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AN EXPERIMENTAL EVALUATION OF THE EFFECT OF HOLE FABRICATION/TREATMENT TECHNIQUES ON RESIDUAL STRENGTH AND FATIGUE LIFE OF POLYCARBONATE SPECIMENS WITH HOLES

DANIEL R. BOWMAN

UNIVERSITY OF DAYTON RESEARCH INSTITUTE
300 COLLEGE PARK
DAYTON, OH 45469-0110

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RICHARD A. SMITH
Aerospace Engineer

for
RALPH J. SPEELMAN III, Chief
Aircrew Protection Branch

Richard E. Colclough, Jr.
RICHARD E. COLCLOUGH JR., Chief
Vehicle Subsystems Division

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An experimental test program was conducted to evaluate different techniques of fabricating/treating holes in extruded polycarbonate. This program included surface finish evaluation and tension-tension fatigue and tensile residual strength testing of polycarbonate specimens with open holes. Eight different hole fabrication/treatment techniques were developed, including drilling (several variations), step drilling, entry and exit radiusing, solvent polishing, shot peening, and cold working. The differences in tensile residual strength for the specimens with holes was minimal; however, fatigue life varied by as much as a factor of ten between the best technique, cold working, and the worst, chemical polishing. In addition, limited testing indicated that annealing extruded polycarboante decreases fatigue life by eliminating favorable residual surface compressive stresses.

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PREFACE

The efforts reported herein were performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33615-92-C-3402. The program was sponsored by the Air Force Wright Laboratory, Flight Dynamics Directorate, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction and technical support were provided by Mr. Richard A. Smith, WL/FIVR.

The work described herein was conducted during the period January 1992 to February 1993. University of Dayton project supervision was provided by Mr. Dale H. Whitford, Supervisor, Aerospace Mechanics Division, and Mr. Blaine S. West, Head, Structures Group. Mr. Daniel R. Bowman was the Principal Investigator. The author would like to thank Dr. Noel Ashbaugh, UDRI, for coupon testing, technical input, and assistance.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(continued)

LIST OF TABLES

SECTION 1
INTRODUCTION/BACKGROUND

As the usage of engineering plastics increases, the desire for better understanding of the plastic material behavior increases. In addition to basic material mechanical properties such as tensile strength, tensile modulus, etc., it is desirable to understand the effect of flaws on material behavior, and to understand joining techniques such as welding, bonding, and fastening with bolts or rivets. Flaws include inclusions, scratches, machined surfaces, rough surfaces etc. Fasteners are often used to join plastics to plastics or other materials. Fasteners require that holes be made in the plastic. These holes and holes made in the plastic for other reasons are potential failure locations as they can be thought of as flaws in the material which result in stress concentrations. One of the uses of plastics for the USAF is aircraft transparencies, which are typically bolted to the aircraft. These transparencies are subject to flight, thermal, and aerodynamic loadings, which independently or in conjunction with chemicals can cause fatigue cracking at the fastener locations[1,2].

In this effort, testing was conducted to evaluate different techniques of hole fabrication/treatment for polycarbonate. While much work in this area has been conducted for metals, essentially no published work exists for plastics.

SECTION 2

PROGRAM OBJECTIVE/SCOPE

The objective of this effort was to identify hole fabrication/treatment techniques which had potential for improving fatigue life, static strength, fracture toughness, and fatigue crack growth properties for polycarbonate. As part of this effort, a number of different hole fabrication/treatment techniques for polycarbonate which had potential for improving the properties listed above were identified and eight of these identified techniques were evaluated. This evaluation consisted of tensile testing and tension-tension fatigue testing of unflawed dogbone polycarbonate specimens as well as tensile residual strength testing and tension-tension fatigue testing of rectangular specimens with a hole at the center of the specimen.

SECTION 3

LITERATURE SEARCH AND INVESTIGATION OF HOLE DRILLING

A literature search was made using the NASA, COMPENDEX, and Chemical Abstracts data bases. Subject areas included hole drilling/fabrication techniques and fatigue, fracture, and tensile testing of specimens with flaws or holes. The majority of the information in the data bases was for metals. Information on fabricating/treating holes to improve engineering properties for plastics was virtually non-existent. Many of the concepts which have been used to improve fatigue life, static strength, fracture toughness, and fatigue crack growth for metals are applicable to plastics.

There are a number of good reviews of fatigue testing of polymers[3-6], and there are a number of papers specifically dealing with fatigue of polycarbonate[7-17]. Tayebi and Agrawal studied the effects of stress concentrations around holes in polycarbonate[18]. They reported significant reductions in effective breaking stress for rectangular bar tensile specimens with a hole drilled in the center. There is a very large body of data in the literature for fatigue testing of metals and other materials. A number of techniques have been investigated and reported on for increasing fatigue life and improving fatigue crack initiation and growth properties for both specimens and engineering systems which have open holes (not loaded by a lug or fastener) or loaded holes (loaded by a lug or fastener).

There are basically four areas in which efforts to increase service life and strength around holes in engineering materials can be focused. These four areas are surface finish of the hole, residual stress in hole vicinity, heat or chemical affected zone in hole vicinity, and mechanical additions to the hole surface or vicinity such as bonded patches and washers or bushings. It should be noted that there can be synergistic effects between these four areas. Surface finish is a function of the hole fabrication/treatment technique and determines flaw size and the effective stress concentration factor associated with the hole. Typically fatigue life and residual strength are believed to increase with increased surface smoothness, both for holes and free edges of structural components (see Figure 1 for a conceptual example); however, some materials are somewhat insensitive to surface smoothness, and it is expected that there is a limit beyond which increases in smoothness do not result in great improvements in fatigue life. An example of the effect of crack length (flaw size) on residual strength, taken from testing of metal specimens, is

