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AFML-TR-77-66

FEASIBILITY OF CUTTING ALUMINUM ALLOYS WITH A 6-KILOWATT LASER

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124

September 1977

Technical Report AFML-TR-77-66

Final Report for Period
15 March 1976 – 15 March 1977

Approved for public release; distribution unlimited

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This final report was submitted by Boeing Commercial Airplane Company, under Contract F33615-76-C-5276, Proj. 777-5, "Feasibility Of Cutting Aluminum Alloys with a 6-Kilowatt Laser," AFML-TR-77-66. Mr. K. L. Love, AFML/LTM, was the Project Manager.

This technical report has been reviewed and is approved for publication.

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Project Manager

FOR THE DIRECTOR

H.A. Johnson

H.A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

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

The results of this program demonstrated that it is feasible to use laser cutting of aluminum without edge enhancement in the fabrication of hardware where a sheared or blanked edge is acceptable to meet engineering requirements. However, it was further shown that it is not feasible to use an as-laser-cut edge for hardware where machined edges or hole filling fasteners are required to meet engineering requirements.

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FOREWORD

This Final Technical Report covers the work performed under Contract F33615-76-C-5275 during the period from 15 March 1976 to 15 March 1977. It was submitted by the author for approval in April 1977. This contract with Boeing Commercial Airplane Company, Seattle, Washington was conducted under the technical direction of Mr. K. L. Love (AFML/LTM) Metals Branch, Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson AFB, OH 45433.

The Aerospace Industry Association co-sponsors and contributors to the program were Rockwell International, United Technologies Corp., Northrup Corp., McDonnell Douglas Corp., Lockheed Georgia Company, Rohr Industries, Lockheed California Company, Bell Helicopter Textron, Vought Corporation, Avco Everett Research Lab, Inc., and The Boeing Company. Mr. Berger O. Anderson, Group Supervisor, Manufacturing Research and Development, Boeing Commercial Airplane Company, was the program manager. Mr. Edmund Bronner, Rockwell International, chairman of the joint AIA/AFML Project MC74.12, coordinated the AIA Activities. Acknowledgement is made to the principal contributing personnel: Gary Whitney, United Technologies; Robert Anderson, Bell Helicopter Textron; Roy Brodie, Lockheed California; Elmer Cox, Jim Lamlinsan, Lockheed Georgia; Frank Bigony, Vought Corporation; Robert Schmidt, Alfred Langolis, Northrop Corporation; David Belforte, Avco Everett Research Lab; Sam Schnider, Rohr Industries; Walt Sather, McDonnell Douglas; Birger Anderson, Devere Lindh, Kale Skutley, The Boeing Company.

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INTRODUCTION

Based on results of an Air Force sponsored program on laser cutting of high-strength steels, the Aerospace Industries Association of America, Inc (AIA) recognized that laser technology might also satisfy the need for a high-speed method, applicable to numerical control techniques, for cutting aluminum alloys. As aluminum still constitutes the major portion of civil and military aircraft, the economic advantage of such a process was the driving force. Laser technology, emerging from the laboratory status to manufacturing tool status under the sponsorship of the Metals Branch, Manufacturing Technology Division of the Air Force Materials Laboratory, was recognized as a potential candidate due to the small heat-affected zone left by the cut and its complete flexibility for sharp, right-angle cuts. A program was initiated by AIA to determine whether laser cutting of aluminum held any promise of replacing blanked and routed edges commonly used in the industry. The results of that study (Project Report MC 74.12) showed that 0.020-inch-thick 2024-T3 and 7075-T6 aluminum alloys could be cut, using a 1-kw laser and demonstrated edge integrity as measured by static strength, corrosion resistance, and fatigue performance equal to a blanked edge without the need to resort to edge enhancement such as sanding or cosmetic routing. In the case of 0.040- and 0.063-inch-thick material in the same alloys, the static fatigue performance was significantly degraded. This was attributed to a large heat-affected zone. At the time the original program was completed, additional data developed using a 6-kw laser showed a significant visual improvement in the cut edge.

The Metals Branch, Air Force Materials Laboratory, was contacted by the AIA to assist in sponsoring a program to investigate the feasibility of using a multi-kilowatt laser with optimized cutting nozzle design to produce as-cut edges on 7075-T6 and 2024-T3 aluminum in thicknesses up to 0.063 inch having integrity equal to a blanked edge without resorting to edge enhancement techniques.

The program is unique in that it was jointly planned and funded by the Air Force and AIA member companies. The ensuing full interchange of ideas and data resulted in rapid technology transition within the participating companies.

SECTION II
EXPERIMENTAL PROGRAM

1. OBJECTIVE

The objective of this program is to establish an effective manufacturing method for laser cutting aluminum alloys and obtain sufficient data to demonstrate its potential application to aerospace structural fabrication.

2. TECHNICAL APPROACH

The experimental approach to achieving the program objective was divided into three phases (see figure 1). Objectives were:

- To optimize the cutting technique over a limited range of variables.

- To conduct tensile, smooth fatigue, notched fatigue, intergranular corrosion, and metallurgical analyses of edges produced by milling, blanking, and laser cutting so that the edges produced by the different processes could be compared for suitability for different applications (figure 1). The milled edge specimens were included as a reference standard. The work was scheduled as shown in the flow chart given in figure 2. A detailed test plan is presented in figure 3 showing tests, number of specimens and spares, material, thickness, and responsible company.

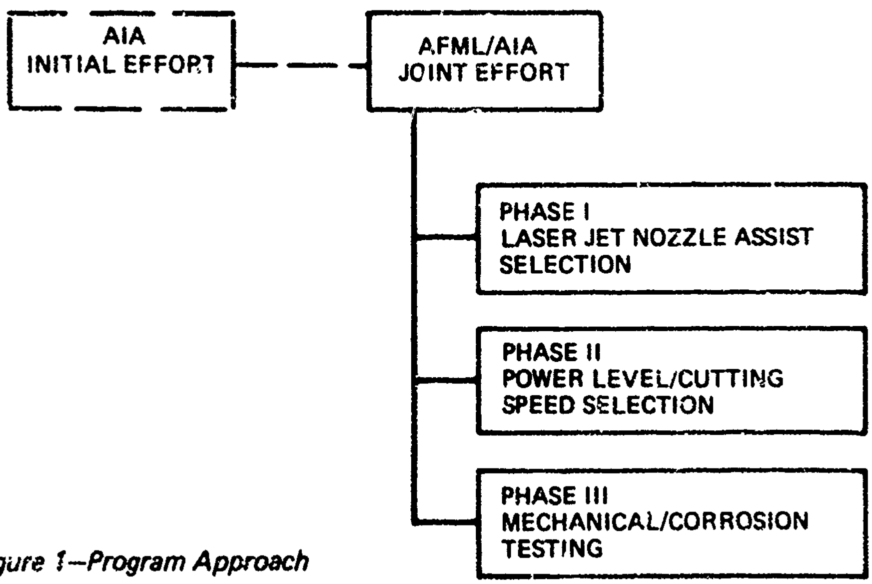


Figure 1—Program Approach

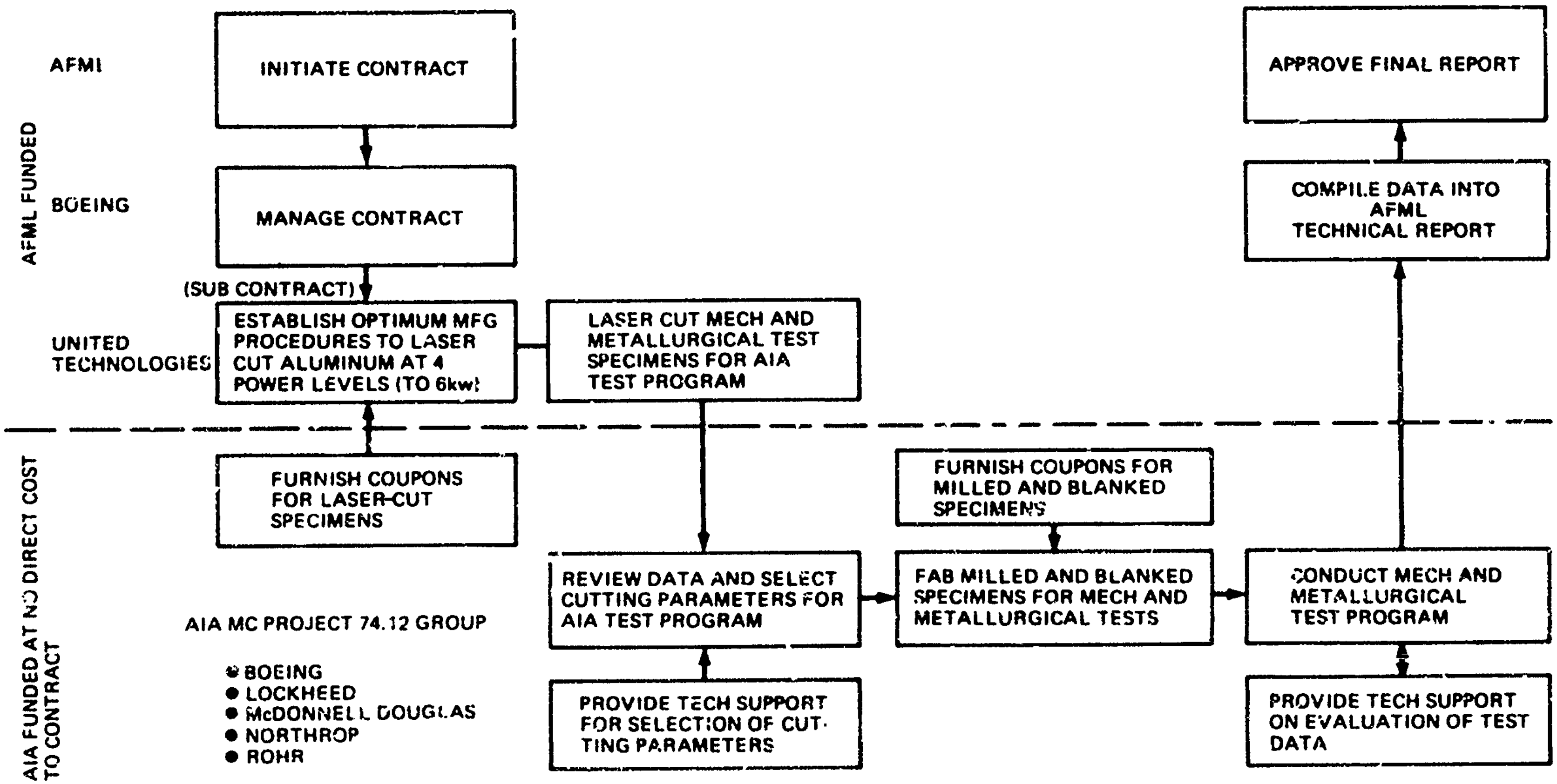


Figure 2—Responsibility and Work Flow Chart

TESTING COMPANY	2024-T3 BARE						TESTS TO BE PERFORMED	7075-T6 BARE						-0**	TESTING COMPANY
	0.040 in			0.063 in				0.040 in			0.063 in			0.063 in	
	M	B	L	M	B	L		M	B	L	M	B	L	–	
BOEING	* 4 (2)	7 (5)	7 (5)	4 (2)	7 (5)	7 (5)	SMOOTH FATIGUE	4 (2)	7 (5)	7 (5)	4 (2)	7 (5)	7 (5)	4 (2)	LOCKHEED, GA
McDONNELL DOUGLAS				4 (2)	7 (5)	7 (5)	NOTCHED FATIGUE (RIVET)				4 (2)	7 (5)	7 (5)		McDONNELL DOUGLAS
McDONNELL DOUGLAS				4 (2)	7 (5)	7 (5)	NOTCHED FATIGUE (HOLE)				4 (2)	7 (5)	7 (5)		McDONNELL DOUGLAS
BOEING	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	TENSILE	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	3 (2)	LOCKHEED, GA
ROHR			2			2	CORROSION	–	–	–	–	–	–	–	
LOCKHEED, CA			3			3	METALLOGRAPHY			3			3	3	LOCKHEED, CA

EDGE CONDITION: M – MILLED
B – BLANKED
L – LASER-CUT

* 4 – MINIMUM SPECIMENS TO BE TESTED
(2) – SPARE SPECIMENS

** 7075-0 TEST SPECIMENS WILL BE HEAT TREATED TO THE T6 CONDITION PRIOR TO TESTING

Figure 3—Test Plan

SECTION III
TECHNICAL DISCUSSION

1. LASER CUTTING (PHASES I AND II)

All laser cutting was accomplished by United Technologies Research Center using a 6-kw coaxial electric-discharge CO_2 laser with an unstable resonator mirror configuration (figure 4). It is neither the intent nor the objective of this program to infer that all lasers, or all CO_2 lasers, or even all CO_2 unstable resonator lasers, will produce identical results. Energy distribution in the focal region, gas-jet configuration, laser power stability, all play a major role in laser cutting performance and must be evaluated for each prospective laser supplier. The test pieces to be cut were positioned on the table of a milling machine schematically illustrated in figures 5, 6, 7 and 8 for circular, straight, or irregular cuts.

The two objectives of the laser cutting parameter investigation–optimization of the cutting parameters and preparation of mechanical, metallurgical, and environmental tests specimens –were accomplished in three phases as illustrated in figure 9. Tables 1 and 2 present a complete parametric summary of the combinations of variables studied in phases I and II.

Phase I of the laser cutting parameter investigation evaluated four different jet configurations (figures 10 through 13). The cuts produced in 0.063-inch-thick 7075-T6 aluminum by each jet is illustrated in figure 14. Note that the cut width shown in all figures were due to mounting techniques and do not represent actual kerf widths. The coaxial jet configuration was selected on the basis of resulting visual edge structure.

The selected jet configuration was utilized to study the effects of cutting parameter variations. Process variables evaluated were power settings, cutting speed, type of gas, and gas pressure. Tests were run at several speeds and power settings on all materials. Figure 15 shows typical results for 7075-T6. Based on these tests, air and CO_2 were found optimum. Air was selected on the recommendation of the participating companies based on economic considerations.

