION
(3) HANGSTERFERS-HE-2 (20:1 WATER MIX)

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Figure A-9 Machine Routing NDT Evaluation

MATERIAL	THICKNESS, IN.	MACHINE TYPE	SPEED, sfm	FEED ipm	STROKES PER MIN	CUTTER TYPE	COOLANT	NDT METHOD: RADIOGRAPHY TRACER FLAW FOUND	RADIOGRAPHY TRACER DEPTH, IN.	MICRO-SECTIONING FLAW FOUND	MICRO-SECTIONING DEPTH, IN.	VISUAL FLAW FOUND	PENETRANT FLAW FOUND
GR/EP + KEV/EP	0.263	ONSRUD	1315	35	–	CARBIDE OPPOSED HELIX	DRY	YES	0.060	YES	0.100	TRANSVERSE	YES
GR/EP + KEV/EP	0.064	ONSRUD	1315	76	–		DRY	YES	0.030	NO	NO	NO	(1)
KEV/EP	0.102	ONSRUD	1315	64	–		DRY	YES	0.035	NO	NO	NO	
GR/EP + B/EP	0.090	ROTO-RECIPRO	851	20	200	DIAMOND PLATED 40-50 GRIT	MIST	YES	0.090	YES	0.100	YES	YES
B/EP	0.136		851	20	200		MIST	NO	NONE	NO	NONE	YES	YES
GR/EP + B/EP	0.346		851	9	200		MIST	NO	NONE	NO	NONE	NO	NO
GR/EP + B/EP	0.500		851	9	200		MIST	NO	NONE	NO	NONE	NO	NO

NOTES:
(1) INTERFERENCE FROM KEVLAR
(2) HANGSTERFERS-HE-2 (20:1 WATER MIX)

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Figure A-10 Machine Trimming NDT Evaluation

MATERIAL	THICKNESS, IN.	SPEED, sfm	FEED, ipm	CUTTER TYPE	COOLANT(1)	NDT METHOD: RADIOGRAPHY TRACER FLAW FOUND	RADIOGRAPHY TRACER DEPTH, IN.	MICRO-SECTIONING FLAW FOUND	MICRO-SECTIONING DEPTH, IN.	VISUAL FLAW FOUND	PENETRANT FLAW FOUND
GR/EP	0.272	851	47	CARBIDE DIAMOND CUT	MIST	NO	NONE	YES	0.065	NO	YES
GR/EP + FG/EP	0.245	851	58		MIST	NO	NONE	NO	NONE	NO	NO
FG/EP	0.148	851	57		MIST	NO	NONE	NO	NONE	NO	NO

NOTE:
(1) HANGSTERFERS-HE-2 (20:1 WATER MIX)

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Figure A-11 Manual Beveling NDT Evaluation