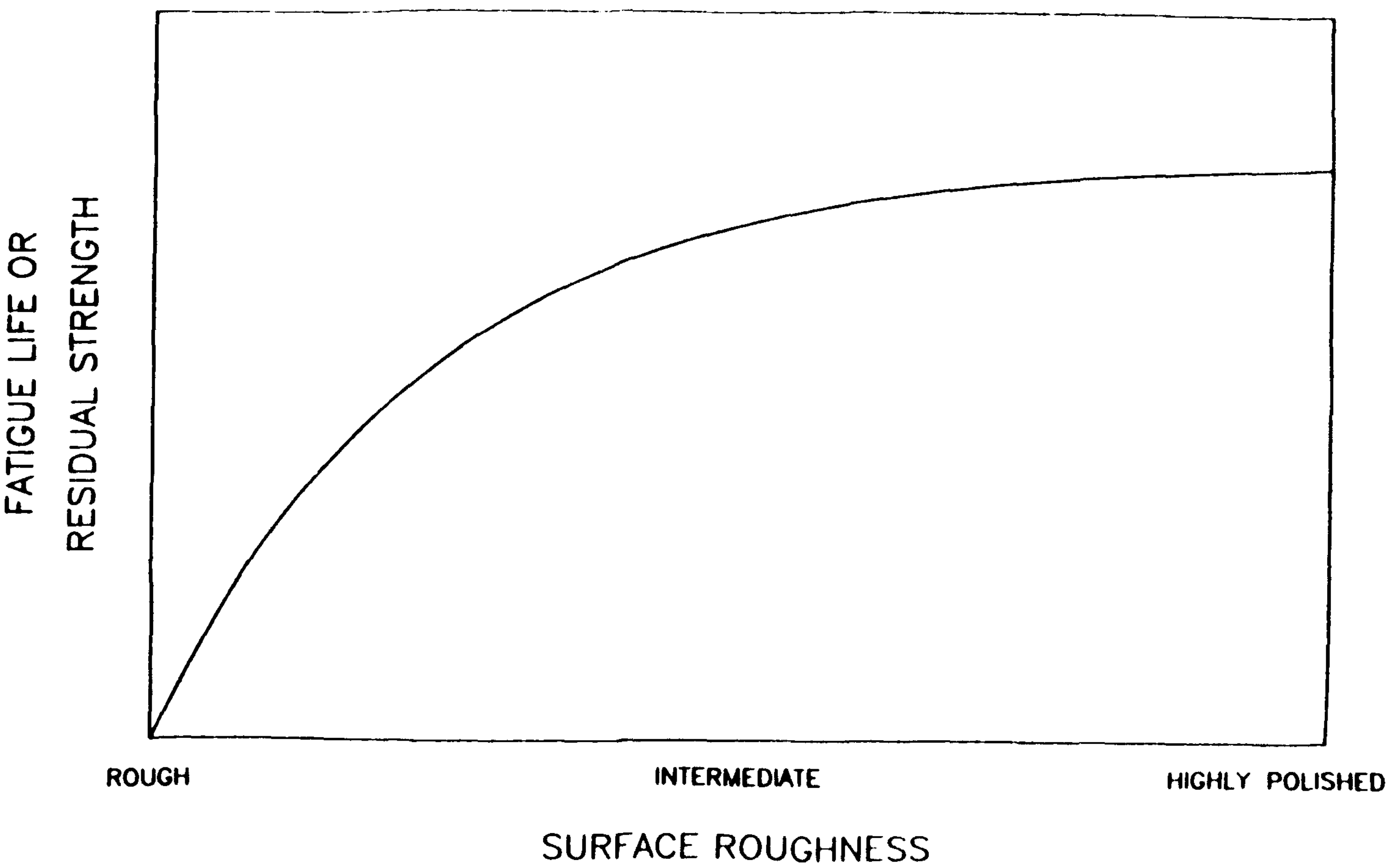


Figure 1. Hypothetical Effect of Surface Roughness on Fatigue Life and Residual Strength

shown in Figure 2. It should be noted that surface roughness can be thought of as a crack (or flaw) of some finite length, such that specimens with different surface roughnesses can be thought of as specimens with different "crack" lengths. Residual stress may be present in the material prior to fabrication of the hole, or it may be caused by the hole fabrication/treatment technique. The heat affected zone is a function of cutting tool speed, feed, and sharpness, as well as post fabrication treatments. The chemical affected zone is a function of the cutting lubricant or post fabrication polishing or chemical treatment. Mechanical additions to the hole surface or interior change the load path through the hole, possibly resulting in a lower stress concentration factor. Table 1 lists the specific potential hole fabrication/treatment techniques identified.

Both surface finish and the disturbed or worked state of the hole surface layer are discussed by Forsyth for metallic specimens with an open hole[19]. For open hole specimens, Jarfall and Magnusson found no correlation between surface roughness and fatigue performance for holes made with the same machining technique[20]. Others have shown that hole surface roughness features such as rifling (spiral) marks, drill chatter, etc. do not adversely affect fatigue performance, while axial surface roughness features such as axial scratches and score marks along the bore of the hole cause early initiation of cracks and reduced fatigue lives, and that surface roughness below a certain value does not increase fatigue performance[21-23]. Similar findings were reported by Noronha et al ; in addition, they reported significant improvement in fatigue performance of open hole specimens and low load transfer specimens with improved drilling techniques which included rotation of the drill upon retraction from the hole to reduce axial scratches; they reported that drilled holes may be slightly better than reamed holes as removal of the reamer can contribute to axial scratches; and, they reported that open holes drilled using non-standard production techniques behaved only slightly worse than properly drilled holes when tested in fatigue[24]. Findings summarized by Coombe were that for open hole specimens and for interference fit fastener loaded holes, hole quality does not affect fatigue life, but for interference fit, interference is critical[25]. Mann et al., found no difference in fatigue life for clearance fit lug loaded holes as a function of surface finish[26].

Fjelstad reported that electrochemical deburring of printed wiring boards can result in rounding of sharp corners of holes in the board, in turn resulting in lower stress concentrations and increased fatigue life[27].

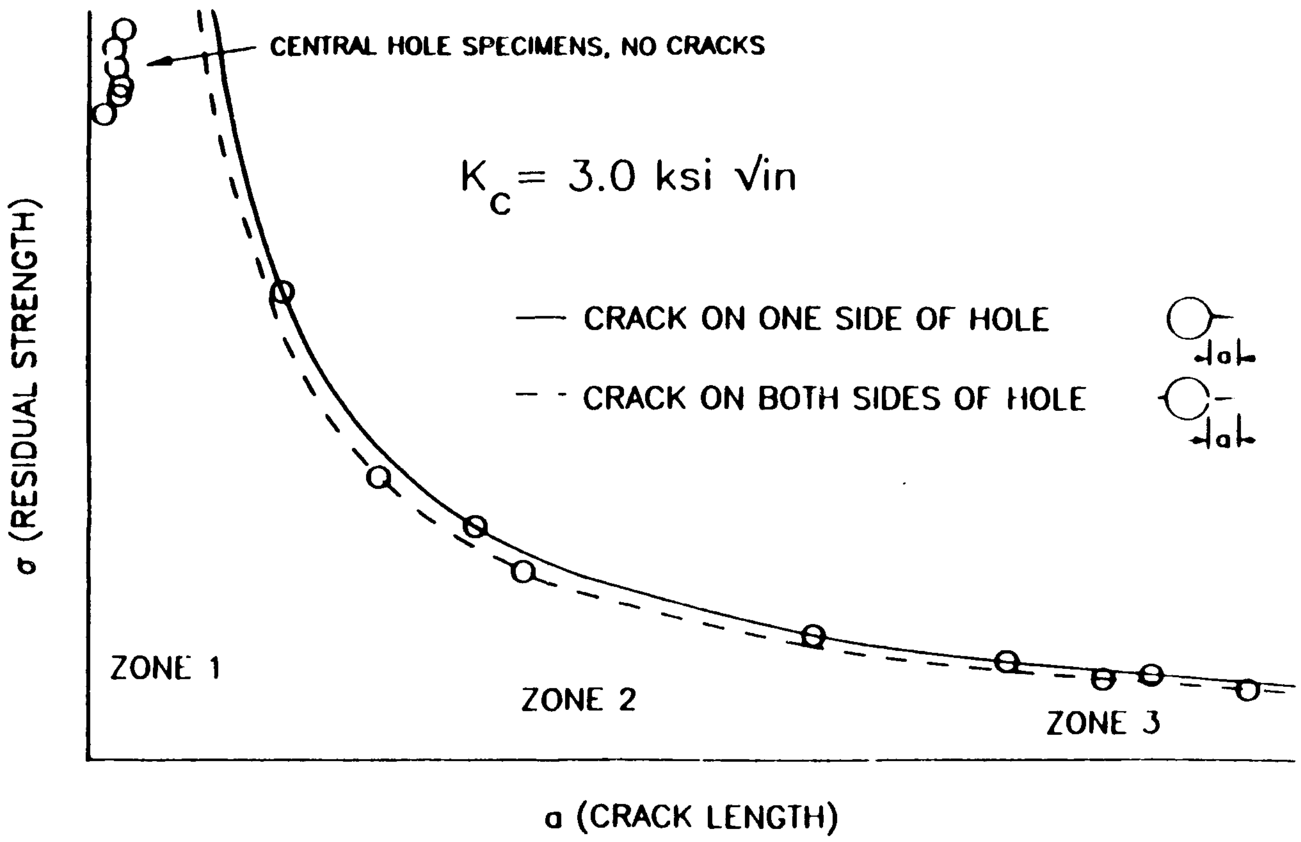


Figure 2. Influence of Crack Length on Residual Strength, from Testing of Metals

Table 1. Potential Hole Fabrication and Treatment Techniques

HOLE FABRICATION TECHNIQUES:

1. Standard Twist Drill
2. End Mill
3. Boring Bar
4. Drills, Mills, and Boring Bars with various geometries and materials
5. Step Drill with (1) through (4)
6. Methods (1) through (5) with Coolant
7. Standard Drill, then Ream
8. Ultrasonic Hole Drilling
9. Water Jet Cutter
10. Laser Cutter
11. Electric Discharge Machining (EDM)
12. Methods (1) through (11) with Radiused Entry and Exit
13. PPG Hole Drilling Technique

HOLE TREATMENT TECHNIQUES:

1. Mechanical Polish
2. Chemical Polish
3. Anneal Specimen
4. Quench specimen
5. Cold Work
    - Tapered pin with or without bushing
    - Ballizing
6. Stress Coining
7. Shot Peening
8. Dimpling
9. Interference Fit Bushing
10. Polymer Coating

Adhesive bonding of fasteners or sleeves into holes has been shown to decrease stress concentration and stress intensity factors and increase fatigue life of lug loaded holes in aluminum specimens, including those which have all ready cracked[28-30].