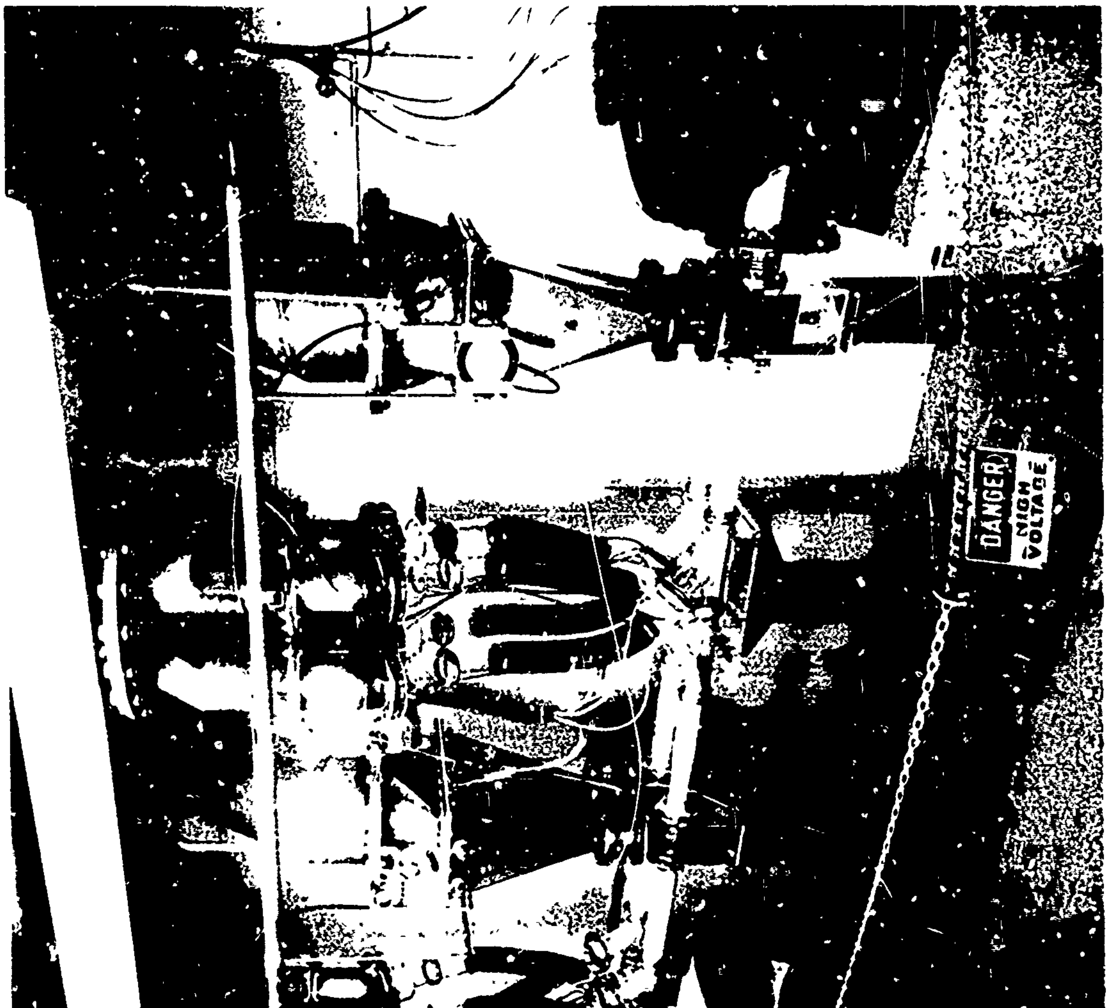
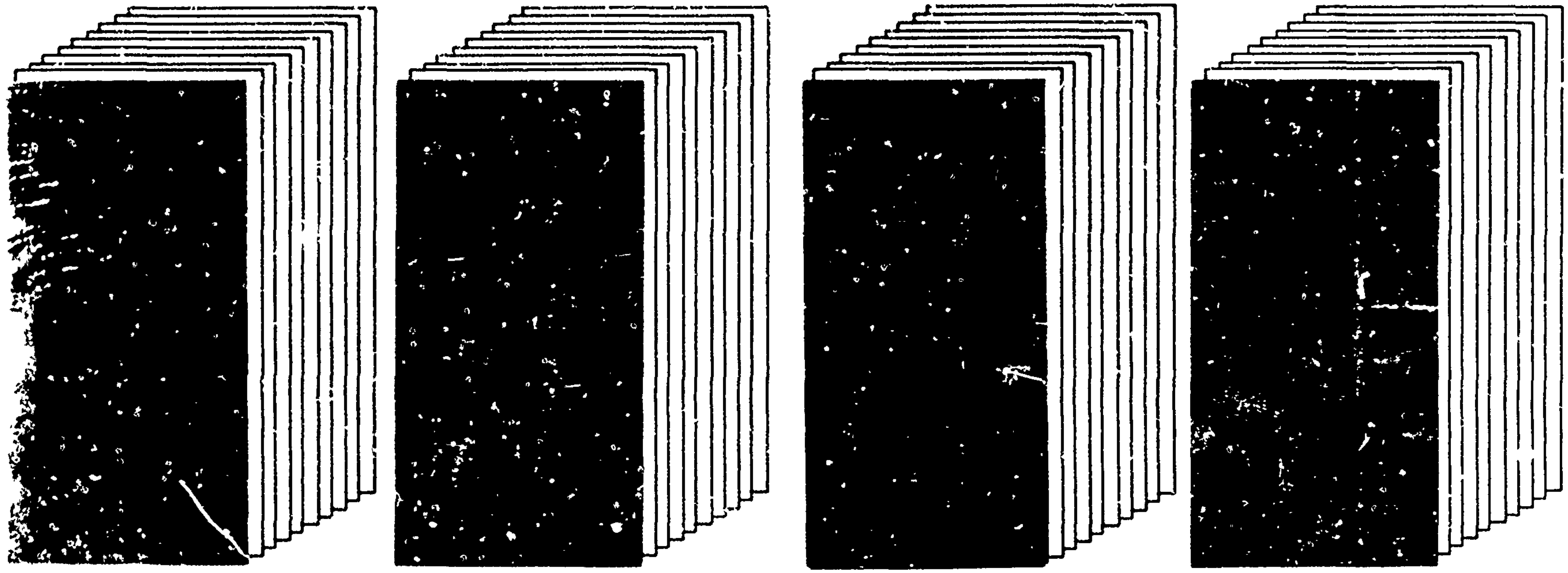


Figure 4—6-kw Coaxial Electric-Discharge Laser



600 CUTS WERE GENERATED AND INSPECTED VARYING:

MATERIAL (ALLOY, THICKNESS), LASER (POWER, JET-ASSIST) AND CUTTING (SPEED. GAS TYPE, GAS PRESSURE)

Figure 5—Summary of Laser Parametric Development

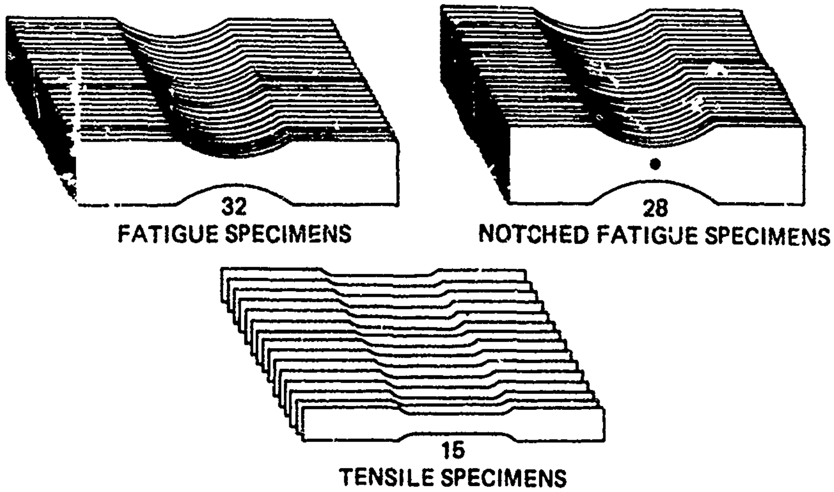


Figure 6—Summary of Laser-Cut Specimens Provided for Test

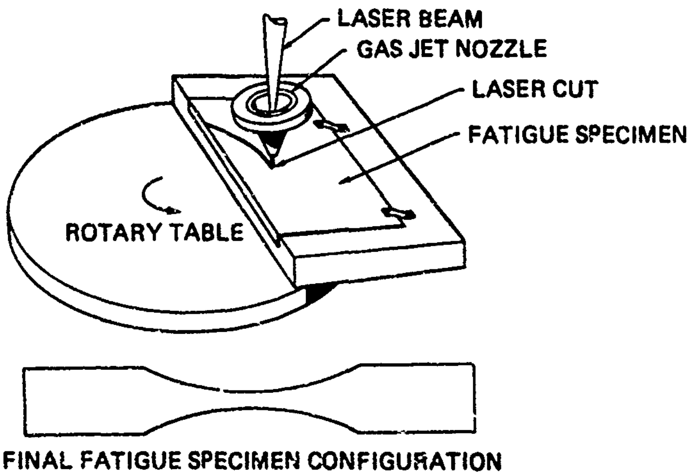


Figure 7—Fixturing for Laser-Cut Fatigue Specimens

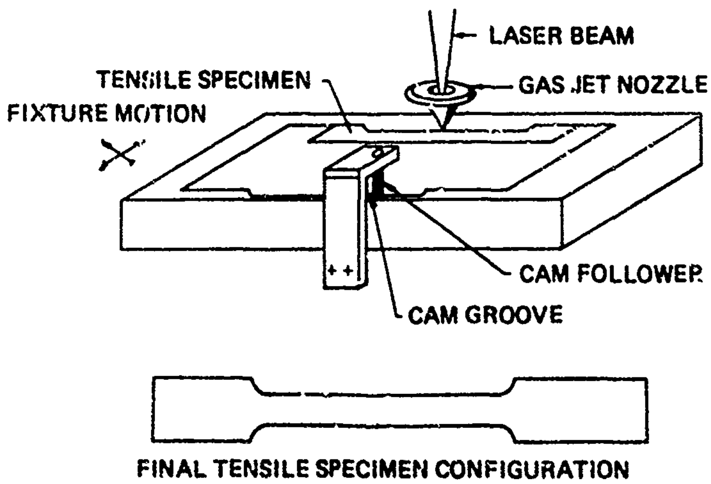


Figure 8—Fixturing for Laser-Cut Tensile Specimens

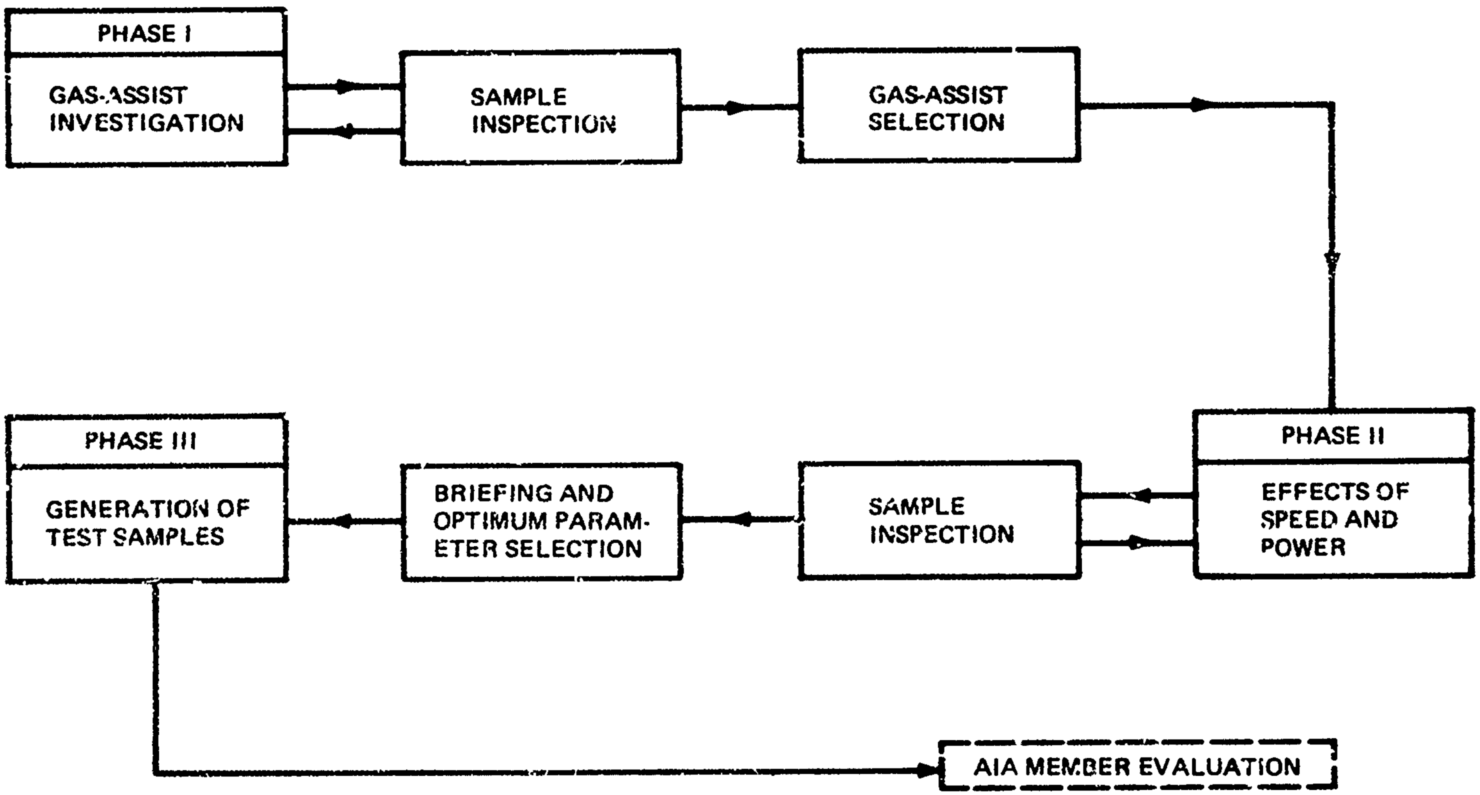


Figure 9—Laser Cutting of Aluminum Alloys Program

Table 1—Parametric Laser Cutting Summary (2024-T3 Aluminum)

Material	Thickness	Laser Power	Gas-Jet Medium	Pressure	Cutting Speed In 50 in/m Intervals
2024-T3	0.063 in	3.5 kw	Air	50	250-300
				100	250-300
				150	150-450
				200	150-400
				250	150-400
			Oxygen	50	500
				100	500
				150	150-700
				200	500
			Helium	50	300
				100	300
				150	150-450
				200	250-300
			Carbon Dioxide	50	450
				100	300-450
				150	150-500
				200	200-450
		1.5 kw	Air	50	100
				100	50-250
				150	100
				200	100
			CO_2	50	100
				100	50-150
				150	100
				200	100
		5 kw	Air	50	550
				100	550
				150	400-700
				200	550
			CO_2	50	600
				100	600
				150	400-800
				200	600
2024-T3	0.040 in	3.5 kw	Air	50	400
				100	400
				150	250-500
				200	400
			Oxygen	50	500
				100	500
				150	250-600
				200	400-500
			Helium	50	450
				100	450
				150	250-550
				200	400-450
			Carbon Dioxide	50	500
				100	500
				150	250-600
				200	400-500

Table 2—Parametric Laser Cutting Summary (7075-T6 Aluminum)

Material	Thickness	Laser Power	Gas-Jet Medium	Pressure	Cutting Speed In 50 in/m Intervals
7075-T6	0.063 in	3.5 kw	Air	100	150-400
				150	150-450
				200	150-450
				250	150-350
			Oxygen	100	150-450
				150	150-450
				200	150-450
				250	150-350
			Helium	100	150-350
				150	100-450
				200	100-350
				250	100-350
			Carbon Dioxide	100	150-350
				150	150-350
				200	150-550
				250	150-300
		1.5 kw	Air	50	100
				100	50-200
				150	100
				200	100
			CO_2	50	100
				100	50-200
				150	100
				200	100
		5 kw	Air	50	550
				100	550
				150	400-650
				200	550
			CO_2	50	600
				100	600
				150	400-750
				200	600
7075-T6	0.040 in	3.5 kw	Air	50	450
				100	450
				150	300-650
				200	450
			Oxygen	50	450
				100	450
				150	250-700
				200	450
			Helium	50	500
				100	500
				150	300-800
				200	500
			Carbon Dioxide	50	600
				100	600
				150	300-800
				200	600