MATERIAL	THICKNESS IN.	DRILL TYPE	SPEED rpm	FEED ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0.300	1/8 DIA ROTA-KOTE	6000	0.001	0.020" – 0.085" DELAMINATION ON ALL HOLES	SMALL HOLES DIFFICULT TO TEST. MANY INDICATION DRILL MARKS GIVE FALSE POSITIVES	ALL HOLES FAIRLY SMOOTH; ALL HAVE BREAKOUTS PROGRESSIVELY WORSTENING TO LAST HOLE
GRAPHITE/ EPOXY	0.300	3/16 DIA ROTA-KOTE CARBIDE	6000	0.001	0 – 0.200" DELAMINATION ON ALL HOLES WORSE TOWARD LAST		FIRST HOLES FAIRLY SMOOTH BUT BECOME ROUGHER. ALL HOLES HAVE BREAKOUT WITH CONDITION WORSTENING AT LAST 50 HOLES
GRAPHITE/ EPOXY	0.275	15/16 DIA DIAMOND-TIPPED (80-100 GRIT)	6000	0.001	ALL HOLE DELAM-INATED 0.100" – 0.125"		HOLES FAIRLY SMOOTH, LITTLE BREAKOUT
GRAPHITE/ EPOXY	0.275	1/4 DIA DIAMOND-TIPPED (220 GRIT)	6000	0.001	ALL HOLES DELAM-INATED 0.055" – 0.125"		HOLES CLEAN; MINOR BREAKOUT ON LASY PLYS
GRAPHITE/ EPOXY	0.275	1/4 DIA DIAMOND-TIPPED (100 – 120 GRIT)	6000	0.001	ALL HOLES DELAMINATED 0.50" – 0.130"	BREAKOUT AND DELAMINATION CAN BE SEEN AT BOTTOM OF HOLE. MANY FALSE POSITIVES	MINOR FIBER PULLOUT IN LAST THREE HOLES; MINOR BREAKOUT
GRAPHITE/ EPOXY	0.275	1/4 DIA CARBIDE-TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.010" 0.075" NO RELATIONSHIP TO NUMBER OF HOLES DRILLED		FIBER PULLOUT IN ALL HOLES; BREAKOUT INCREASES AS NO. OF HOLES INCREASE, SOME DELAMINATION ON ENTRANCE SIDE.
GRAPHITE/ EPOXY	0.300	1/4 DIA MICROGRAINED CARBIDE	6000	0.001	ALL HOLES DELAMINATED 0 – 0.125" DELAMINATION WORSTENING FROM HOLE 1 to 60		FIBER PULLOUT BECOMES PROGRESSIVELY WORSE WITH INCREASED HOLE NUMBER NO SIGNIFICANT BREAKOUT FOR FIRST 20 HOLES. THEN BREAKOUT INCREASES TO LAST HOLE
GRAPHITE/ EPOXY	0.275	1/4 DIA FISH TAIL POINT, CARBIDE-TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.055" – 0.130"		FIBER PULLOUT IN ALL HOLES, MINOR BREAKOUT FROM ALL HOLES
GRAPHITE/ EPOXY	0.300	1/8 DIA ROTA-KOTE HSS	6000	0.001	DELAMINATION AND BREAKOUT ON ALL HOLES TO 0.125" MAX.	MANY INDICATORS HOLES SMALL TO TEST ACCURATELY	SOME FIBER PULLOUT; BAD BREAKOUT ON ALL HOLES
GRAPHITE/ EPOXY	0.275	0.190 DIA ROTA-KOTE HSS	6000	0.001	ALL HOLES DE-LAMINATED 0.110" – 0.140"	SOME FALSE INDICATIONS	HOLES FAIRLY SMOOTH SOME FIBER PULLOUT BREAKOUT ON ALL HOLES;

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(1/2)

Figure A-12 Summary of Non-Destructive Evaluation of Drilled Holes (Sheet 1 of 2)