A transverse normal pressure in the vicinity of a hole in sheet molding compound, induced by using a bolt with washers on each end to create a clamping force, was shown to increase tensile static strength and fatigue life of an open hole (no load applied to the hole surfaces) specimen[31].

Shewchuk and others reported on a dimpling technique used for sheet metals which cold works the material in the vicinity of the hole and results in increased fatigue life for fastener joined sheet metal specimens[32,33].

There is a significant body of literature dealing with cold working of holes to improve fatigue life and fatigue crack growth performance. Stress coining techniques were reported by Speakman[34]. Other cold working techniques are summarized by Phillips and Champoux[35-37]. A large number of papers deal with specific applications of coldworking, a sampling of which are referenced herein[23,38-45]. In addition, significant theoretical treatment of coldworking has been conducted along with measurement of induced stresses, a sampling of which are referenced herein[46-56].

Shot peening has been used extensively for automotive and aerospace applications. General summaries of shot peening with many references have been published by the Society of Automotive Engineers[57], and by the Metal Improvement Company in a trade publication[58]. A brief summary of theory and application is included in a company brochure by Pangborn[59]. Shot peening of metal parts is covered by a Military Specification, MIL-S-13165C[60].

The most common, basic, and inexpensive technique of fabricating holes in engineering materials is drilling. As this technique was considered to be the baseline against which other fabrication/treatment techniques would be measured, a limited investigation of hole drilling as a stand-alone topic was conducted. Based on an evaluation of hole drilling and machining techniques for polycarbonate by UDRI[61] and on work conducted at UDRI in the development of a technique for measuring residual strain in plastics using the strain gage hole drilling technique[62], the standard twist drill was chosen as the technique for producing all holes in the test specimens. Figure 3, reproduced from Reference 62, shows induced machining strain in cast

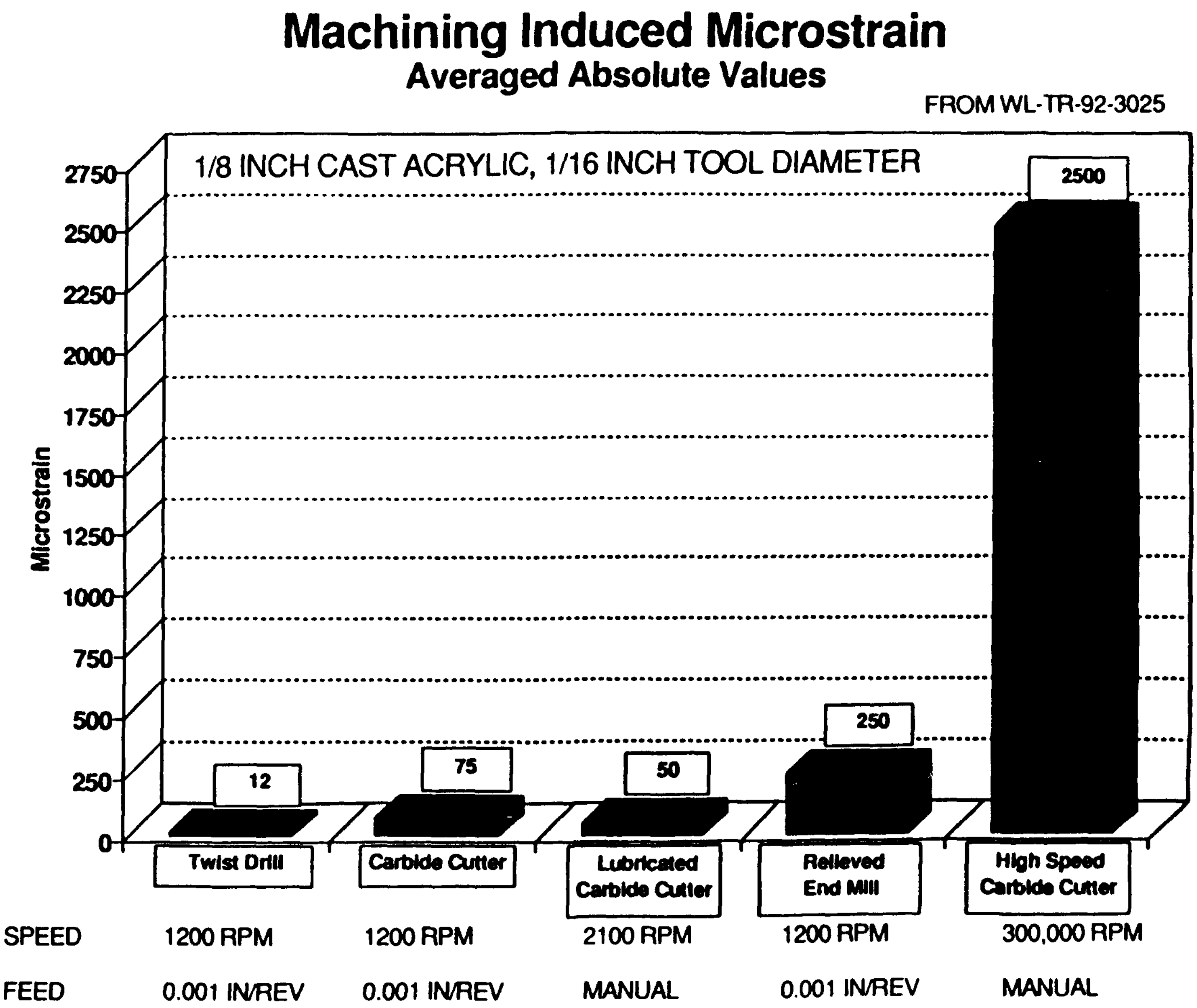


Figure 3. Machining Induced Strain for Cast Acrylic

acrylic for a standard twist drill, a carbide cutter, a lubricated carbide cutter, a relieved end mill, and a high speed carbide cutter. The induced strain caused by drilling a hole with a standard drill was 4 to 200 times smaller for the standard twist drill than for the other types of tools. While multiple drill tools and machining tools exist, evaluation of these was beyond the scope of this program.

Prior to drilling holes in each of the specimens, a brief evaluation of the effect of hole drilling parameters on induced residual stress was conducted. A matrix of holes were drilled in a ten inch square blank of polycarbonate, with feed rate/RPM combinations including feed rates of 0.0015, 0.003, and 0.006 inches per revolution and tool speeds between 50 and 2500 RPM. The holes were drilled in a Bridgeport vertical milling machine. The procedure was as follows: the holes were initiated with a No. 3 centering drill and then a new 0.250-inch high speed drill, general purpose, manufactured by Cleveland Drill Company was used in the machine with constant RPM and constant automatic feed. After allowing the blank of material to relax for 24 hours, stress in the vicinity of the holes was estimated by viewing the vicinity of the hole using polarized sheets on the front and back of the specimen. Fringe orders were counted and stress was calculated using a fringe order constant of 150 psi. The lowest induced stress was for specimens drilled at the lowest tool speed; no gross differences in residual stress were discernable between the different feed rates. The effect of tool speed on residual stress is shown in Figure 4 and Table 2.