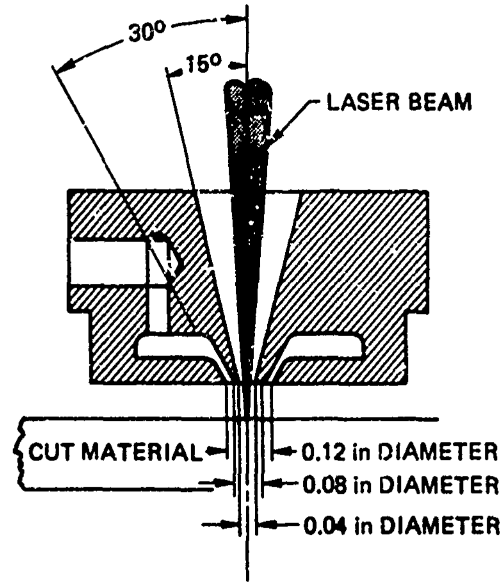


Figure 10—Concentric Jet-Assist Configuration

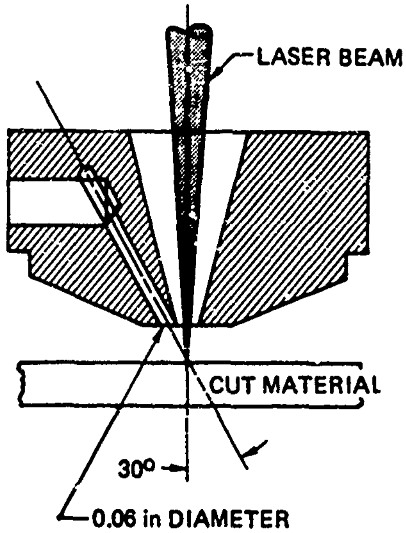


Figure 11—Off-Axis Jet-Assist Configuration

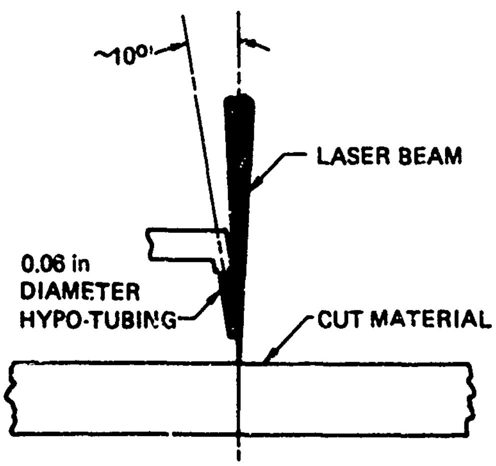


Figure 12—Needle Jet-Assist Configuration

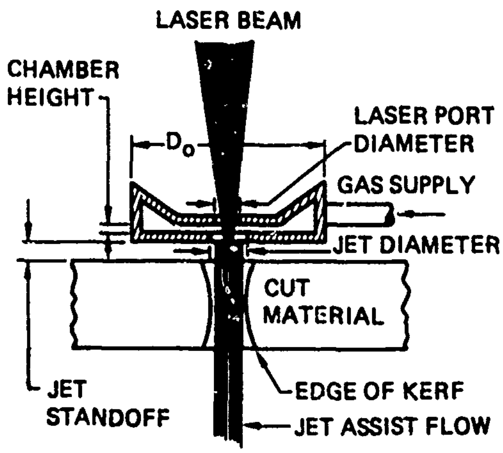


Figure 13—Coaxial Jet-Assist Configuration

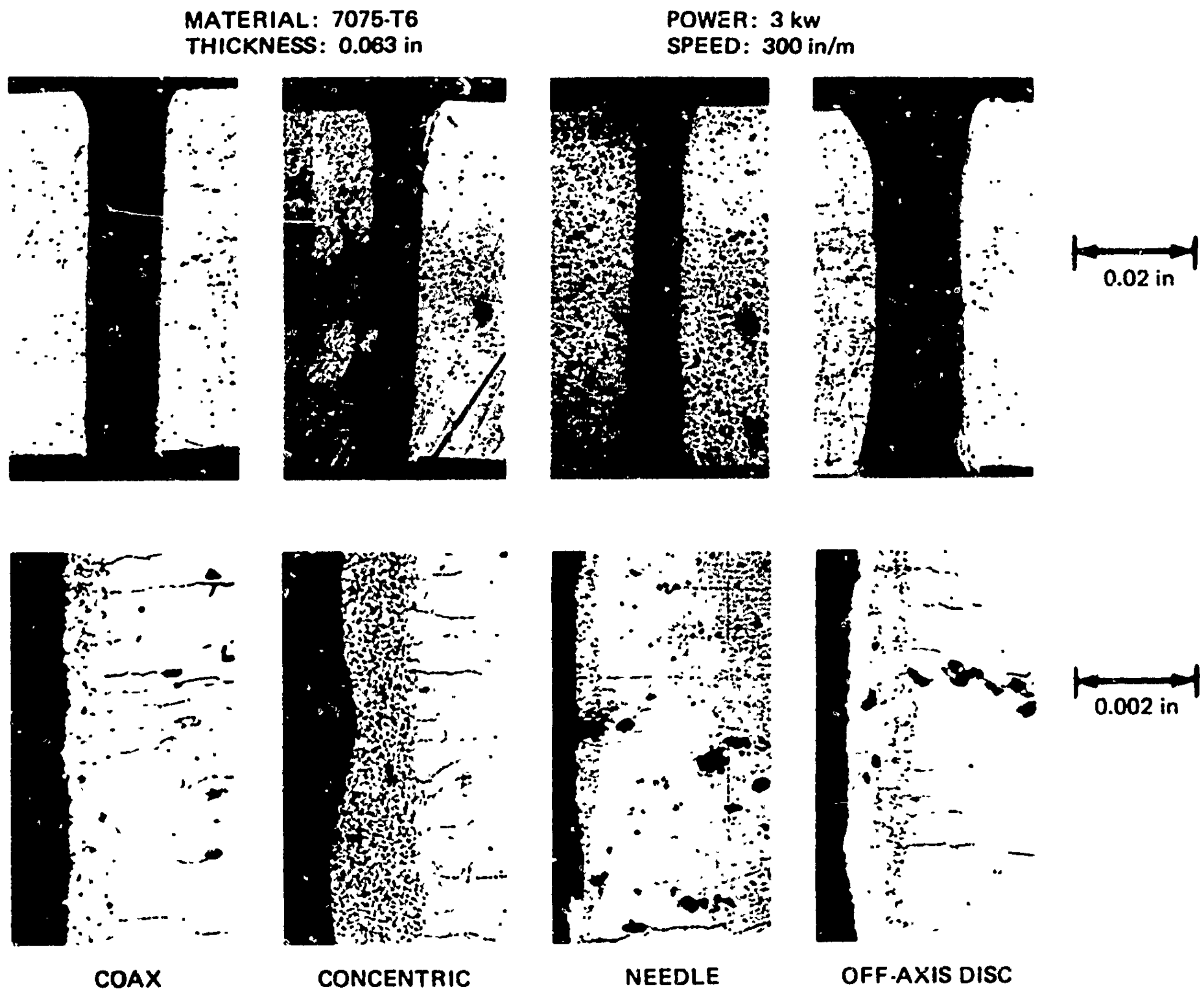


Figure 14—Effect of Jet Configurations on Cut Characteristics

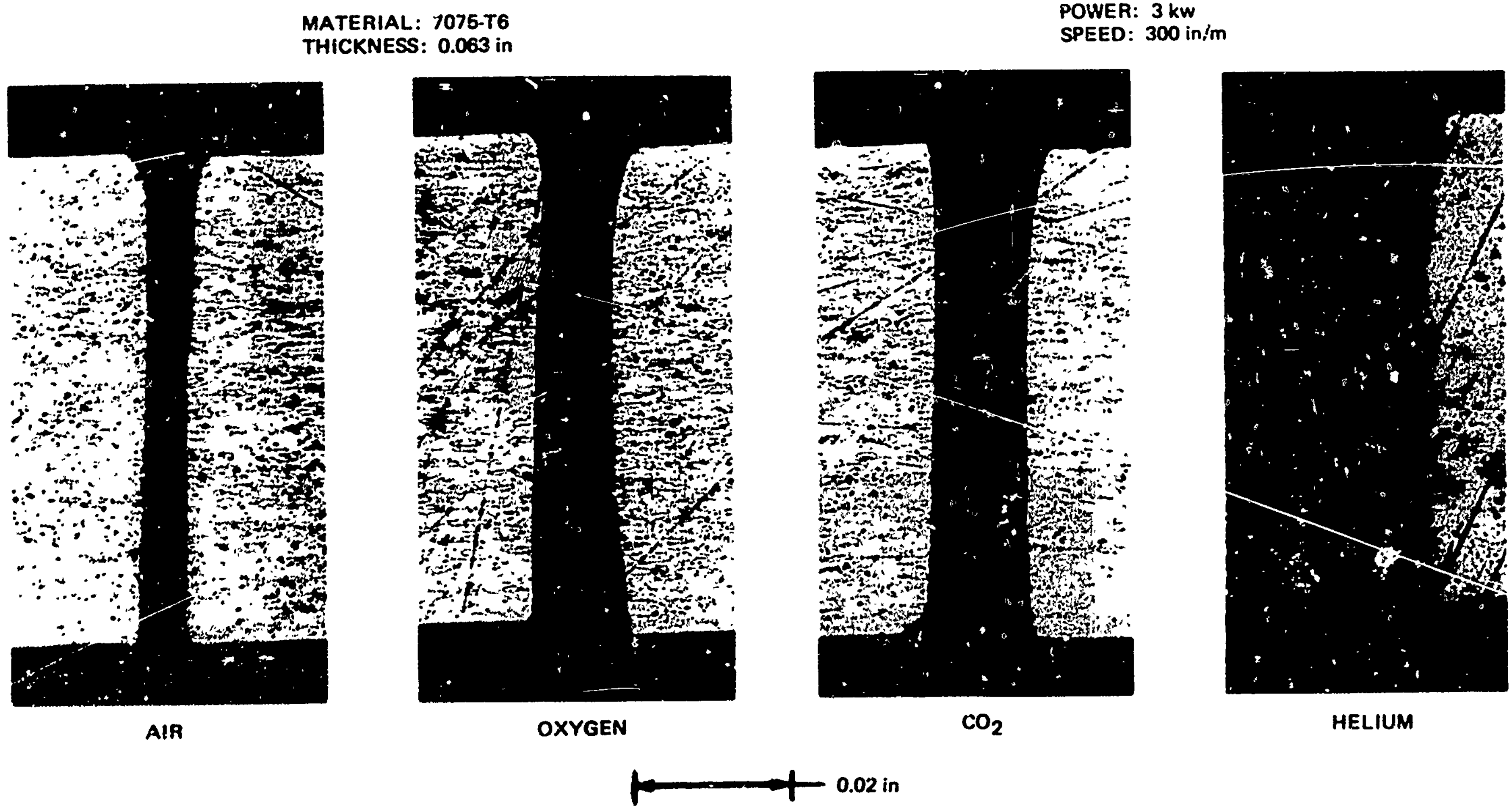


Figure 15—Effect of Gas on Cut Characteristics

Phase II laser cutting parameter optimization consisted of determining the optimum values for power level, speed, and gas pressure for each alloy and thickness, using the selected jet configuration and air as a gas. Figures 16, 17, and 18 show typical effects of variation in three parameters on cuts in 7075-T6. Based on these tests, as well as evaluation of samples by Lockheed-California, Lockheed-Georgia, Douglas, and Boeing, the following optimum cutting parameters were selected for both 2024-T3 and 7075-T aluminum alloys and used for the test phase of this program:

	Thickness	
	0.040 inch	0.063 inch
Power (kw)	3.5	3.5
Speed (in/m)	450	300
Gas	Air	Air
Gas pressure (psig)	200	200

At power levels above and below 3.5 kw, visual quality of the cut decreased at all speeds and pressures used (see tables 1 and 2).

2. MECHANICAL TESTS (PHASE III)

a. Specimen Preparation and Test Procedure

Tensile and tension-tension fatigue tests were conducted on specimens fabricated from 0.040- and 0.063-inch, 2024-T3, 7075-T6, and 7075-0 aluminum heat treated to -T6 after laser cutting. All specimens for each thickness of each alloy were from a single lot of material. Specimen edges were produced by milling, blanking, and laser cutting plus a belt sanding operation to remove the burr on the flat rface only of blanked and laser-cut specimens. The cut surface was not altered. Figure 19 shows the smooth and hole-notched fatigue and static tensile test specimens.

The fatigue tests were conducted by Boeing, Lockheed and McDonnell Douglas using Baldwin-Lima-Hamilton Universal Fatigue Testing Machines. The machines operated at 1800 cycles per minute and the relative humidity (RH) was maintained at approximately 80 percent for the smooth specimens and approximately 35 percent for the notched specimens. The fatigue ratio was +0.10.

Tensile tests were conducted by Boeing and Lockheed per ASTM E-8 at a strain rate of 0.005- to 0.006-inch-per-inch-per-minute using Baldwin Universal Testing Machines.

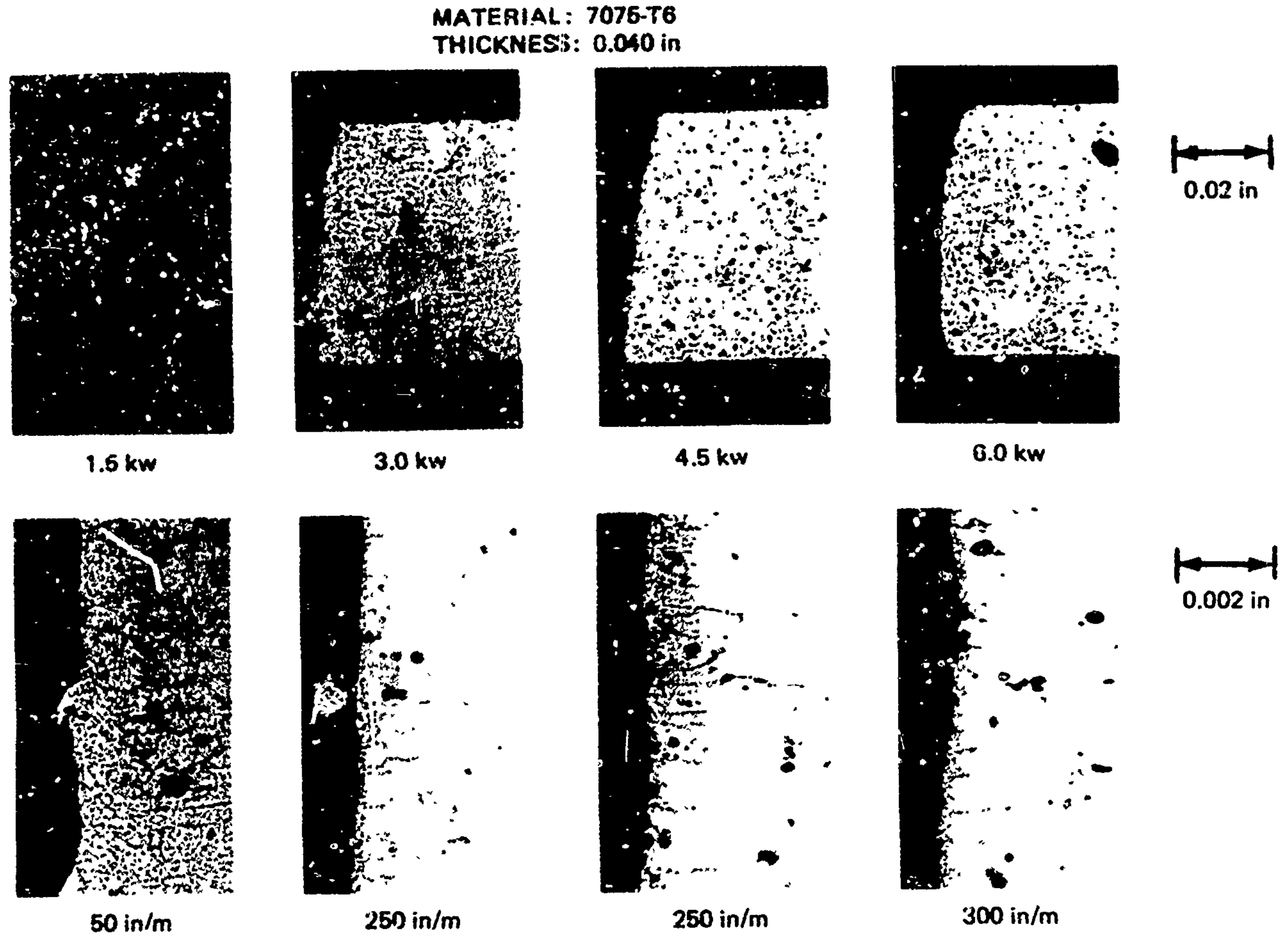
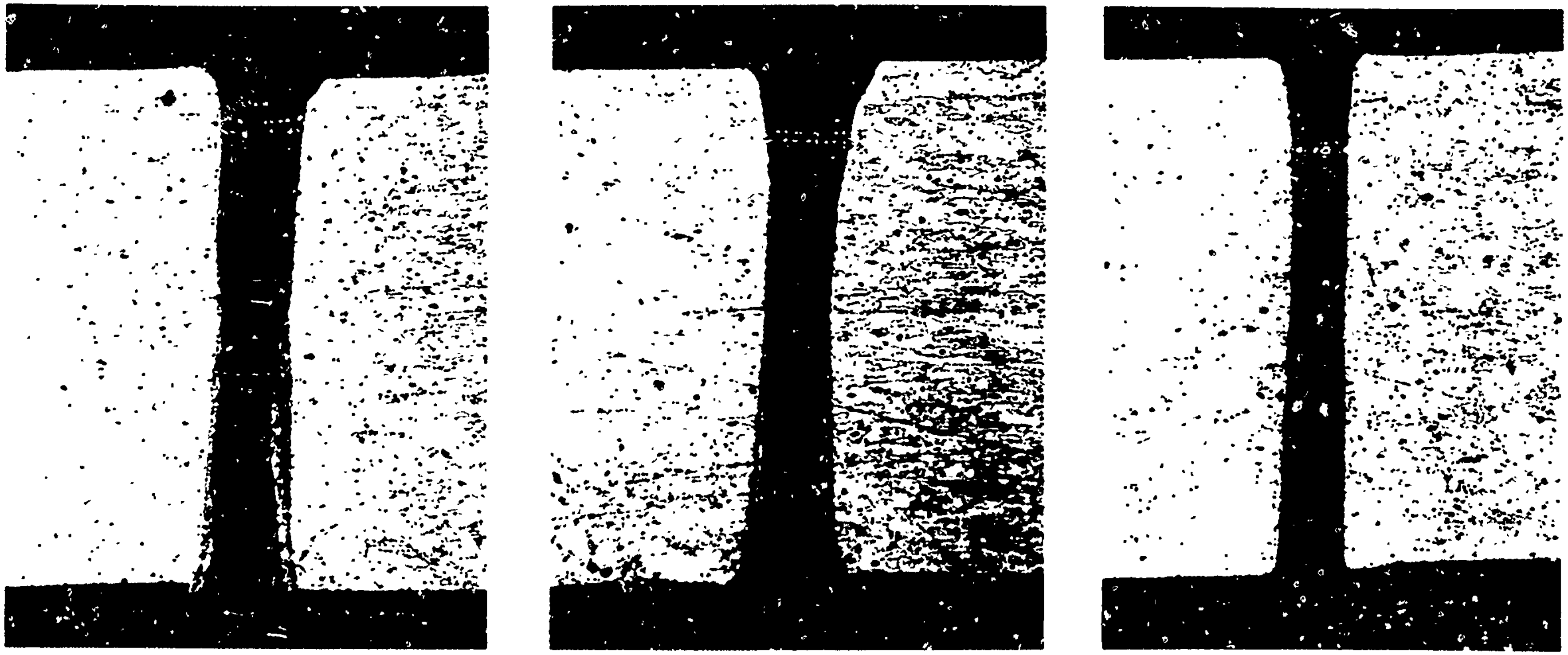