MATERIAL	THICKNESS, IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0 270	0.250 DIA TWIST HSS	3000	0.003	DELAMINATION OF HOLE 1 OF 0.120" PROGRESSING TO 0.150" AT LAST HOLE	MATERIAL IN HOLE HOLDS PENETRANT, FALSE INDICATIONS	HOLE SMOOTH AT FIRST PROGRESSIVELY GETTING ROUGHER TO HOLE 14. BAD BREAKOUT ON ALL HOLES.
GRAPHITE/ EPOXY	0.270	0.250 DIA TWIST HSS	6000	0.003	DELAMINATION IN ALL HOLES 0.120" – 0.150"		ALL HOLES FAIRLY SMOOTH OF SOME OUALITY THROUGH ALL SIX SOME FIBER PULLOUT, BAD BREAKOUT ON ALL HOLES
GRAPHITE/ EPOXY	0.270	0.250 DIA CARBIDE TIPPED	6000	0.001	ALL HOLES DELAMINATED 0.120" – 0.150"		HOLE OUALITY ESSENTIALLY THE SAME THROUGH OUT ALL 60 HOLES, BREAKOUT ON ALL HOLES; SOME GOUGING BY DRILL.
GRAPHITE/ EPOXY	00.270	0.190 DIA CARBIDE DRILL/C'SINK Z114104 0.2055 DIA	6000	0.001	HOLES DELAMINATED 0.080"		HOLE OUALITY SIMILAR FOR ALL 140 HOLES. ALL HOLES DELAMINATED WITH BREAKOUT.
GRAPHITE/ EPOXY	0.270	MEGADIAMOND TIPPED	2500 4500	0.001	DELAMINATION AT HOLE 1 of 0.120" PROGRESSING TO 0.150" AT HOLE #60		HOLE OUALITY THE SAME FOR ALL 60 HOLES. SOME FIBER PULLOUT, ALL HOLES HAVE BREAKOUT
GRAPHITE/ EPOXY	0.275	0.250 DIA TWIST, CARBIDE TIPPED	21,000	0.001	DELAMINATION AT HOLE # 1 OF 0.005" PROGRESSING TO 0.125" AT HOLE # 120	PENETRANT GIVES MANY FALSE POSITIVES	FAIR SURFACE FINISH IN ALL 120 HOLES. ALL HOLES HAVE BREAKOUT
GRAPHITE/ EPOXY	0.275	0.190 DIA CARBIDE Z114104	21,000	0.001	DELAMINATION AT HOLE # 1 OF 0.050 PROGRESSING TO 0.130" AT LAST HOLE # 250		FAIR SURFACE FINISH IN ALL 250 HOLES. ALL HOLES HAVE BREAKOUT

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Figure A-12 Summary of Non-Destructive Evaluation of Drilled Holes (Sheet 2 of 2)

MATERIAL	THICKNESS IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY + BORON/ EPOXY	0.223	3/16 DIA QUACKEN-BUSH ULTRASONIC	3000	0.005	27 OF 75 HOLES DELAMINATED 0.055" – 0.070" OTHER HOLES ACCEPTABLE	SOME DELAMIN-ATIONS PICK UP IN HOLE SOME FALSE POSITIVES	HOLES BACKED BY MASONITE; GETTING PROGRESSIVELY WORSE TOWARD HOLE # 75. SOME BREAKOUT; SURFACE RELATIVELY SMOOTH

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Figure A-13 Summary of Non-Destructive Evaluation of Ultrasonically Drilled Holes

MATERIAL	THICKNESS, IN.	DRILL TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
KEVLAR/ EPOXY	0.118	0.250 DIA JANCY 2 FLUTE C'BORE W/PILOT	6000	0.001	AVERAGE DE-LAMINATION THROUGH HOLE 5 IS 0.050" MAXIMUM IS 0.120" INCREASING AT LAST HOLE	CANNOT DETECT	DELAMINATION ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.118	0.250 DIA JANCY 2 FLUTE C'BORE WITHOUT PILOT	3000	0.001	NO DELAMINATION THROUGH HOLE 8, AVERAGE DELAMINATION THROUGH HOLE 21 IS 0.055 WITH MAX OF 0.100"	CANNOT DETECT	DELAMINATION ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.11B	0.250 DIA TWIST CARBIDE TIPPED	6000	0.001	RANGE OF DELAMINATION 0.050" TO 0.75"	CANNOT DETECT	DELAMINATION ON ALL HOLES ON ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.11B	0.250 DIA FISH TAIL CARBIDE TIPPED	6000	0.001	DELAMINATION RANGE OF 0.055" TO 0.0B5" ON ALL HOLES	CANNOT DETECT	DELAMINATION ON ALL ENTRANCE AND EXIT SIDES OF PANEL
KEVLAR/ EPOXY	0.11B	0.250 DIA FISH TAIL CARBIDE TIPPED	3000	0.002	DELAMINATION RANGE ON ALL HOLES 0.090" TO 0.115"	CANNOT DETECT	ENTRANCE DELAMINATION ON ALL HOLES; ALSO EXIT DELAMINATION
KEVLAR/ EPOXY	0.118	0.250 DIA SPADE (SLANT) CARBIDE	6000	0.001	DELAMINATION RANGE ON ALL HOLES 0.0B0" TO 0.150"	CANNOT DETECT	EXIT DELAMINATION ON ALL HOLES. NEGLIGIBLE ENTRANCE DELAMINATION
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.2B0	0.250 DIA FISH TAIL CARBIDE TIPPED	6000	0.001	DELAMINATION RANGE FOR ALL HOLES 0.050" TO 0.150"	SOME PENETRANT INDICATIONS KEVLAR INTERFERRED	ALL HOLES BADLY DELAMINATED AT EXIT SIDE SLIGHT ENTRANCE DELAMINATION