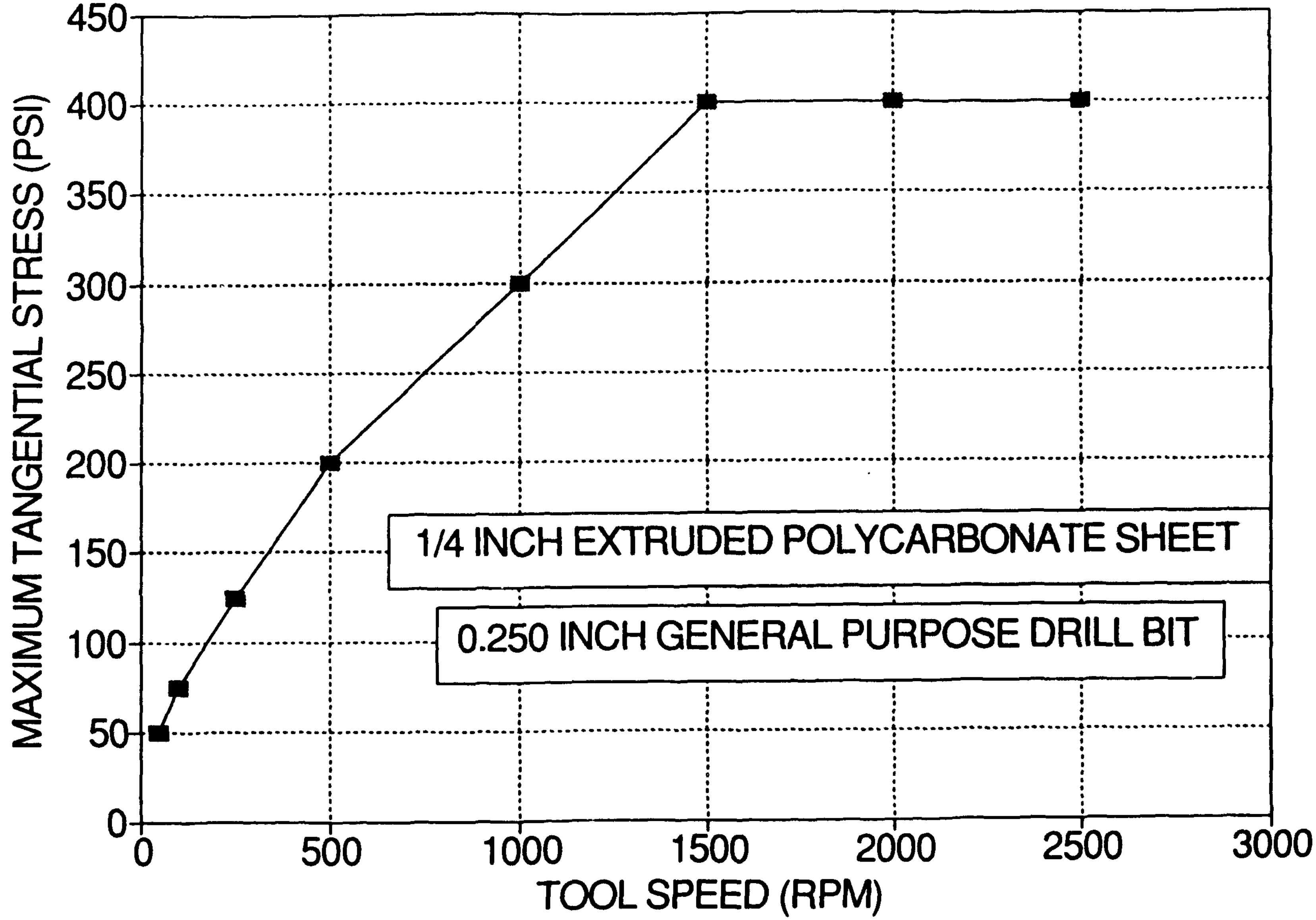


Figure 4. Approximate Maximum Tangential Stress Induced in Extruded Polycarbonate Sheet as a Function of Drilling Parameters

Table 2. Approximate Maximum Tangential Stress (PSI) Induced by Drilling 1/4 Inch Polycarbonate Sheet with a 0.250 Inch Drill Bit as a Function of Drilling Parameters

RPM SPEED (FPM)	50 3.3	100 6.3	250 15.8	500 31.5	1000 63	1500 95	2000 130	2500 160
FEED (IN/REV)								
0.006	50	75	125	200	300	400	400	400
0.003	50	75	125	200	300	400	400	400
0.0015	50	75	125	200	300	400	400	400

SECTION 4

CHOICE AND DESCRIPTION OF HOLE FABRICATION/TREATMENT TECHNIQUES

The techniques chosen for evaluation are discussed below. These techniques cover a broad spectrum of the potential techniques from Table 1. Many of the techniques shown in Table 1 were considered to be too exotic and expensive for this program, or not suited for plastics.

Hole fabrication/treatment techniques chosen for evaluation in this program are as follows:

[Notes: All holes were started with a centering drill except those drilled by PPG, and a new drill bit was used for each different group of holes except as noted.]

Group 1. Holes were drilled in a Bridgeport vertical milling machine with a constant speed of 60 RPM and a constant feed rate of 0.0015 inches/revolution, using a new 0.250 inch general purpose high speed steel standard twist drill from Cleveland Drill Company. This technique represented the highest quality most controlled single step production of holes. The shape of the standard twist drill evolved over the early history of machining of materials, and has remained essentially unchanged for many years.

Group 2. Holes were step drilled with technique 1 using a new 0.242 inch drill first and then a new 0.250 inch drill. Step drilling decreases the amount of material which must be removed with each cut, which, in turn, reduces the heat affected zone surrounding the hole.

Group 3. Holes were drilled using technique 1, then the entry and exit corners of the hole were radiused with a modified counter sink which had a 1/32 inch radius and a 0.250 inch pilot mounted in a drill press with a stop counter sink to control depth of cut and run at approximately 200 rpm with manual feed. The surfaces of the holes were shot peened by Metal Improvement Inc. with various shot sizes and intensities as shown in Table 3. Shot peening can be used to relieve residual stresses, or to impart compressive residual stresses which tend to retard crack initiation and crack growth. The entry and exit corners of the hole were radiused to allow shot peening of the hole corners.

Group 4. Holes were drilled by PPG Industries, using a new 0.250 inch general purpose high speed steel standard twist drill and a proprietary hole drilling technique which they have developed specifically for drilling polycarbonate aircraft transparencies. They have reported a

Table 3. Shot Peening Data

SHOT SIZE	MI-70-H	MI-70-H	MI-70-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H
AIR PRESSURE (PSI)	10	20	70	5	10	20	30	40	80
ALMEN INTENSITY	4.4N	7.4N	7.4A*	2.0N	4.6N	8.7N	4.3A	5.2A	7.5A
GROUP NUMBER	3.6	3.8	3.1	3.5	3.3	3.2	3.9	3.4	3.7

*MEASUREMENT UNCERTAIN

SHOT PEENING CONDUCTED BY METAL IMPROVEMENT COMPANY, CINCINNATI DIVISION substantial increase in birdstrike resistance of F-111 ADBIRT windshield transparencies with this technique over standard hole drilling techniques.

Group 5. Holes were drilled using technique 1, and were then polished by inserting a cotton swab soaked in toluene into the hole and rotating the swab five times, and then inserting the swab into the hole from the other side and rotating the swab five times. Chemical polishing techniques potentially could be used to reduce burrs and minor surface irregularities at minimal cost. Solvents can be used to polish the surface by dissolving burrs and softening the surface material, allowing irregularities to be smoothed out. Care must be taken not to contaminate the specimens and not to apply the chemicals to specimens with high residual stresses, as crazing would result. A number of candidate chemicals were identified as possible choices for polishing the holes. These candidates included THF, MEK, acetone, methylene chloride, and toluene. Dichloro-Methane was used to solvent polish machined edges in Reference 61 in an attempt to increase craze resistance of the machined edge. No noticeable improvement in solvent resistance was detected, however the edges did become glassy smooth. Polycarbonate is at least partially soluble in all of these chemicals.

Group 6. Holes were drilled using technique 1, then cold worked using the setup shown in Figure 5 by pushing a vaseline lubricated 0.2812 inch diameter tapered pin through the hole. Some developmental work was conducted to choose an appropriate amount of interference (12.5 % was chosen), but no effort was made to optimize the interference. Interferences of 2 to 4 % are common for aircraft grade aluminums, where the yield strain is on the order of 0.5 %. For polycarbonate the actual yield strain is defined in different ways by different people. Herein it is defined as the strain which corresponds to the yield stress, where the yield stress is the first stress peak in the stress strain curve. For static strain rates, the nominal yield stress for polycarbonate is 9500 psi and the corresponding yield strain is 8%. Cold working is one of the most promising techniques and has been studied extensively for metals. Cold working results in compressive stresses at the surfaces of the hole, which tend to retard crack initiation and crack growth.