Figure 16—Effect of Power on Cut Characteristics

MATERIAL: 7075-T6
THICKNESS: 0.063 in

POWER: 3 kw
AIR PRESSURE: 150 psig



200 in/m | 250 in/m | 300 in/m

Figure 17—Effect of Speed on Cut Characteristics

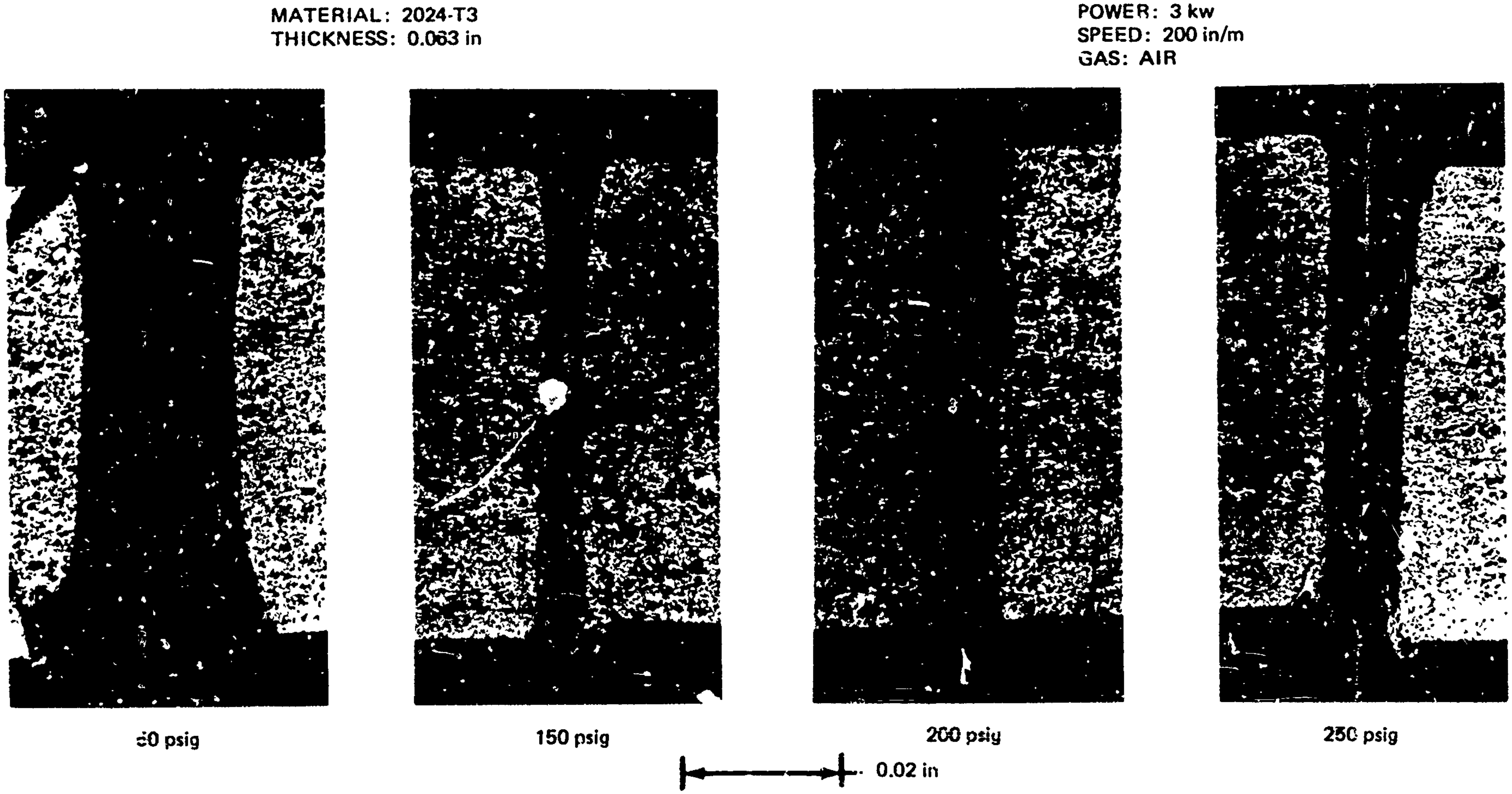
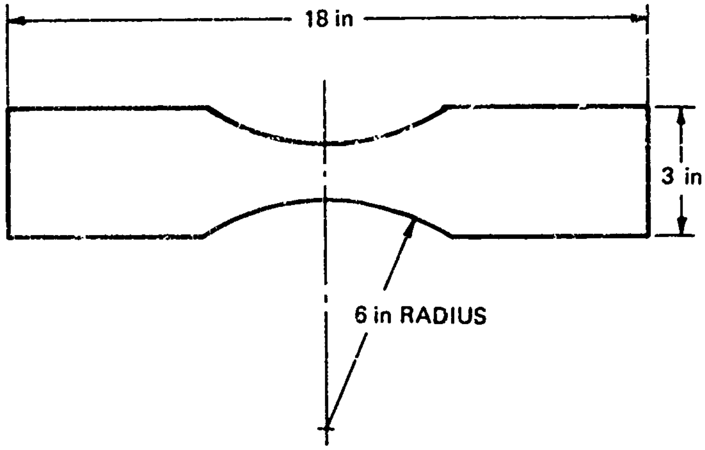
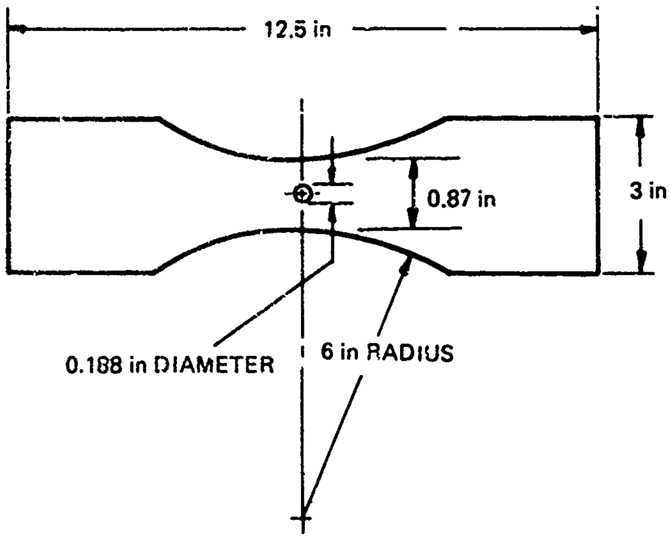


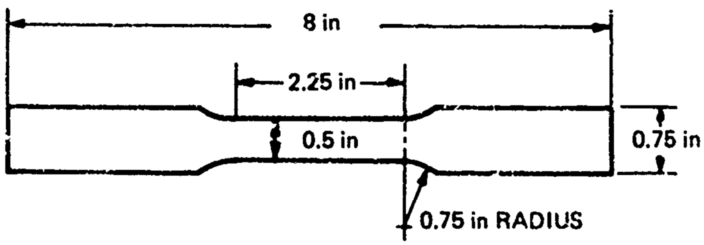
Figure 18—Effect of Gas Pressure on Cut Char 'cteristics



GEOMETRY OF SMOOTH FATIGUE SPECIMEN



GEOMETRY OF NOTCHED FATIGUE SPECIMEN



GEOMETRY OF TENSILE TEST SPECIMEN

Figure 19—Geometry of Fatigue and Tensile Test Specimens

b. Results of Unnotched Fatigue Tests

The results of fatigue tests on unnotched specimens are presented in Appendix A and figures 20 and 21. The data indicate that for both 0.040- and 0.063-inch 2024-T3 and 7075-T6 aluminum, fatigue properties of blanked and laser-cut specimens are similar. Both blanked and laser-cut specimens have fatigue properties lower than base line (milled specimens). The reason for the reduction in fatigue performance is attributed to stress risers in the case of blanked edges, since it is not a thermal process. In the case of the laser-cut edges, both a mechanical notch and thermal effect must be considered. The influence of the thermal effect is identified by looking at the test results for 0.063-inch 7075-0 aluminum that was solution treated and aged to -T6 after laser cutting, thereby minimizing thermal overaging and diffusion of alloying elements at grain boundaries. The data indicate slightly better, but not necessarily significant, fatigue performance than specimens with an as-laser-cut edge, leading to the inference that the significant reason for reduction in fatigue strength exhibited by the laser-cut edge is due to the mechanical effects rather than metallurgical irregularities in the surface.

c. Results of Hole-Notched Fatigue Tests

The results of the hole-notched fatigue tests are presented in Appendix B and figures 22 and 23. The data indicate that milled, blanked, and laser-cut specimens have the same fatigue strength in the presence of a drilled open hole. It was also observed that the failure origins were all at the hole surface. It can be concluded from this that an open hole represents a much more damaging condition than either a milled, blanked, or laser-cut edge.

If the hole is filled by a fastener, and further if the fastener was installed into slight interference with the hole, the fatigue life of specimens containing the now filled hole are increased significantly. This behavior was observed for the milled specimens as shown in figure 23. The blanked and laser-cut specimens showed an improvement in fatigue life but not to the extent of the milled specimen.

The data indicate a slightly better fatigue strength for 7075-T6 filled-hole specimens which were laser-cut as compared to 7075-T6 specimens which were blanked. In the case of 2024-T3, a reverse trend is indicated. Examination of the fracture origins verify the data which show the milled specimens to have better fatigue strength than both blanked and laser-cut specimens as all failures were still at the hole. The blanked and laser-cut specimens failed primarily from the cut edge, however, some of the blanked and laser-cut specimens have equivalent fatigue properties, although a tendency seems to exist for the blanked specimens to have slightly better properties.

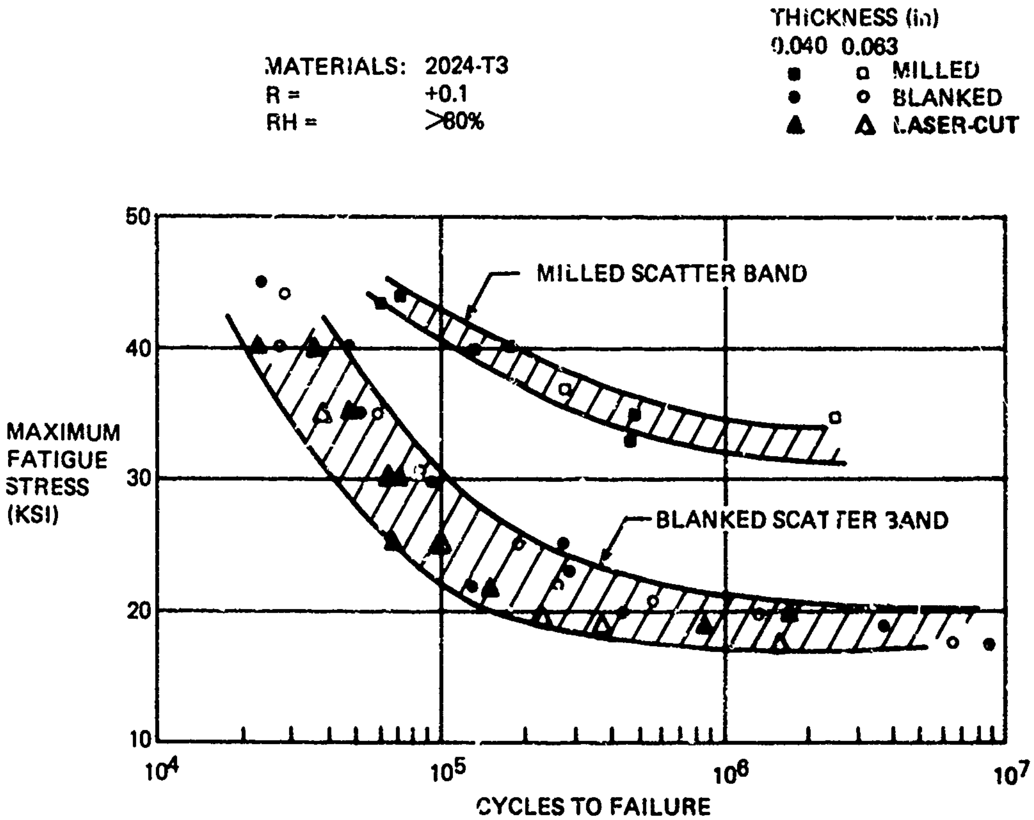


Figure 20—Results of Unnotched Fatigue Tests (2024-T3)

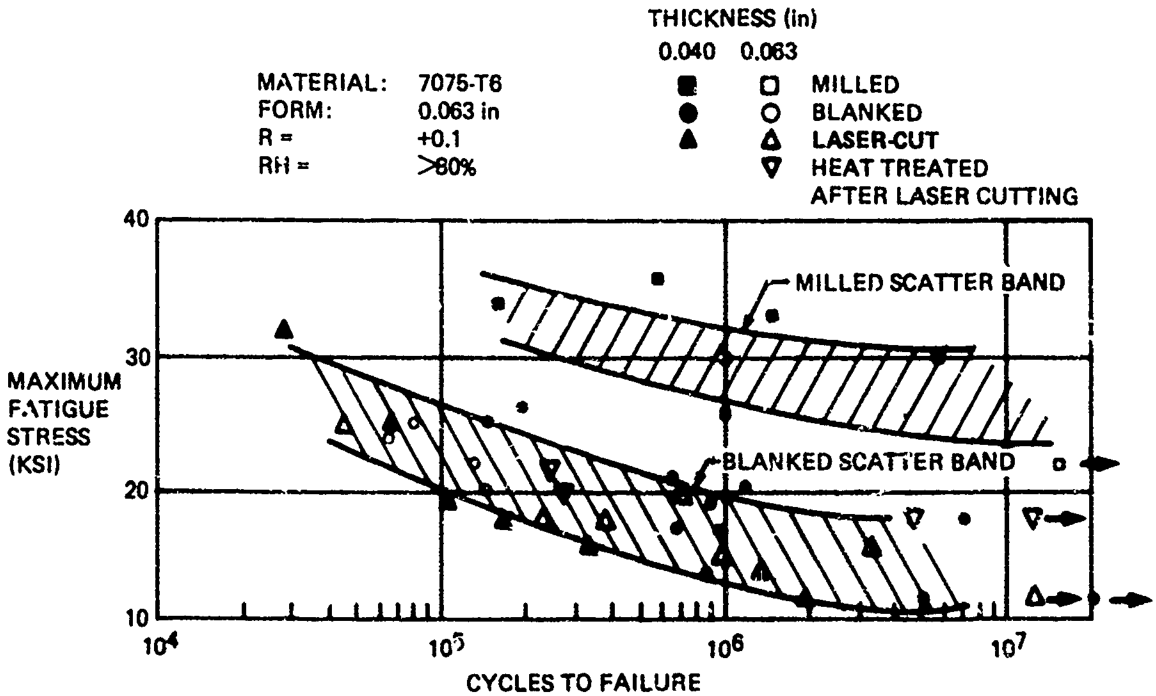


Figure 21—Results of Unnotched Fatigue Tests (7075-T6)