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Figure A-14 Summary of Non-Destructive Evaluation of Drilled Holes

MATERIAL	THICKNESS, IN.	C'SINK TYPE	SPEED, rpm	FEED, IPR	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY + KEVLAR/ EPOXY	0.275	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/ C'SINK	2400	0.002	INTERFERENCE FROM KEVLAR	INTERFERENCE FROM KEVLAR	ENTRANCE SIDE OF COUNTER SUNK HOLE BADLY FRAYED + SPLIT
GRAPHITE/ EPOXY + FIBER-GLASS/ EPOXY	0.260	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/C'SINK	2400	0.002	LITTLE DELAMINATION 0.005	NO SIGNIFICANT INDICATIONS	SLIGHT SURFACE DELAMINATION ON SOME HOLES. COUNTER SUNK AREAS LOOK CLEAN
FIBER-GLASS/ EPOXY	0.125	2 FLUTE CARBIDE COUNTERSINK Z114105 DRILL/ C'SINK	2400	0.002	LITTLE DELAMINATION 0.005"	NO SIGNIFICANT INDICATIONS	SLIGHT SURFACE DELAMINATION ON VERY FEW HOLES.

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Figure A-15 Summary of Non-Destructive Evaluation of Countersunk Holes

MATERIAL	THICKNESS, IN.	COUNTERBORE TYPE	SPEED, rpm	FEED, ipr	TRACER RADIOGRAPHY	PENETRANT	COMMENTS
GRAPHITE/ EPOXY	0.270	3 FLUTE CARBIDE TIPPED	2400	0.002	NO FLAWS DETECTED	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY	0.270		2400	0.001	NO FLAWS DETECTED	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY	0.270		4800	0.0005	SPORADIC DELAMINATION ON A FEW OF THE HOLES 0.020" – 0.050"	GOOD	GOOD CLEAN COUNTER BORE
GRAPHITE/ EPOXY + FIBER-GLASS EPOXY	0.270		3600	0.001	SLIGHT DELAMINATION ON SOME HOLES 0.200" - 0.040"	GOOD, NO SIGNIFICANT INDICATIONS	SOME ENTRANCE DELAMINATION ON A FEW OF THE 25 COUNTER-BORE HOLES.
GRAPHITE/ EPOXY + KEVLAR EPOXY	0.270		3600	0.001	KEVLAR INTERFERRED WITH METHOD	KEVLAR INTERFERRED WITH METHOD	TOP SURFACE OF ALL COUNTER BORES BADLY FRAYED; DIFFICULT TO EVALUATE. NO DELAMINATION SEEN
FIBER-GLASS/ EPOXY	0.145		3600	0.001	NO DELAMINATION TO 0.020" DETECTED	GOOD	ALL HOLES LOOK GOOD; SOME SLIGHT DELAMINATION ON ENTRANCE SIDE OF COUNTER BORE HOLE.

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Figure A-16 Summary of Non-Destructive Evaluation of Counterbored Holes

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