Group 7. Holes were drilled using technique 1, then the entry and exit corners of the hole were radiused with a modified counter sink which had a 1/32 inch radius and a 0.250 inch pilot

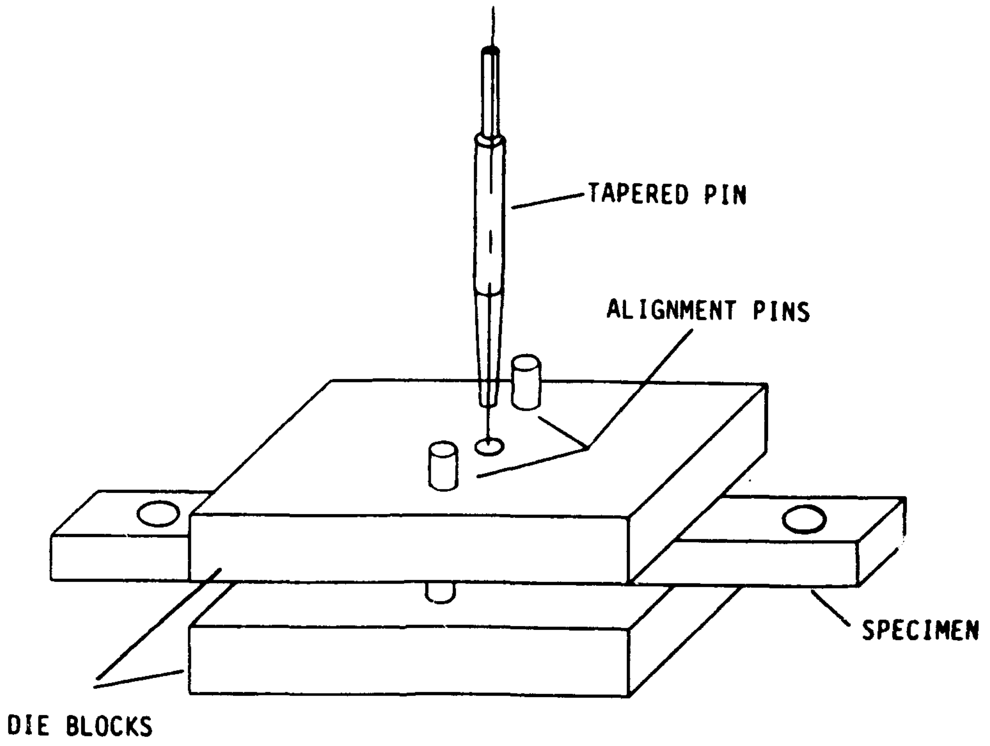
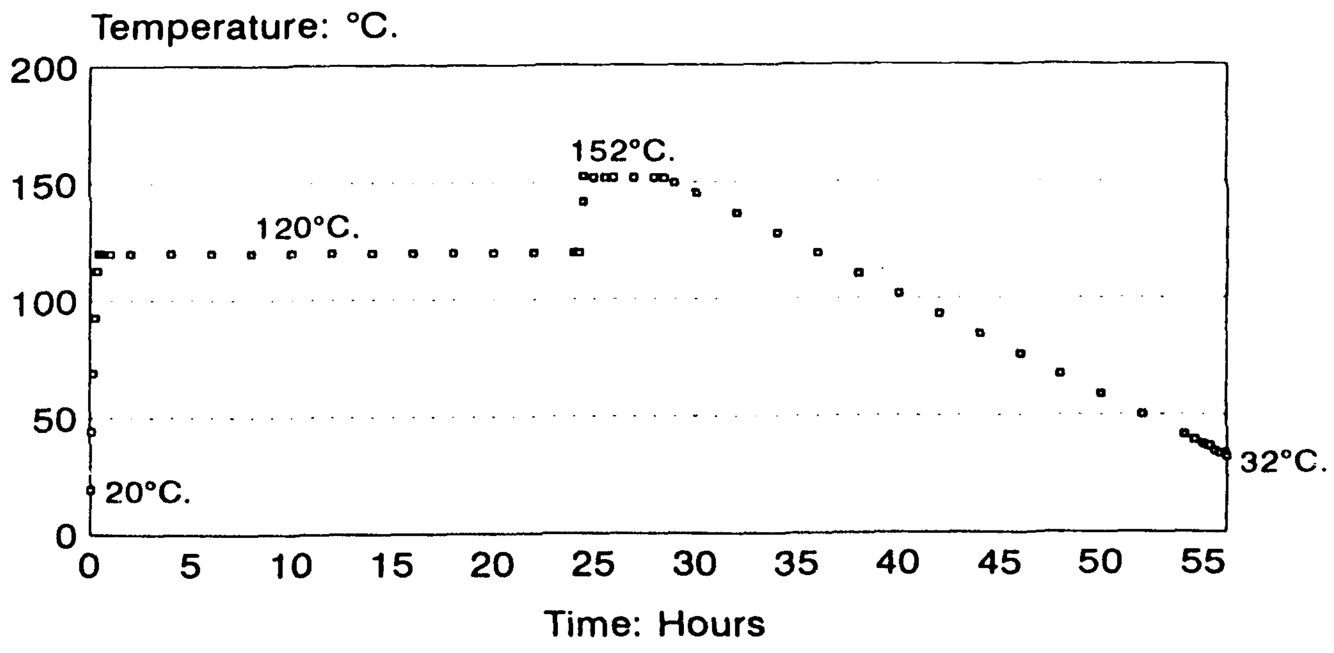


Figure 5. Cold Working Setup

mounted in a drill press with a stop counter sink to control depth of cut and run at approximately 200 rpm with manual feed. Sharp corners are generally associated with high stress concentrations. Removing the sharp corners by radiusing the hole entry and exit reduces the stress concentration at these locations.

Group 8. Holes were drilled manually using a 0.250 inch general purpose high speed steel standard twist drill from the machinist's tool box with a high speed air drill at a nominal speed of 3640 RPM. This technique was considered representative of typical field or shop drilling of holes by hand. Hand drilling with the standard twist drill is the most basic and inexpensive technique for producing holes in plastics.

Extruded polycarbonate sheet has residual compressive stresses at the surface which may result in an increase in various engineering properties such as fatigue, fatigue crack growth, fracture toughness, and toughness during tensile testing. These residual stresses can be removed by annealing the polycarbonate. It is well established that thermal history affects many properties of polycarbonate[63-78]; yield strength increases with annealing, and toughness (or elongation) decreases. The majority of the test specimens from this program were fabricated directly from the extruded sheet with no additional thermal treatment; however, a number of tensile dogbone specimens and several specimens with holes were annealed as per the thermal profile shown in Figure 6, to evaluate the effect of annealing on tensile fatigue properties.



Turned chamber off at 37.6°C. allowed specimens to cool to 33.8°C. Switched specimens to a 32°C. preheated chamber and allowed to cool to ambient temperature.

Figure 6. Temperature Profile to Anneal Specimens

SECTION 5

TEST ARTICLE, SPECIMEN FABRICATION DESCRIPTION, AND TEST MATRIX

The material used for all testing conducted in this program was removed from a single 86 inch x 86 inch x 0.25 inch sheet of aircraft grade polycarbonate Tuffak sheet manufactured by Rohm and Haas to meet Mil-P-83310. The polycarbonate molecular weight of two samples from the sheet were characterized by UDRI; sample 1: $M_n = 15166$, $M_w = 31008$, $M_z = 48908$; sample 2: $M_n = 16132$, $M_w = 31299$, $M_z = 48184$. The material was subjected to no special conditioning except as noted in Section 4 for annealed specimens. The tensile dogbone specimen designs used are shown in Figures 7-10. At certain stress levels, the tensile dogbone specimens consistently failed outside of the gage length during fatigue testing. Initially specimen design was thought to play a role in the failure outside the gage section, and several designs were tested with no change in the failure mode (failure was still consistently outside the gage section at certain stress levels). A more complete discussion of this phenomenon is included in Section 8. The specimen design for the rectangular specimens with holes is shown in Figure 11. The specimens were fabricated in the UDRI experimental fabrication shop. The specimens were blanked out using a bandsaw. The dogbone specimens were fabricated one at a time sidecutting with an 1/2 to 3/4 inch end mill at 800-1000 rpm with hand feed. For the specimens with holes, stacks of four were cut with a 1 and 1/4 inch diameter fly cutter at 1200 rpm, with a table speed of 2-4 inches/minute. The holes were produced as described in Section 4. The test matrix is shown in Table 4.