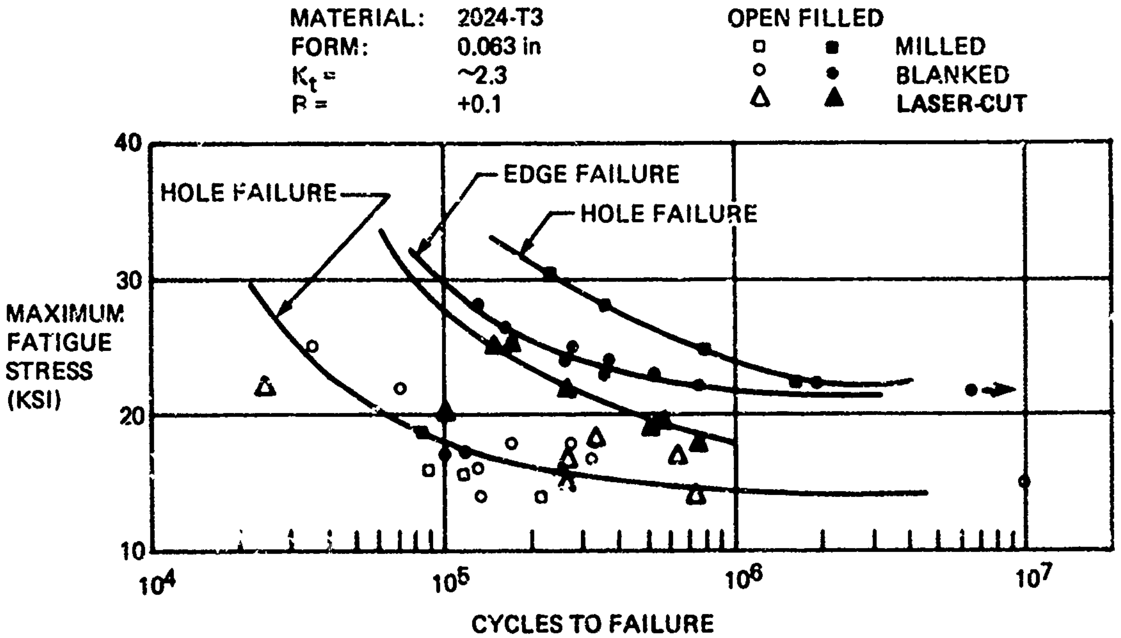


Figure 22—Results of Notched Fatigue Tests (2024-T3)

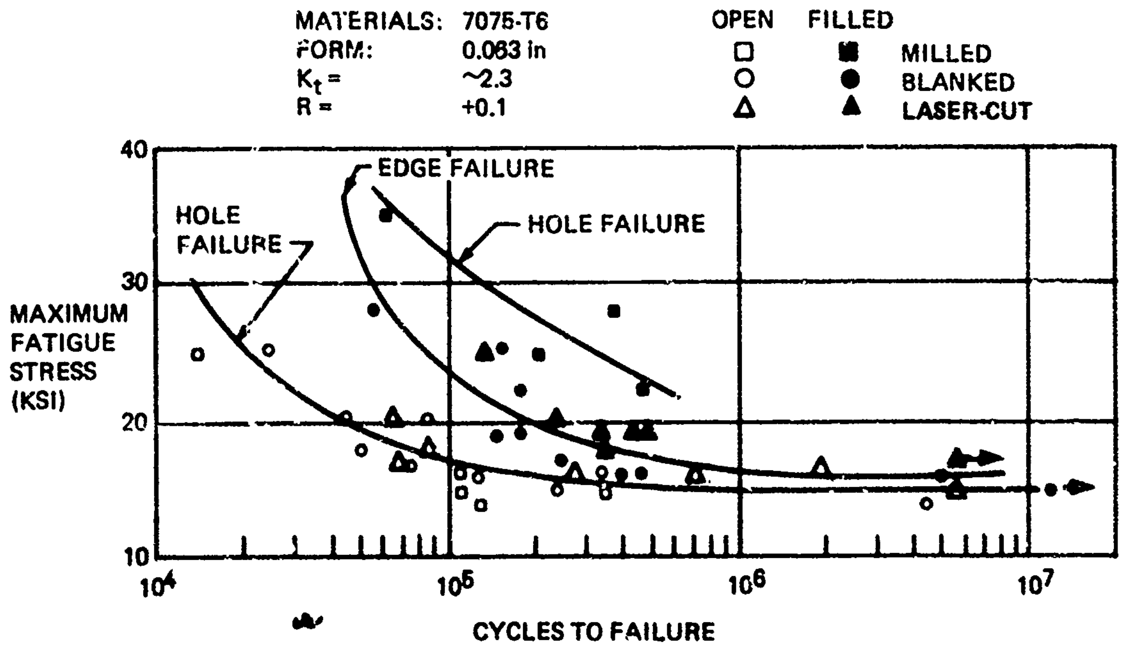


Figure 23—Results of Notched Fatigue Tests (7075-T6)

d. Results of Tensile Tests

The results of static tensile tests are given in tables 1 and 2. The data show no significant degradation in strength or elongation of either 2024-T3 or 7075-T6 aluminum due to the laser cutting. The strength properties developed, including the heat-treated 7075 aluminum, are consistent with typical property values.

3. METALLURGICAL EVALUATION

a. Metallurgical Procedure

Sections were taken from broken laser-cut fatigue specimens for metallographic examination. The sections were taken in the radii area to avoid areas of secondary fatigue cracking damage as shown in tables 3 and 4.

The examination and photomicrographs were made on a Zeiss Balphot II metallograph. The heat penetration depth and recast metal thickness measurements were made at 200X with an eyepiece having uniform grid lines. Photomicrographs were taken at 60X, 100X, and 200X to show the laser-cut surfaces and specific features.

b. Results

Laser-Cut Surfaces–The laser-cut surfaces showed varying degrees of heat penetration and recast metal. The cuts were essentially flat and normal to the rolled surfaces of the sheet. The specimens were free of the exit erosion that was observed on material cut in the previous program (MC 74.12 Project Report dated December 1975). The belt sanding had removed the recast exit burr; however, one microsection of 0.063-inch 2024-T3 aluminum showed 0.0137 inch of recast metal at the exit surface. The maximum depths of heat penetration observed and maximum height of recast metal are shown in table 5.

Heat Penetration Depth–Heat penetration was observed on all transverse sections. The 2024 material had more intergranular diffusion sites than 7075 material; however, the 0.063-inch 7075 material had deeper penetration. These features are shown in figures 24 through 43.

Recast Layer–The recast layer observed was least on the 0.040-inch materials and on the 7075 material heat treated after laser cutting. These features are also shown in figures 32 through 35.

Table 3—Results of Tensile Tests on Specimens with Milled, Blanked, and Laser-Cut Edges (2024-T3 Aluminum) [1]

Material	Thickness (Inch)	[2] Edge	Tensile Ultimate KSI	Tensile Yield KSI	Elongation % In (2) Inches
2024-T3	0.040	M	65.5	45.2	16.0
2024-T3	0.040	M	67.0	45.1	16.0
2024-T3	0.040	M	66.5	44.6	18.0
2024-T3	0.040	B	80.0	45.3	7.0
2024-T3	0.040	B	65.5	46.0	14.0
2024-T3	0.040	B	65.5	46.0	13.0
2024-T3	0.040	L	65.7	44.5	16.0
2024-T3	0.040	L	65.5	44.1	16.0
2024-T3	0.040	L	64.6	43.6	16.0
2024-T3	0.063	M	67.5	48.0	19.0
2024-T3	0.063	M	67.5	47.3	17.0
2024-T3	0.063	M	67.5	47.3	15.0
2024-T3	0.063	B	65.5	46.9	14.0
2024-T3	0.063	B	66.0	46.9	13.0
2024-T3	0.063	B	66.5	47.4	13.0
2024-T3	0.063	L	66.0	46.5	14.0
2024-T3	0.063	L	66.3	47.0	14.0
2024-T3	0.063	L	66.6	47.2	12.0

Table 4—Results of Tensile Tests on Specimens with Milled, Blanked, and Laser-Cut Edges (7075-T6 Aluminum) [1]

Material	Thickness (inch)	[2] Edge	Tensile Ultimate KSI	Tensile Yield KSI	Elongation % In (2) Inches
7075-T6	0.040	M	84.0	73.1	12.0
7075-T6	0.040	M	84.3	72.7	13.0
7075-T6	0.040	M	84.0	73.1	13.0
7075-T6	0.040	B	84.5	72.7	10.0
7075-T6	0.040	B	83.4	72.4	7.0
7075-T6	0.040	B	82.9	72.4	6.0
7075-T6	0.040	L	81.2	72.1	6.5
7075-T6	0.040	L	82.3	71.9	10.0
7075-T6	0.040	L	81.5	71.9	9.0
7075-T6	0.063	M	86.9	75.2	8.0
7075-T6	0.063	M	87.2	76.3	12.0
7075-T6	0.063	M	87.4	76.4	11.0
7075 T6	0.063	B	86.2	75.2	6.0
7075-T6	0.063	B	86.8	75.4	7.0
7075-T6	0.063	B	87.5	75.3	10.0
7075-T6	0.063	L	82.3	72.4	9.0
7075-T6	0.063	L	85.6	73.6	11.0
7075-T6	0.063	L	85.4	73.3	11.0
7075-T6	0.063	L	85.8	73.7	12.0
7075-0 [3]	0.063	L	84.6	74.7	12.0
7075-0	0.063	L	84.7	75.0	11.0
7075-0	0.063	L	84.5	74.8	9.5

[1] Belt sanded to remove burr [2] M—Milled, B—Blanked, L—Laser cut [3] Heat Treat to 7075-T6 after Laser cutting

Table 5—Metallurgical Features of Laser Cut Aluminum

MATERIAL	FATIGUE COUPON NO	THICKNESS (in)	EDGE	(1) SECTION	(2) HPD, MAX (in)	(3) RECAST, MAX (in)	PHOTOMICROGRAPHS
2024-T3	3L-10	0.040	A	T	0.0032	0.0017	100X & 200X
			A	L	0.0038	0.0010	EXIT SURFACE (100X)
			B	T	0.0032	0.0008	100X
2024-T3	3L-13	0.063	A	T	0.0034	0.0021	60X & 200X
			A	L	0.0038	0.0137	EXIT SURFACE (100X)
			B	T	0.0042	0.0029	60X
7075-T6	6L-10	0.040	A	T	0.0021	0.0015	100X & 200X
			A	L	0.0015	0.0019	EXIT SURFACE (100X)
			B	T	0.0032	0.0008	100X
7075-T6	6L-23	0.063	A	T	0.0049	0.0019	60X
			A	L	0.0048	0.0034	EXIT SURFACE (100X)
			B	T	0.0049	0.0034	60X & 200X
7075-0 CUT & HT TO T6	0L-5	0.063	A	T	0.0055	0.0002	60X
			A	L	NONE	0.0019	EXIT SURFACE (100X)
			B	T	0.0061	0.0006	60X & 200X

(1) T IS TRANSVERSE TO CUTTING DIRECTION AND L IS PARALLEL TO CUTTING DIRECTION

(2) HPD IS HEAT PENETRATION DEPTH OBSERVED

(3) RECAST IS THE ADHERENT METAL REMAINING ON LASER CUT SURFACE

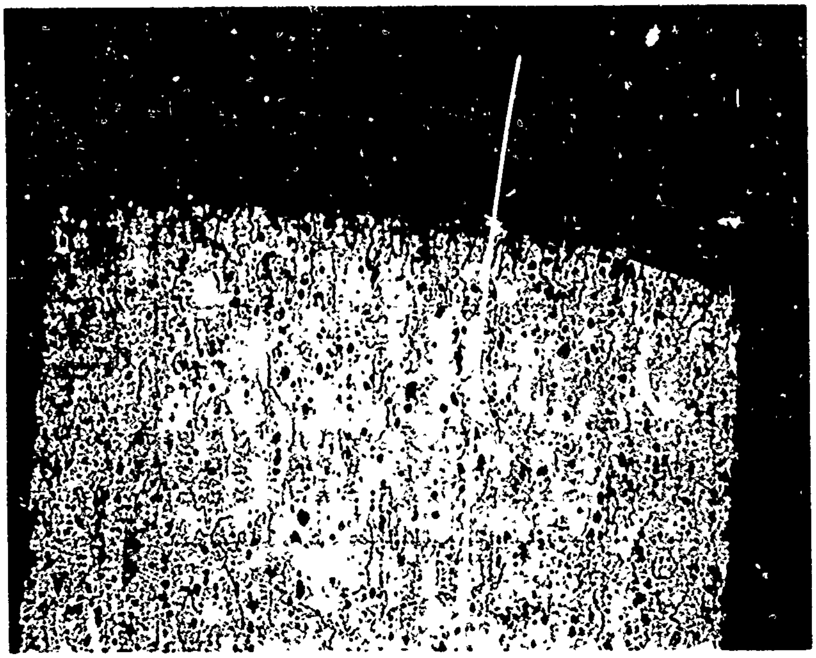


Figure 24—2024-T3, 0.040-inch Sheet, Edge A, Transverse, 100X, 3L-10

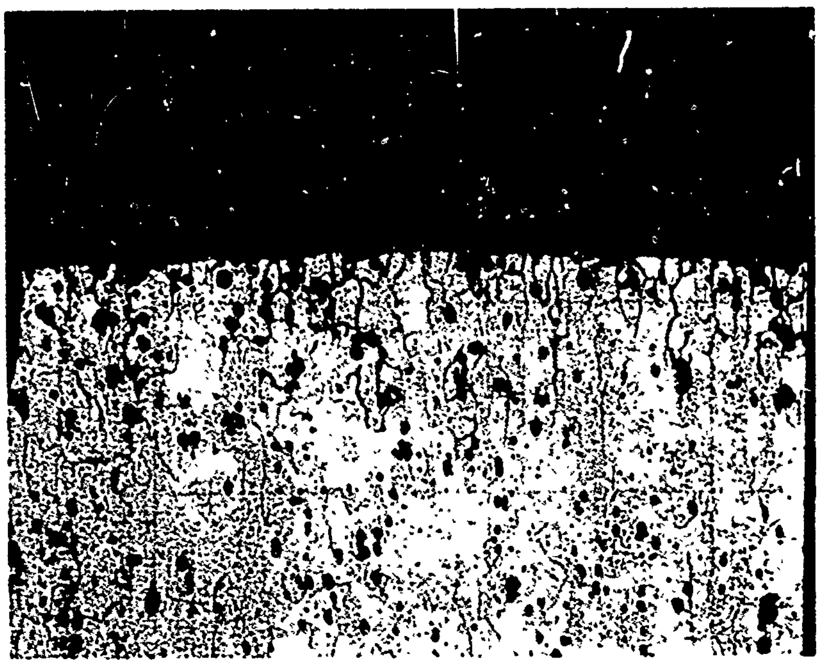


Figure 25—2024-T3, 0.040-inch Sheet, Edge A, Transverse, 200X, 3L-10

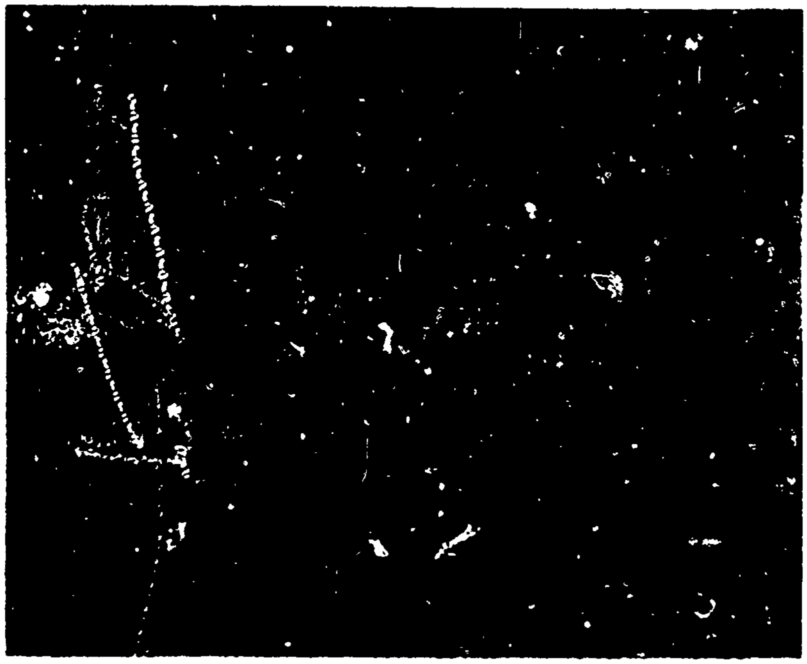


Figure 26—2024-T3, 0.040-inch Sheet, Edge A, Exit Surface, Longitudinal, 100X, 3L-10