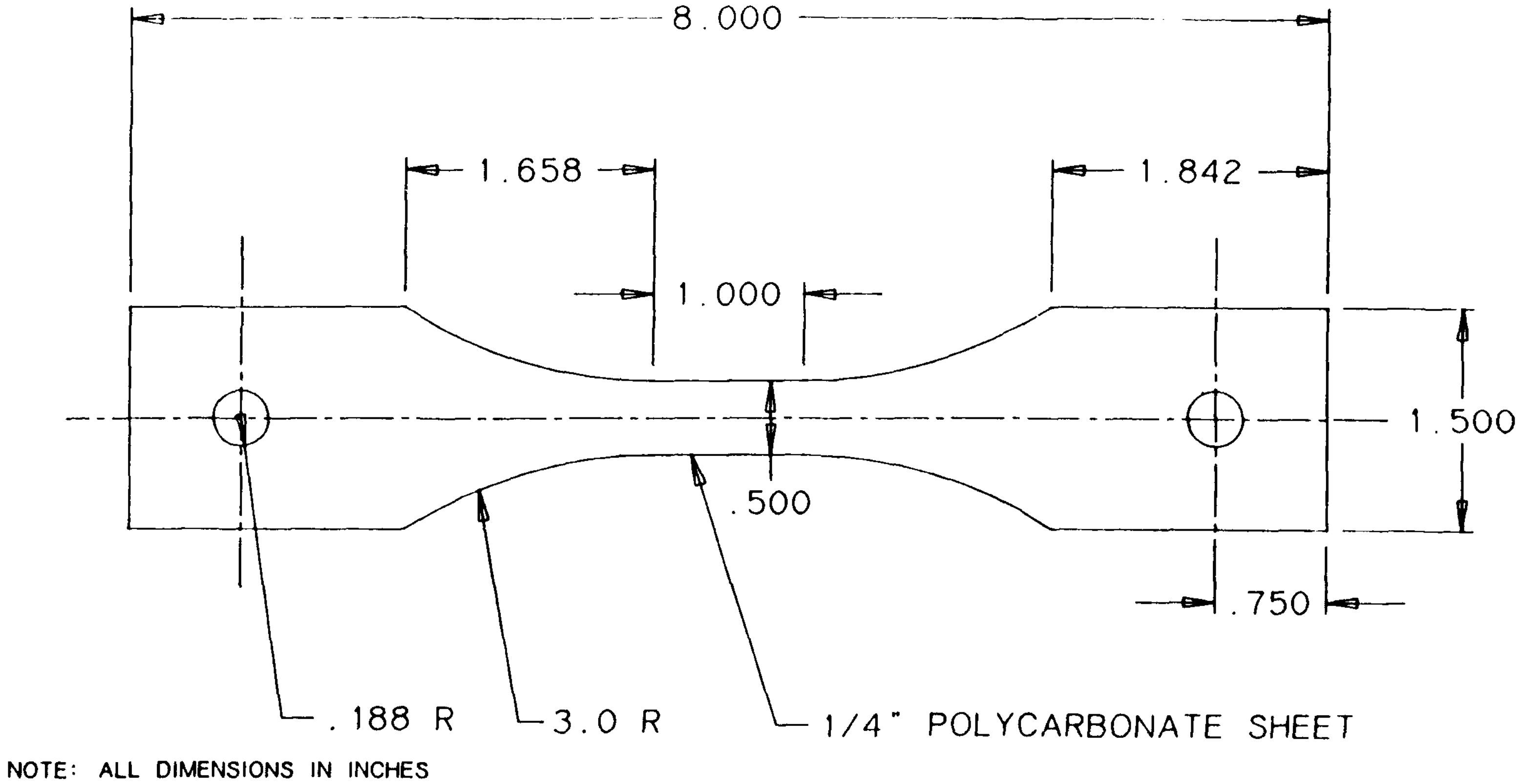
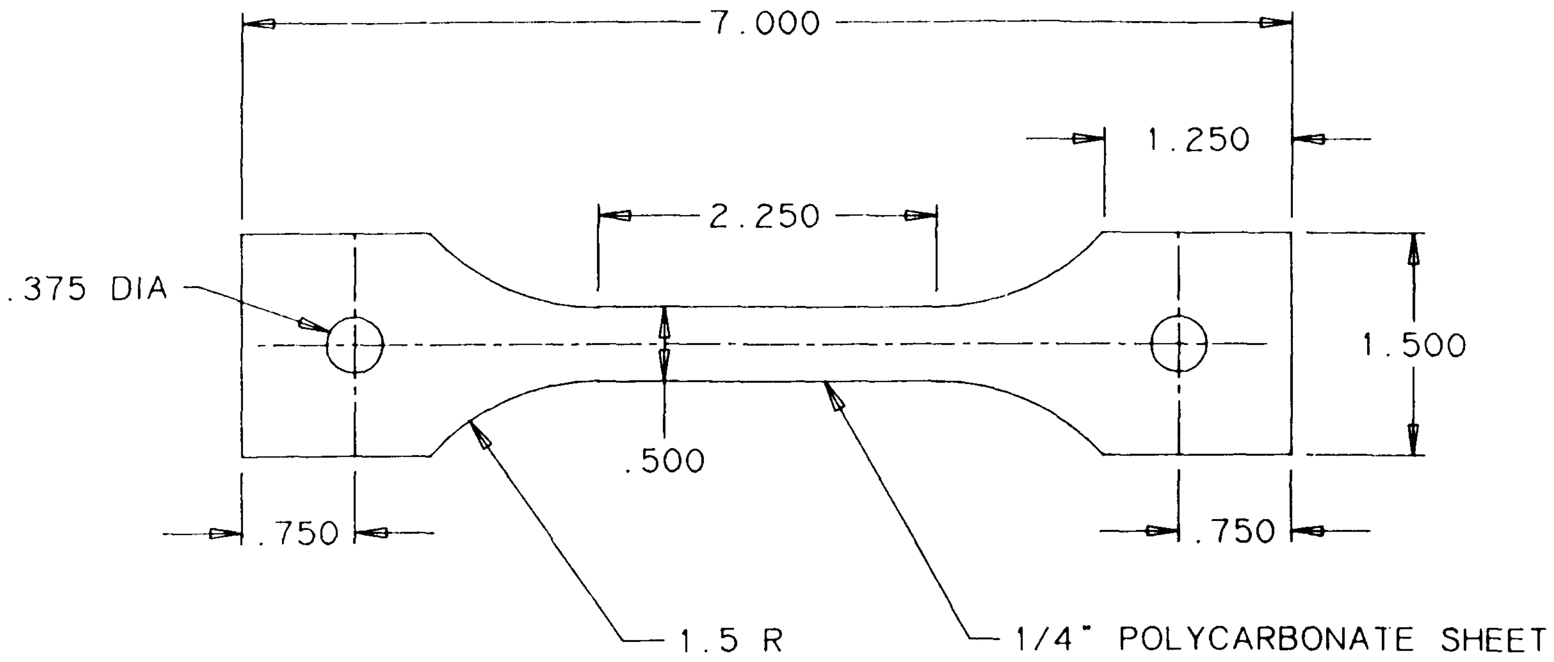
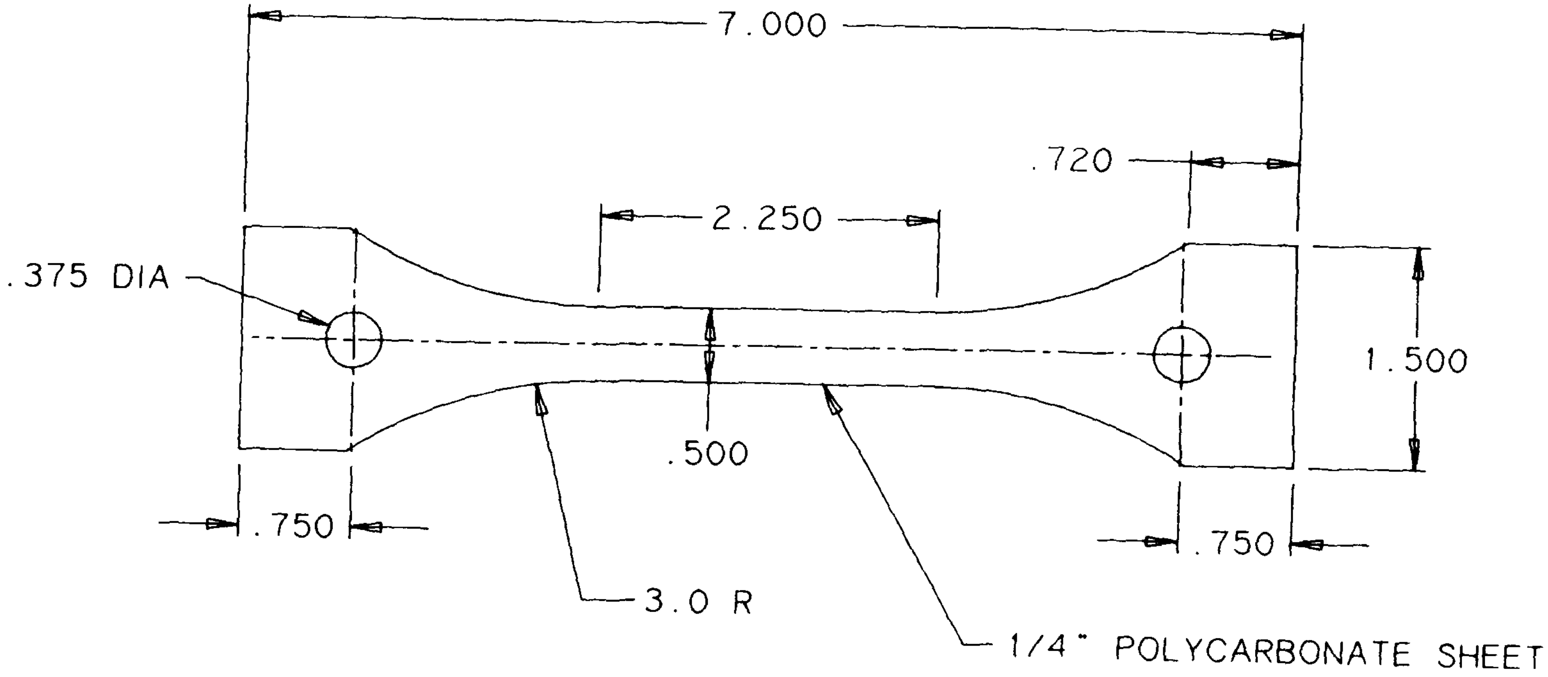


Figure 7. Test Specimens without Holes, Group A.



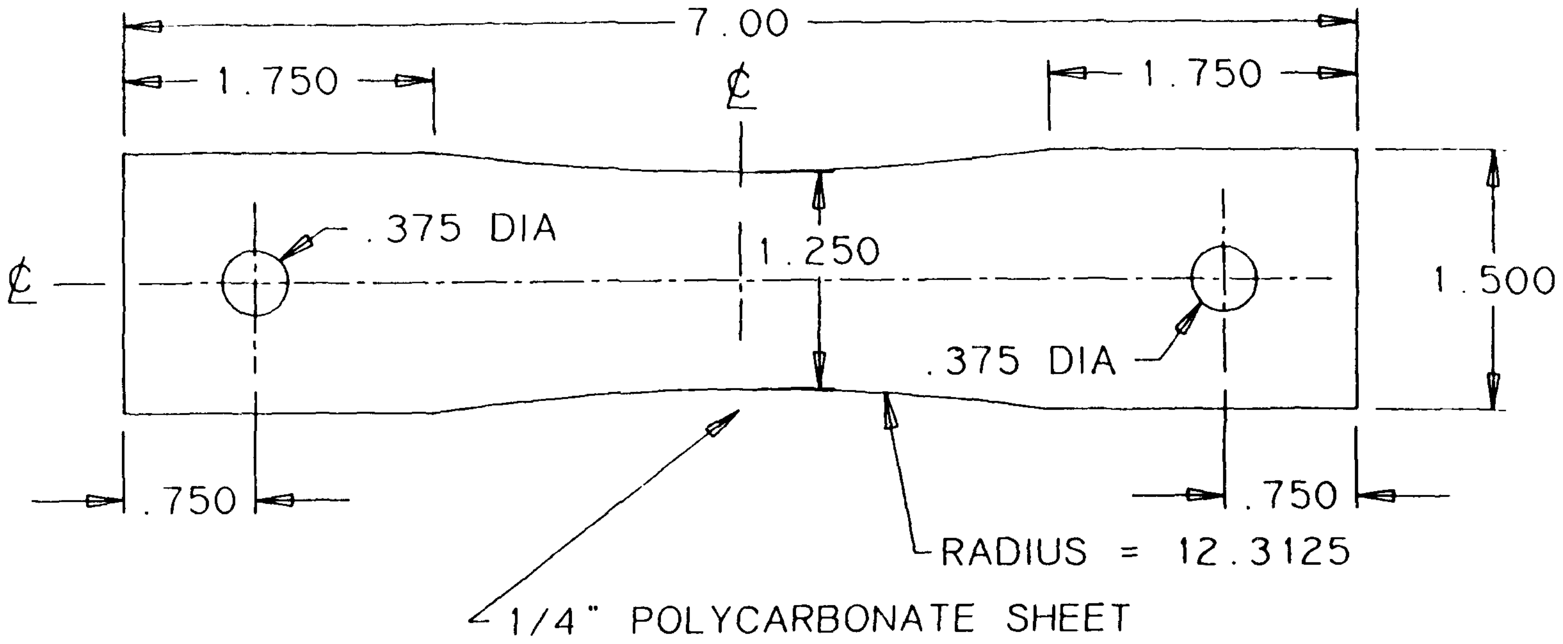
NOTE: ALL DIMENSIONS IN INCHES

Figure 8. Test Specimens Without Holes, Group B.



NOTE: ALL DIMENSIONS IN INCHES

Figure 9. Test Specimens Without Holes, Group O.



NOTE: ALL DIMENSIONS IN INCHES

Figure 10. Test Specimens Without Holes, Group 9.

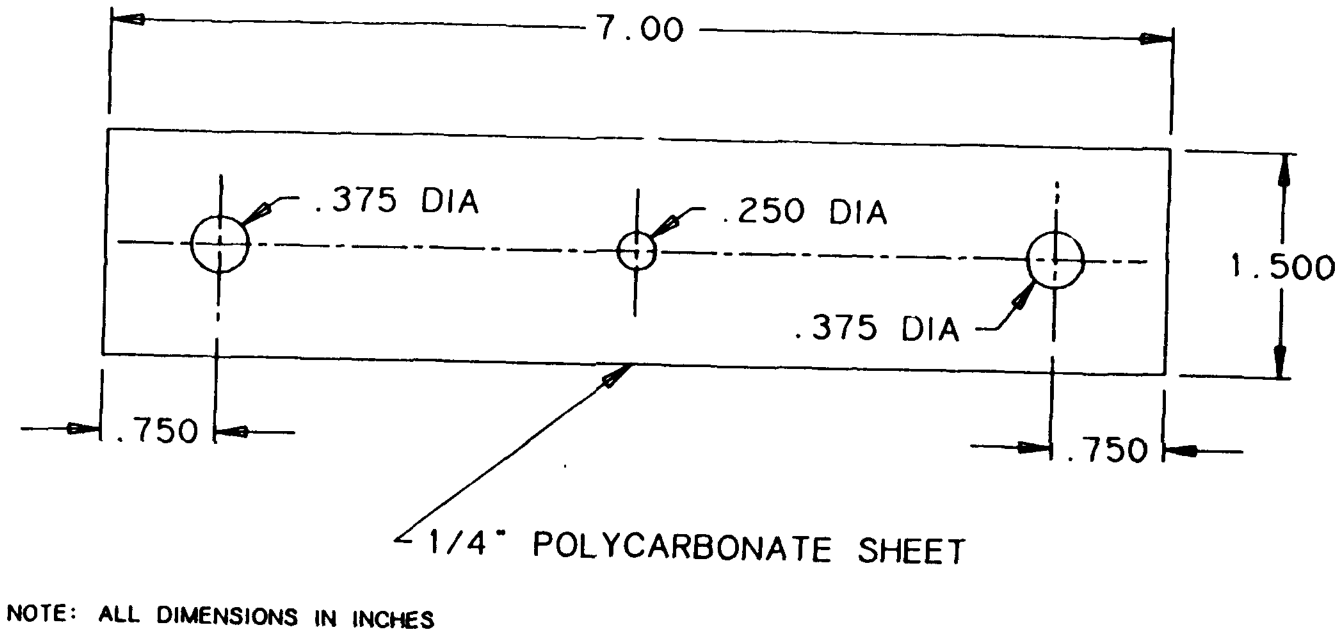


Figure 11. Test Specimens with Holes.