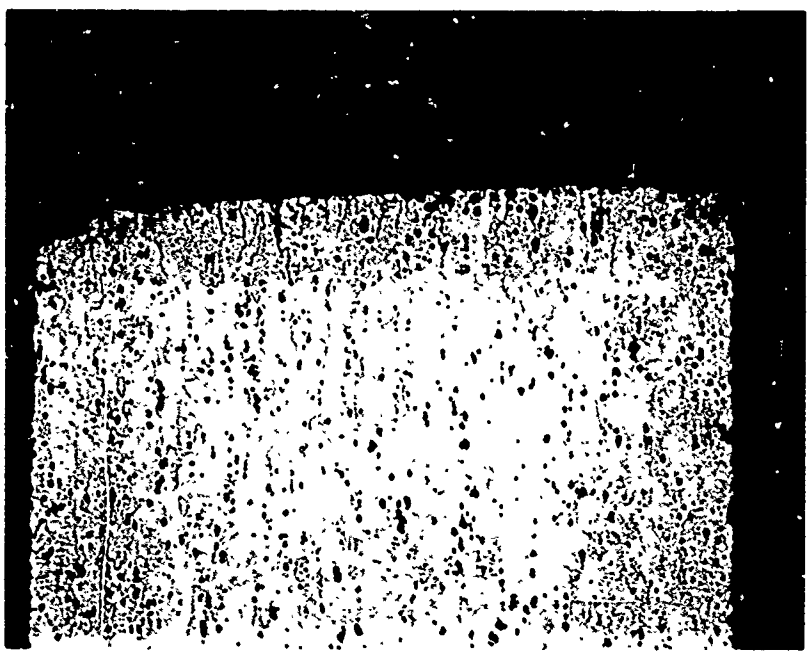


Figure 27—2024-T3, 0.040-inch Sheet, Edge B, Transverse, 100X, 3L-10

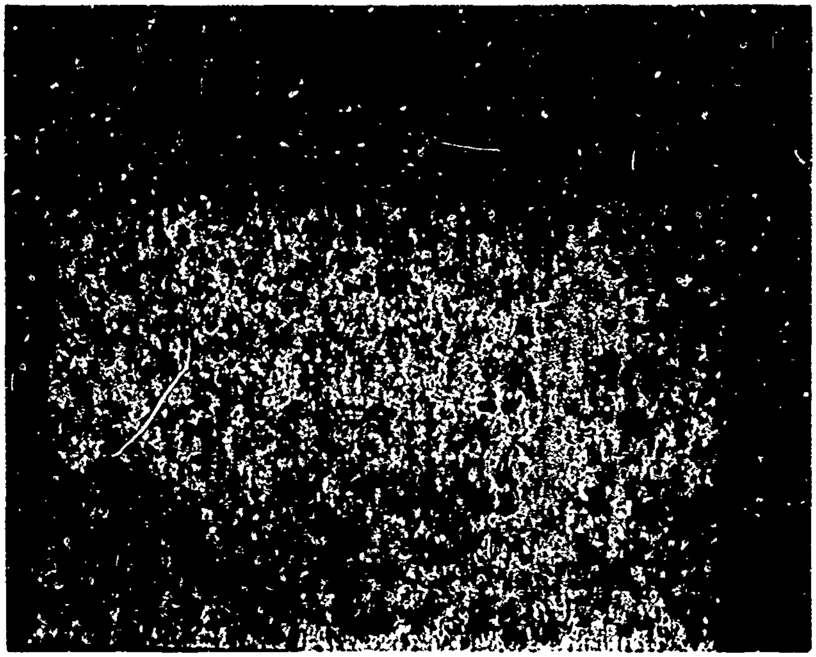


Figure 28—2024-T3, 0.061-inch Sheet, Edge A, Transverse, 60X, 3L-13

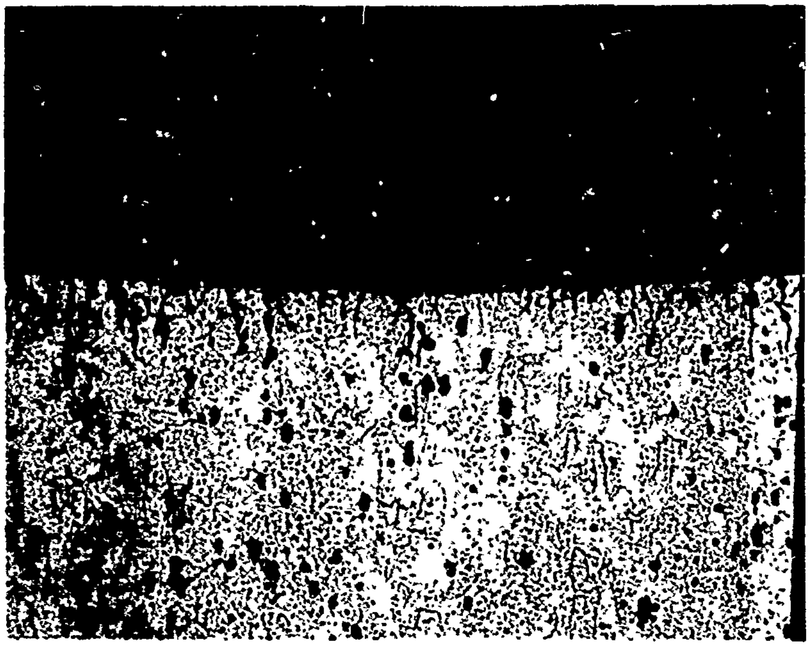


Figure 29—2024-T3, 0.061-inch Sheet, Edge A, Transverse, 200X, 3L-13

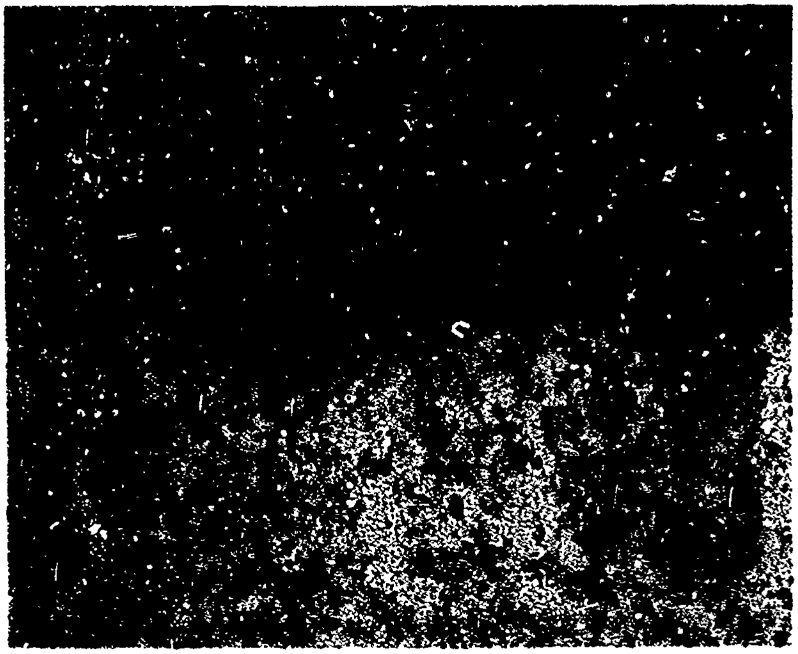


Figure 30—2024-T3, 0.061-inch Sheet, Edge A, Exit Surface, Longitudinal, 100X, 3L-13

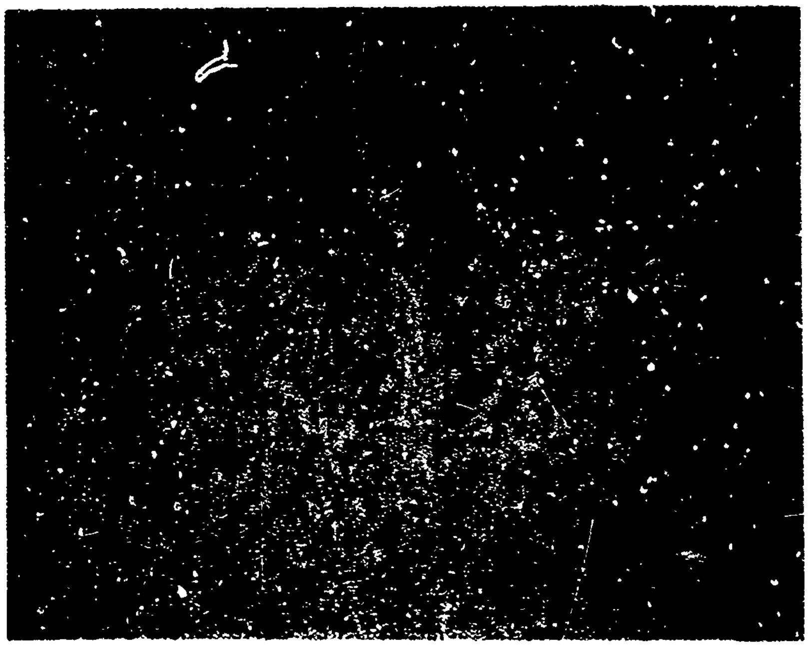


Figure 31—2024-T3, 0.061-inch Sheet, Edge B, Transverse, 60X, 3L-13

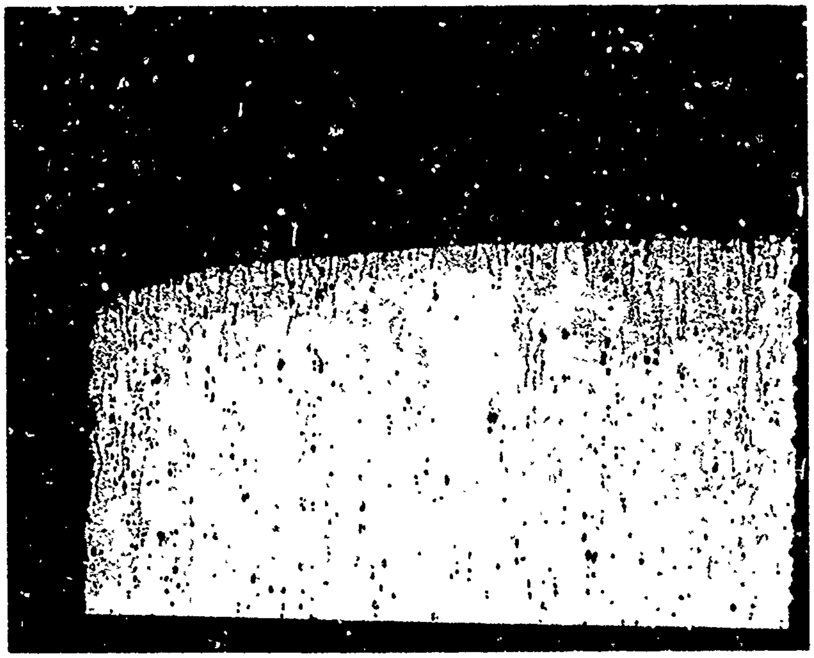


Figure 32—7075-T6, 0.040-inch Sheet, Edge A, Transverse, 100X, 6L-10

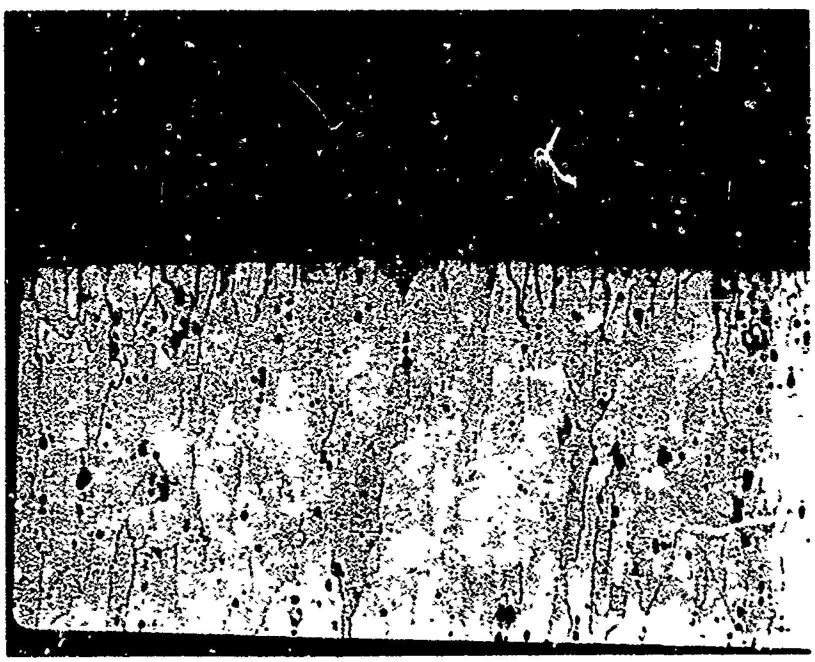


Figure 33—7075-T6, 0.040-inch Sheet, Edge A, Transverse, 200X, 6L-10

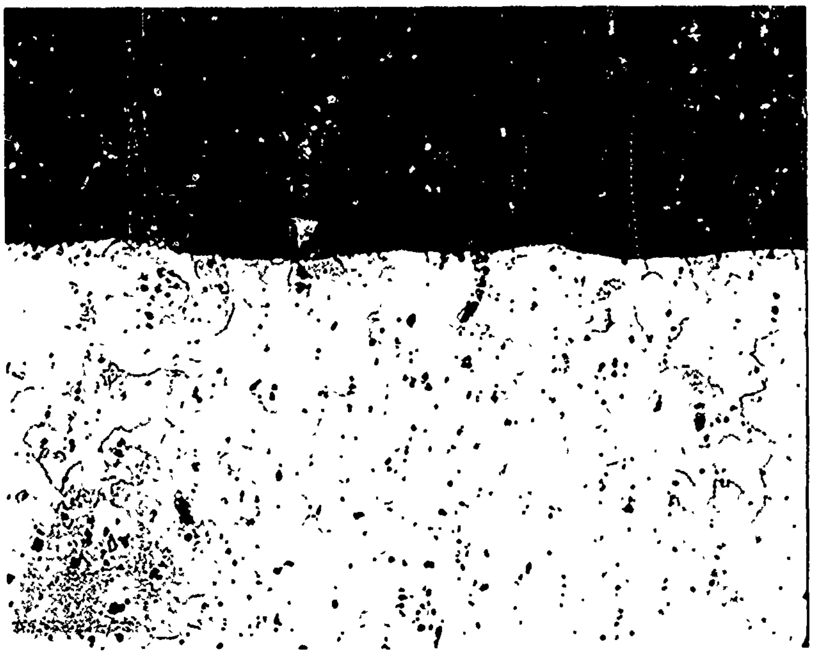


Figure 34—7075-T6, 0.040-inch Sheet Edge A, Exit Surface, Longitudinal, 100X, 6L-10

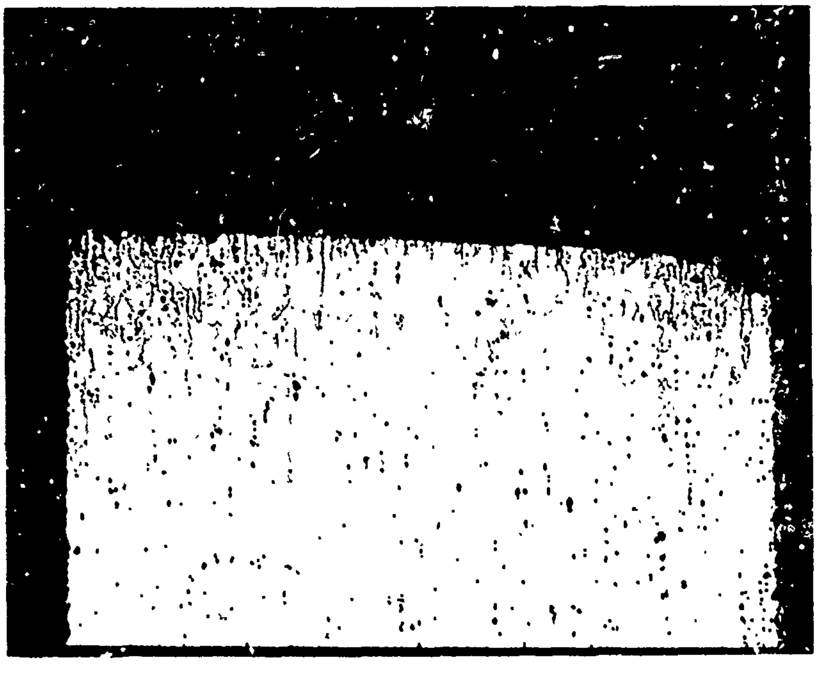


Figure 35—7075-T6, 0.040-inch Sheet, Edge B, Transverse, 100X, 6L-10

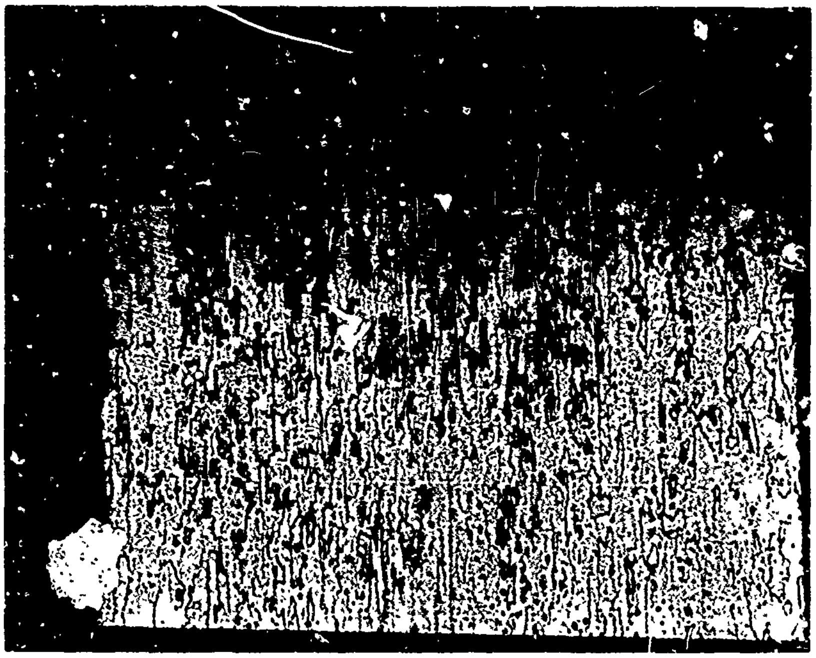


Figure 36—7075-T6, 0.063-inch Sheet, Edge A, Transverse, 60X, 6L-23

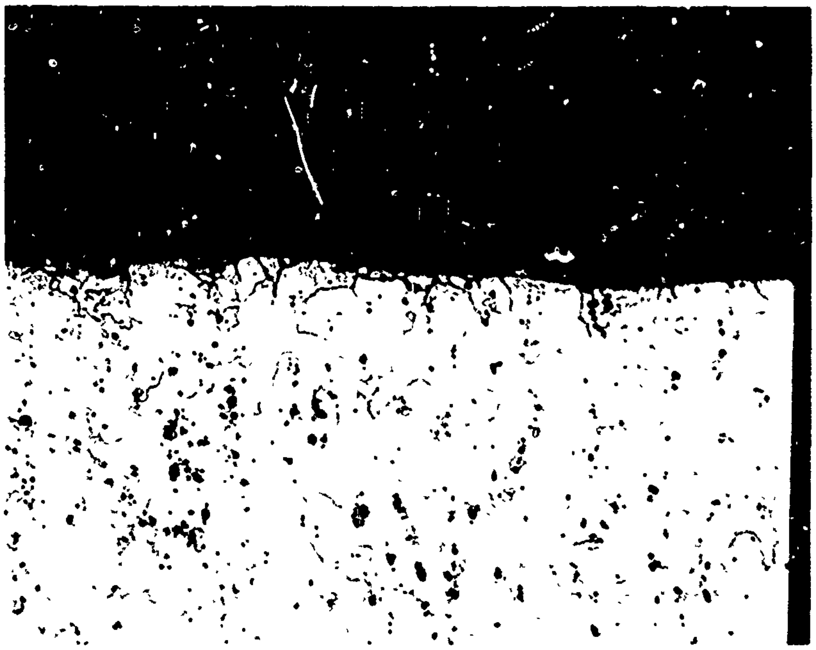


Figure 37—7075-T6, 0.063-inch Sheet, Edge A, Exit Surface, Longitudinal, 100X, 6L-23

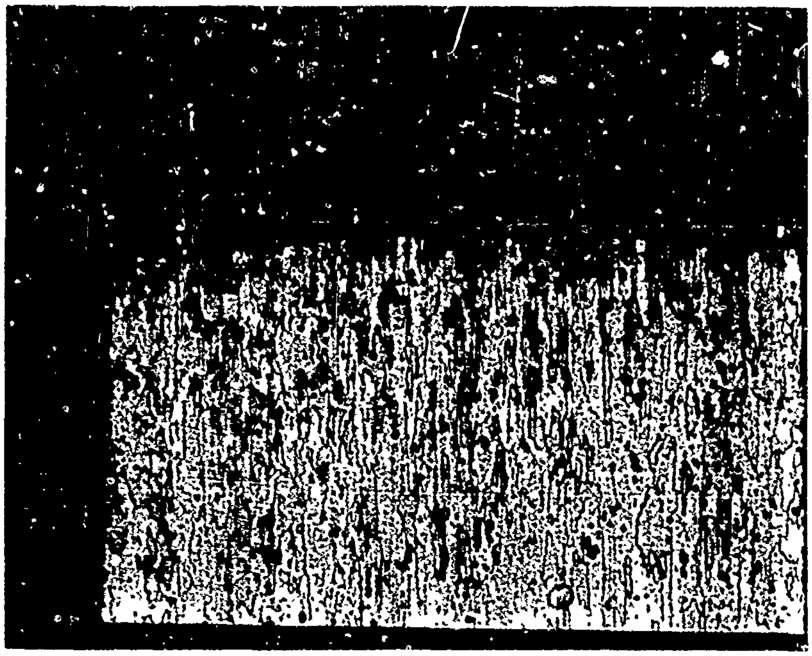


Figure 38—7075-T6, 0.063-inch Sheet, Edge B, Transverse, 60X, 6L-23

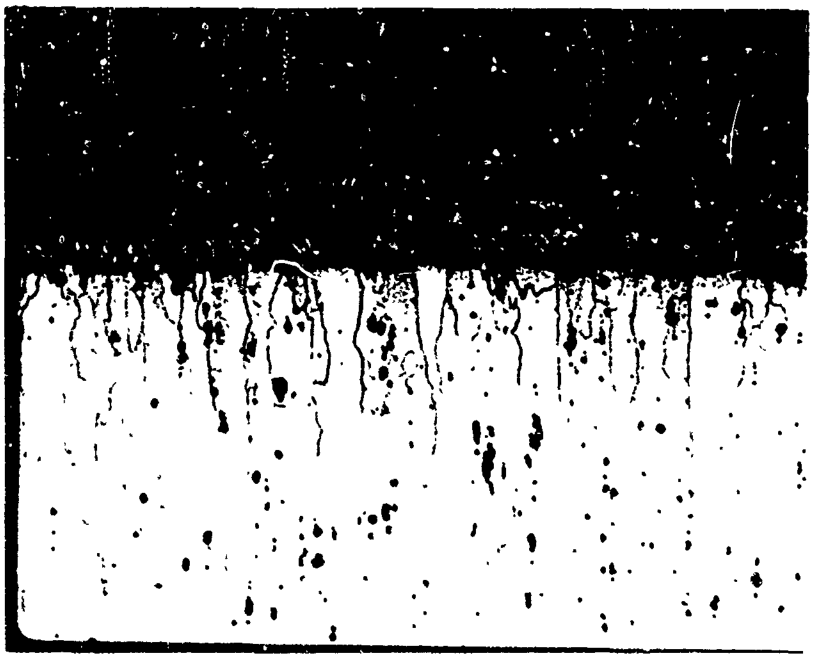


Figure 39—7075-T6, 0.063-inch Sheet, Edge B, Transverse, 200X, 6L-23

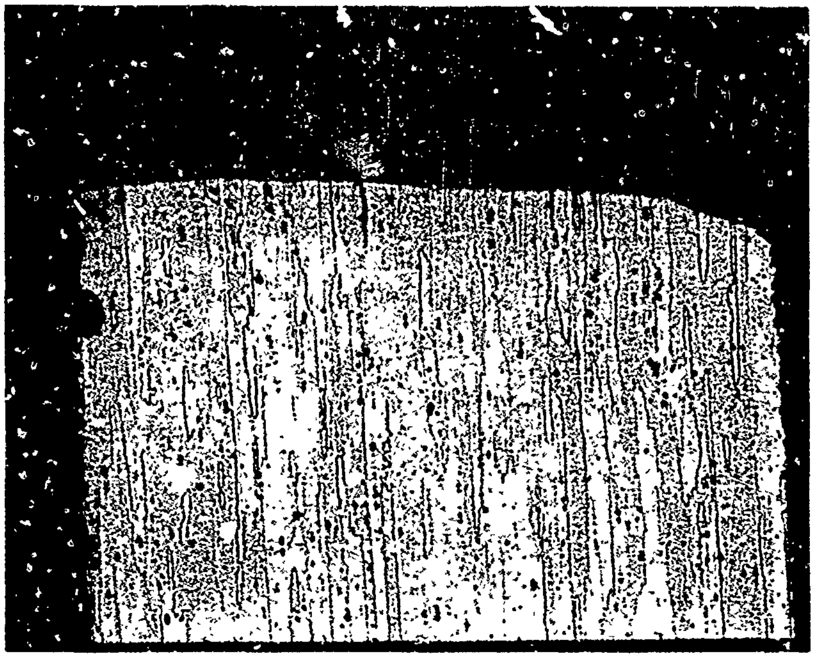


Figure 40—7075-0/Cut/HT to T6, 0.063-inch Sheet, Edge A, Transverse, 60X, OL-5

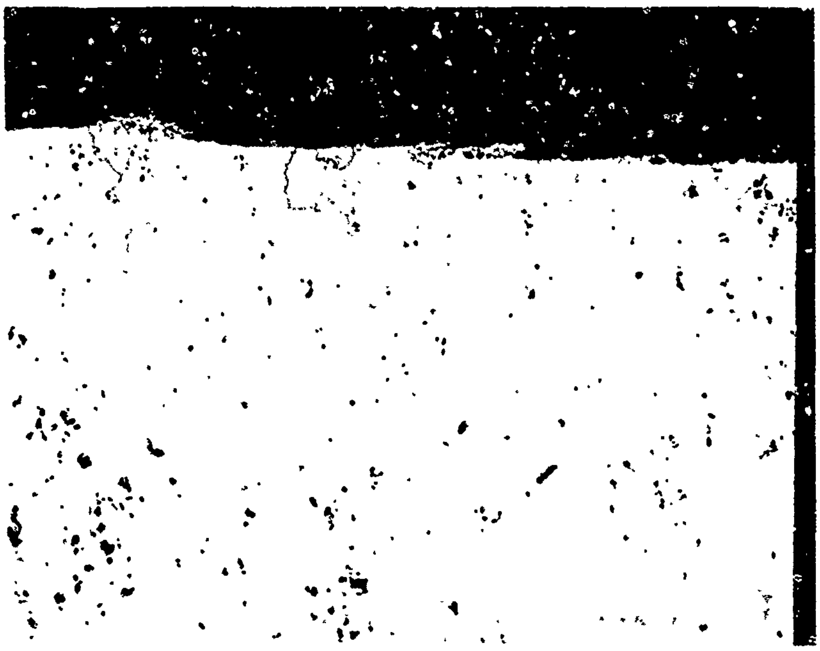


Figure 41—7075-0/Cut/HT to T6, 0.063-inch Sheet, Edge A, Exit Surface, Longitudinal, 100X, OL-5

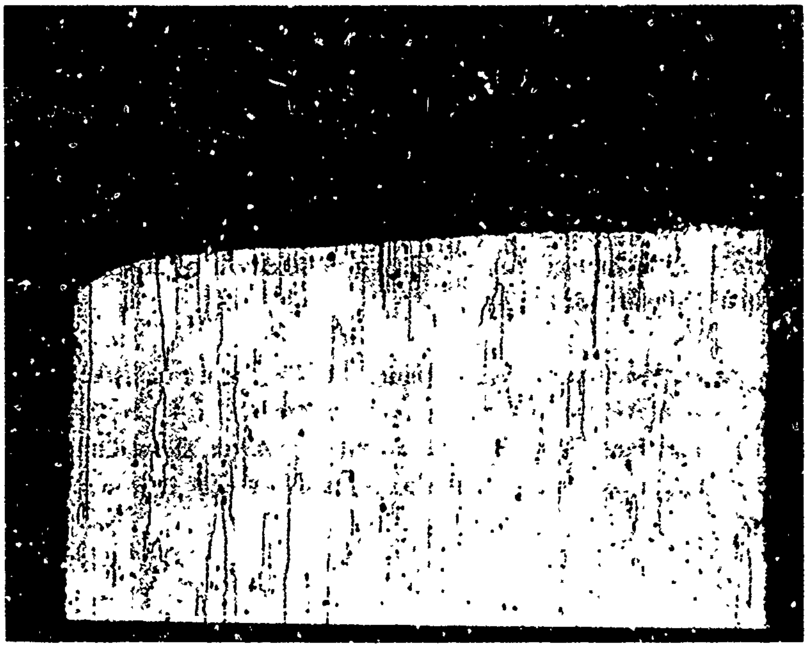


Figure 42—7075-0/Cut/HT to T6, 0.063-inch Sheet, Edge B, Transverse, 60X, OL-5

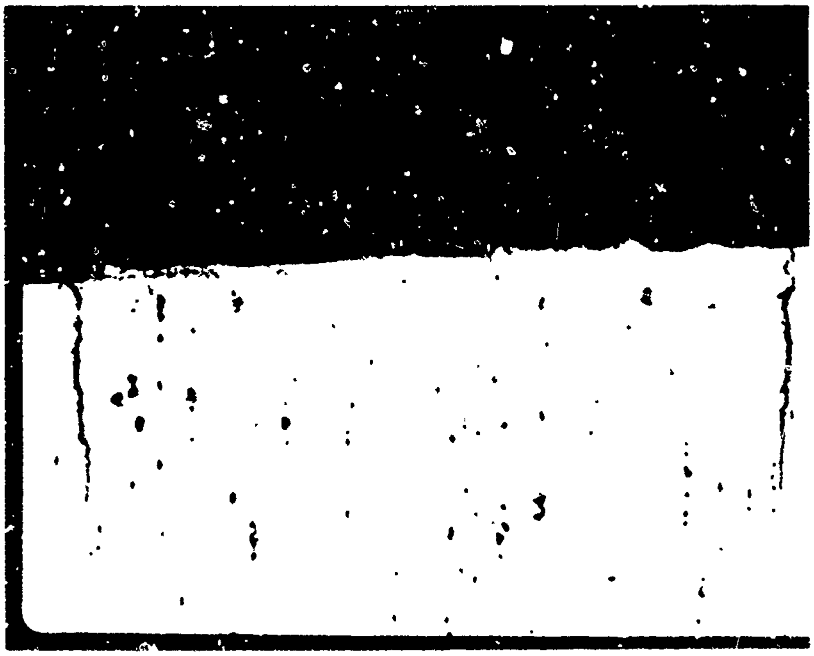


Figure 43—7075-0/Cut/HT to T6, 0.063-inch Sheet, Edge B, Transverse, 200X OL-5

4. INTERGRANULAR CORROSION EVALUATION

Accelerated intergranular corrosion tests were performed on 2024-T3 specimens in accordance with MIL-H-6088E. The test samples were immersed in an etching solution of nitric acid, hydrofluoric acid, and distilled water maintained at 200°F to produce a uniform surface. They were then immersed for 6 hours in a solution of sodium chloride, hydrogen peroxide, and distilled water at 86°F.

The samples were sectioned as shown in figure 44. The depth of attack was limited to less than 0.006 inch which corresponds to the previous (ref. MC 74.12) AIA-developed data for blanked and laser-cut edges. The most recent data, however, showed more attack sites. The reason for the greater attack may be due to material or heat treatment; however, this has not been verified.

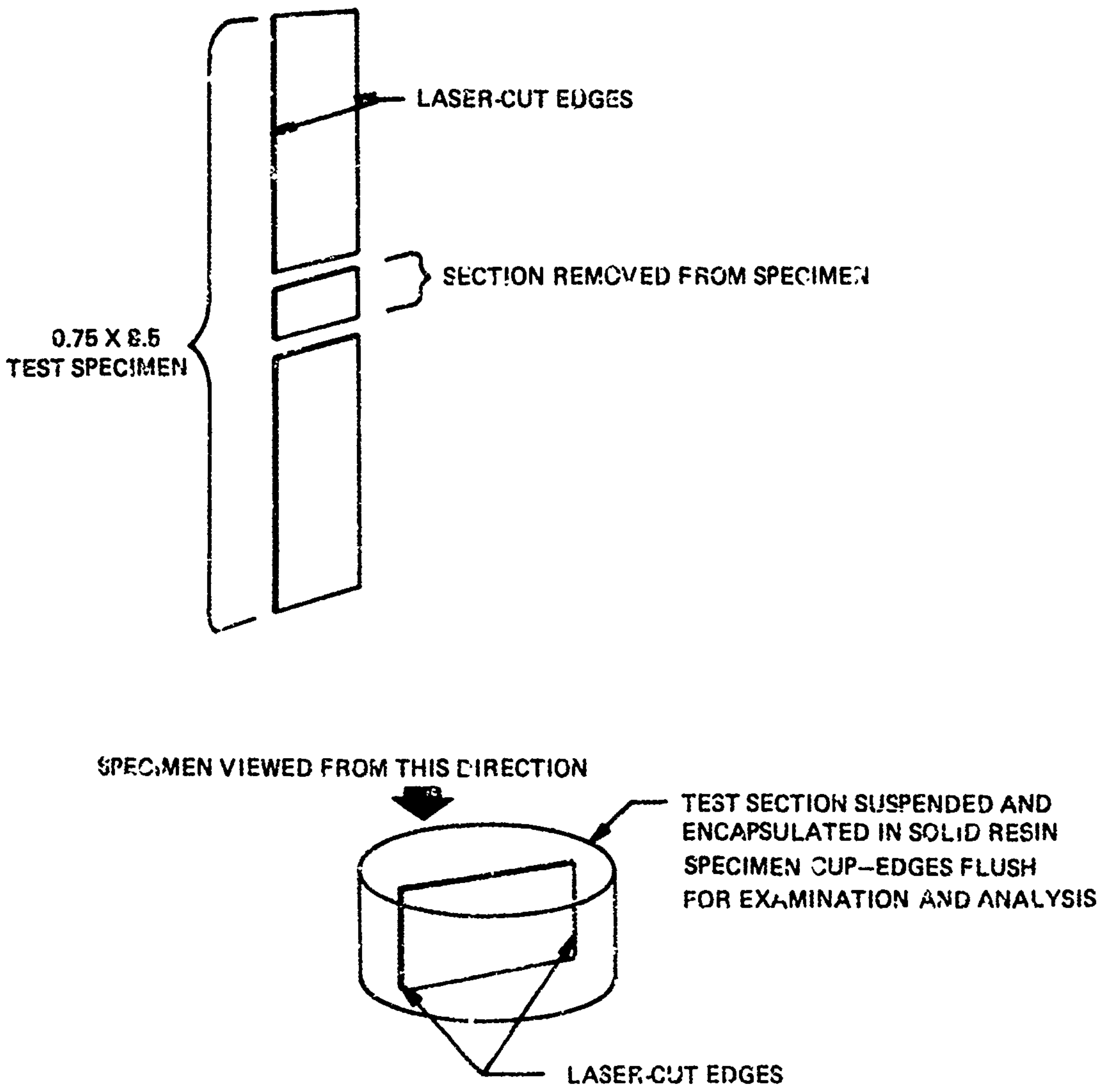


Figure 44—Section of Heavy Corrosion Specimen

SECTION IV
CONCLUSIONS

The results of this program demonstrated that it is feasible to use laser cutting of aluminum without edge enhancement in the fabrication of hardware where a sheared or blanked edge is acceptable to meet engineering requirements. However, it was further shown that it is not feasible to use an as-laser-cut edge for hardware where machined edges or hole filling fasteners are required to meet engineering requirements.

- Fatigue performance of laser-cut edges are very nearly equal to blanked edges for the material thicknesses investigated. (Data for 2024 material shows a trend towards lower fatigue performance, however, data are insufficient to determine the significance)
- Fatigue strength reduction resulting from laser cutting is less than that resulting from an open hole and greater than that resulting from a hole filled with a squeeze installed rivet
- Laser cutting of edges has no significant effect on static tensile properties for sections as narrow as 0.875 inch
- The small number of specimens laser-cut in the 0 condition and subsequently heat treated to T-6 tended toward improved fatigue properties over the specimens that were laser cut in the T-6 condition. This would infer that the slight metallurgical alteration incurred during laser cutting may be mostly eliminated by post heat treatment
- Metallurgical alteration of laser-cut surfaces can be limited to witnin 0.005 inch of the surface.

SECTION V
RECOMMENDATIONS

Based on the encouraging results of this limited effort, additional work should be conducted to implement laser cutting of aluminum as a production process.

APPENDIX A

RESULTS OF SMOOTH FATIGUE TESTS [1]

.063 7075-T6			
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3
Milling	6M-7	35	Invalid
Milling	6M-8	30	1 036
Milling	6M-9	26	1 006
Milling	6M-10	22	18 000 NF
Milling	6M-11 [2]	24	3 728
Milling	6M-12 [2]	40	62
Blanking	6B-13	20	144
Blanking	6B-14	17	970
Blanking	6B-15	14	881
Blanking	6B-16	10	9 178
Blanking	6B-17	12	5 143
Blanking	6B-18	13	10 000 NF
Blanking	6B-19	25	81
Blanking	6B-20	22	134
Laser	6L-14	20	698
Laser	6L-15	18	222
Laser	6L-18	16	3 189
Laser	6L-20	18	385
Laser	6L-21	15	956
Laser	6L-22	12	14 000
Laser	6L-23	25	44

APPENDIX A

RESULTS OF SMOOTH FATIGUE TESTS (1)

.040 7075-T6			
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE $\times 10^3$
Milling	6M1	36	587
Milling	6M2	34	163
Milling	6M3	30	5 768
Milling	6M4	33	1 507
Blanking	6B1	25	148
Blanking	6B2	20	679
Blanking	6B3	18	7 018
Blanking	6B4	13	892
Blanking	6B5	20	1 171
Blanking	6B6	24	66
Blanking	6B7	17	683
Blanking	6B8	26	195
Laser	6L3	32	28
Laser	6L4	25	67
Laser	6L5	20	105
Laser	6L6	18	177
Laser	6L7	16	325
Laser	6L8	14	1 393
Laser	6L9	12	10 272 NF
Laser	6L10	13	15 699
Milling	6M5 (2)	40	297
Milling	6M6 (2)	32	868

APPENDIX A

RESULTS OF SMOOTH FATIGUE TESTS [1]

.063 2024-T3			
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3
Milling	3M-7	44	63
Milling	3M-8	35	2 449
Milling	3M-9	40	127
Milling	3M-10	37	254
Blanking	3B-13	25	198
Blanking	3B-14	20	1 319
Blanking	3B-15	30	87
Blanking	3B-16	44	27
Blanking	3B-17	35	58
Blanking	3B-18	22	262
Blanking	3B-19	21	559
Blanking	3B-20	40	26
Blanking	3B-21	19	Invalid
Blanking	3B-22	18	6 319
Laser	3L-13	25	98
Laser	3L-14	35	36
Laser	3L-15	30	62
Laser	3L-18	40	34
Laser	3L-20	20	210
Laser	3L-21	19	354
Laser	3L-22	18	1 524

APPENDIX A

RESULTS OF SMOOTH FATIGUE TESTS [1]

.040 2024-T3			
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3
Milling	3M-1	40	165
Milling	3M-2	35	476
Milling	3M-3	44	68
Milling	3M-4	33	432
Blanking	3B-1	25	273
Blanking	3B-2	35	51
Blanking	3B-3	3[illegible]	91
Blanking	3B-4	40	45
Blanking	3B-5	20	429
Blanking	3B-6	45	21
Blanking	3B-7	18	8 872
Blanking	3B-8	23	279
Blanking	3B-9	29	122
Blanking	3B-10	19	3 780
Laser	3L-2	35	44
Laser	3L-3	25	63
Laser	3L-4	40	21
Laser	3L-7	20	1 794
Laser	3L-8	22	139
Laser	3L-9	30	70
Laser	3L-10	19	867

APPENDIX A

RESULTS OF SMOOTH FATIGUE TESTS [1]

.063 7075-0 [3]			
EDGE CUTTING METHOD	**SPECIMEN NO.**	**MAXIMUM GROSS STRESS KSI**	**CYCLES TO FAILURE $\times 10^2$**
Laser	OL-1	20	273
Laser	OL-2	18	12 250 NF
Laser	OL-3	22	252
Laser	OL-5	18	4 583

[1] RELATIVE HUMIDITY > 90% R = 0.1

[2] CONTROL SPECIMENS RUN BECAUSE OF DELAY IN TEST BETWEEN MILLED, BLANKED & LASER CUT

[3] 7075-0 MATERIAL LASER CUT, DEBURRED & HEAT TREATED TO T-6 TEMPER

APPENDIX B

RESULTS OF HOLE NOTCHED FATIGUE TESTS [1]

OPEN HOLE 2024-T3				
EDGE CUTTING METHOD	**SPECIMEN NO.**	**MAXIMUM GROSS STRESS KSI**	**CYCLES TO FAILURE x 10^3**	**FAILURE ORIGIN**
Milling	3M19	19	87	Hole
Milling	3M20	16	112	Hole
Milling	3M21	16	91	Hole
Milling	3M22	14	212	Hole
Blanking	3B37	18	179	Hole
Blanking	3B38	15	10 000 NF	Hole
Blanking	3B39	17	126	Hole
Blanking	3B40	17	104	Hole
Blanking	3B41	18	29[illegible]	Hole
Blanking	3B42	25	37	Hole
Blanking	3B43	17	32[illegible]	Hole
Blanking	3B44	22	72	Hole
Blanking	3B45	19	138	Hole
Blanking	3B46	16	117	Hole
Laser	3L38	17	613	Edge
Laser	3L39	17	278	Hole
Laser	3L40	22	23	Hole
Laser	3L42	20	100	Hole
Laser	3L44	18	311	Hole
Laser	3L45	15	278	Hole
Laser	3L46	14	703	Not Apparent

APPENDIX B

RESULTS OF HOLE NOTCHED FATIGUE TESTS [1]

OPEN HOLE 7075-T6				
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3	FAILURE ORIGIN
Milling	6M19	16	110	Hole
Milling	6M20	25	14	Hole
Milling	6M21	15	106	Hole
Milling	6M22	14	124	Hole
Blanking	6B37	18	50	Hole
Blanking	6B38	14	4 625	Hole
Blanking	6B39	16	119	Hole
Blanking	6B40	15	242	Edge
Blanking	6B41	15	349	Edge
Blanking	6B42	17	75	Hole
Blanking	6B43	20	86	Edge
Blanking	6B44	25	24	Hole
Blanking	6B45	21	43	Hole
Blanking	6B46	16	346	Edge
Laser	6L38	16	279	Hole
Laser	6L39	16	696	Hole
Laser	6L40	17	70	Hole
Laser	6L41	20	62	Hole
Laser	6L44	15	5 567	Hole
Laser	6L45	16	2 996	Hole
Laser	6L46	18	82	Hole

APPENDIX B

RESULTS OF HOLE NOTCHED FATIGUE TESTS [1]

FILLED HOLE 2024-T3				
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3	FAILURE ORIGIN
Milling	3M13	30	210	Hole
Milling	3M14	28	338	Hole
Milling	3M15	25	780	Hole
Milling	3M16	22	1 708	Hole
Blanking	3B25	28	129	Edge
Blanking	3B26	25	288	Edge
Blanking	3B27	22	6 301	Edge
Blanking	3B28	24	364	Edge
Blanking	3B29	23	350	Edge
Blanking	3B30	23	524	Edge
Blanking	3B31	22	732	Edge
Blanking	3B32	22	1 820	Edge
Blanking	3B33	26	159	Edge
Blanking	3B34	24	269	Edge
Laser	3L25	25	144	Edge
Laser	3L27	25	157	Edge
Laser	3L28	22	262	Edge
Laser	3L29	20	536	Edge
Laser	3L33	19	496	Edge
Laser	3L35	18	725	Edge
Laser	3L36	19.4	58	Not Apparent

APPENDIX B

RESULTS OF HOLE NOTCHED FATIGUE TESTS [1]

FILLED HOLE 7075-T6				
EDGE CUTTING METHOD	SPECIMEN NO.	MAXIMUM GROSS STRESS KSI	CYCLES TO FAILURE x 10^3	FAILURE ORIGIN
Milling	6M13	35	61	Hole
Milling	6M14	28	385	Hole
Milling	6M15	25	202	Hole
Milling	6M1[illegible]	22	449	Hole
Blanking	6B25	28	58	Edge
Blanking	6B26	25	152	Edge
Blanking	6B27	22	172	Edge
Blanking	6B28	15	12 093 NF	Edge
Blanking	6B29	19	171	Edge
Blanking	6B31	19	140	Edge
Blanking	6B32	17	246	Edge
Blanking	6B33	16	447	Edge
Blanking	6B34	16	404	Edge
Blanking	6B28 (Retest)	16	5 201	Edge
Laser	6L25	19	423	Under Rivet Head
Laser	6L28	19	486	Edge
Laser	6L29	25	131	Edge
Laser	6L30	20	233	Edge
Laser	6L32	17	5 624 NF	-
Laser	6L33	19	338	Under Rivet Head
Laser	6L35	18	346	Hole

[1] RELATIVE HUMIDITY BETWEEN 30 & 40%   R=.1   THICKNESS .063 TYPICAL

*U.S.Government Printing Office: 1978 — 757-080/312