TABLE 4

TEST MATRIX

TEST	WITHOUT HOLE	HOLE DESIGN GROUP NUMBER							
		#1	#2	#3	#4	#5	#6	#7	#8
FATIGUE	45	16	17	25	17	17	14	14	18
TENSILE/ RESIDUAL STRENGTH	13	3	3	0	3	3	3	3	4
SURFACE FEATURES/ ROUGHNESS		1	1	1	1	1	1	1	1
	TOTAL								226

SECTION 6

DOCUMENTATION OF HOLE SURFACE FINISH

Surface roughness measurements were made using one specimen from each group (typically the 21st specimen produced). For the shot peened specimens, the surface roughness was characterized for only the Group 3.1 specimens, as sufficient specimens were not available for the other specimens shot peened using different conditions. Circumferential surface roughness measurements were made circumferentially around the hole surface at approximately half the depth of the hole, and axial surface roughness measurements were made along four lines separated by 90 degrees parallel to the axis of the hole. Measurements were made at the Giddings and Lewis Company Eli Whitney Metrology Laboratory using a Sheffield Indicorder Spectre. The hole surface roughnesses are summarized in Tables 5 and 6. For a more complete discussion of the parameters measured, see Reference 79. It should be noted that the circumferential surface roughness (which detects axial surface features) is probably the most important measurement, since axial features (such as scratches caused by removing the drilling tool) reportedly influence crack initiation and fatigue life. This agrees with intuition as cracks tend to be purely axial; that is, they are parallel to the thickness dimension of the material. Axial surface roughness (which detects circumferential features) has less of an effect on fatigue life and crack initiation, as these features are perpendicular to the axis of the cracks.

In terms of circumferential surface roughness, Groups 6, 2, and 1 have the lowest roughness averages, R_a, of 10, 12, and 12 microinches respectively; followed by groups 4, 5, and 7 for which R_a is 35, 40, and 58 microinches respectively; the roughest holes are from Group 8 with $R_a = 110$ microinches, and Group 3 with $R_a = 142$ microinches. Group 6 holes were cold worked by pushing a vaseline lubricated tapered oversize pin through the hole. This apparently provides a polishing effect resulting in a slightly better surface finish than the drilled hole alone. Group 2 holes were the step drilled holes. The surface finish of these holes is nearly indistinguishable from the surface finish of the Group 1 holes which were drilled in one step. Group 4 holes were drilled by PPG Industries. Group 5 holes were the same as group 1 except they were polished with toluene. This polishing did not result in better surface finish; in fact the surface finish of the toluene polished holes was worse than the surface finish of the unpolished holes. Group 7 holes were the same as Group 1 holes except that the entry and exit of the holes

Table 5. Summary of Hole Circumferential Surface Roughness Measurements

MEASUREMENT	GROUP 1	GROUP 2	GROUP 3.1	GROUP 4	GROUP 5	GROUP 6	GROUP 7	GROUP 8
Ra	12	12	142	35	40	10	58	110
Rt	118	115	963	292	345	90	503	840
Rz	58	55	257	82	90	48	330	312
Rtm	75	78	702	185	205	62	413	555
Rq	15	15	185	50	52	12	80	142
Rp	70	60	510	138	170	38	305	430
Rv	-48	-55	-453	-155	-175	-52	-197	-410
Rsm	600	600	5100	900	1600	600	1700	2900
Rlq	500	500	4400	1700	1600	500	1900	3700

NOTES:
ALL MEASUREMENTS REPORTED IN MICROINCHES
CIRCUMFERENTIAL MEASUREMENTS MADE AT HALF THE HOLE DEPTH

KEY:
Ra = ARITHMETIC AVERAGE ROUGHNESS HEIGHT
Rt = MAXIMUM ROUGHNESS HEIGHT IN FIVE CUTOFFS
Rz = MAXIMUM ROUGHNESS HEIGHT IN ONE CUTOFF
Rtm = MEAN "Rt"
Rq = RMS (ROOT MEAN SQUARE) AVERAGE ROUGHNESS HEIGHT
Rp = MAXIMUM PEAK HEIGHT IN ONE CUTOFF
Rv = MAXIMUM VALLEY HEIGHT IN ONE CUTOFF
Rsm AND Rlq ARE ROUGHNESS SPACING PARAMETERS FOR KEY FEATURES

Table 6. Summary of Hole Axial Surface Roughness Measurements

MEASUREMENT	GROUP 1				GROUP 2				GROUP 3.1				GROUP 4			
Ra	20	20	15	20	20	15	25	15	150	265	255	215	50	65	125	130
Rt	230	275	300	510	240	140	520	145	1250	1780	2430	1290	425	530	1200	650
Rz	85	75	100	65	70	70	100	60	350	505	595	425	56	80	130	110
Rtm	150	130	130	180	135	100	205	100	795	1310	1380	1095	230	310	525	470
Rq	25	25	20	35	25	20	40	20	185	335	345	260	70	85	200	155
Rp	150	120	80	390	95	80	160	95	740	1085	820	630	145	170	475	280
Rv	-80	-155	-220	-120	-145	-60	-360	-50	-510	-695	-1610	-660	-280	-360	-725	-370
Rsm	2300	2000	1900	2100	2700	1700	2600	2100	6700	7500	7800	8100	5000	5200	5400	8400
Rlq	1400	1500	1100	1400	1700	1100	1700	1200	5500	6900	7000	7000	3400	4000	7900	7300

MEASUREMENT	GROUP 5				GROUP 6				GROUP 7				GROUP 8			
Ra	110	58	50	70	25	35	30	35	70	75	70	50	220	325	215	130
Rt	935	427	355	505	195	230	295	385	625	700	825	575	2065	3315	2060	1480
Rz	190	95	85	135	95	115	75	135	300	370	355	290	310	585	915	290
Rtm	485	283	250	340	155	185	175	230	455	505	545	420	1240	1795	1430	715
Rq	155	75	60	90	30	40	40	45	90	105	100	75	290	490	290	185
Rp	690	235	190	265	85	110	175	250	265	245	335	250	965	1755	1015	825
Rv	-245	-192	-165	-240	-110	-120	-120	-135	-360	-455	-490	-325	-1100	-1560	-1045	-655
Rsm	8400	5500	5100	6100	3700	3600	3700	4800	3900	4300	2900	2500	6500	5300	4500	6400
Rlq	6100	5600	3600	5000	2100	2500	2600	2700	2800	3500	2700	2300	5400	7500	4400	4500

NOTES:

ALL MEASUREMENTS REPORTED IN MICROINCHES

FOUR AXIAL MEASUREMENTS MADE PER HOLE AT INTERVALS OF 90 DEGREES AROUND THE PERIMETER OF THE HOLE was radiused. For reasons unknown, the surface finish of the Group 7 holes is not nearly as good as that of the Group 1 holes. They should have been very similar. Group 8 holes were hand drilled with a used drill bit which explains the higher surface roughness. Group 3 holes were the same as Group 7 except they were also shot peened, resulting in the highest surface roughness of any of the holes.

SECTION 7

TEST SETUP AND METHODS

Special grips were made for this testing and are shown in Figure 12. The shoulder bolts used in the specimens grips were torqued to 40 foot pounds. A special fixture was used to align the specimens in the grips. The grip design was marginal in terms of grip area for the tensile residual strength specimens with holes, as a number of those specimens failed in the grip. No problems with the grips were experienced with the fatigue testing. The testing was conducted with MTS test machines. A displacement rate of 2 inches/minute was used for the tensile testing, and the tensile fatigue tests were conducted at 2 Hz. The ratio of the minimum load to the maximum load was 0.10 (no compression).

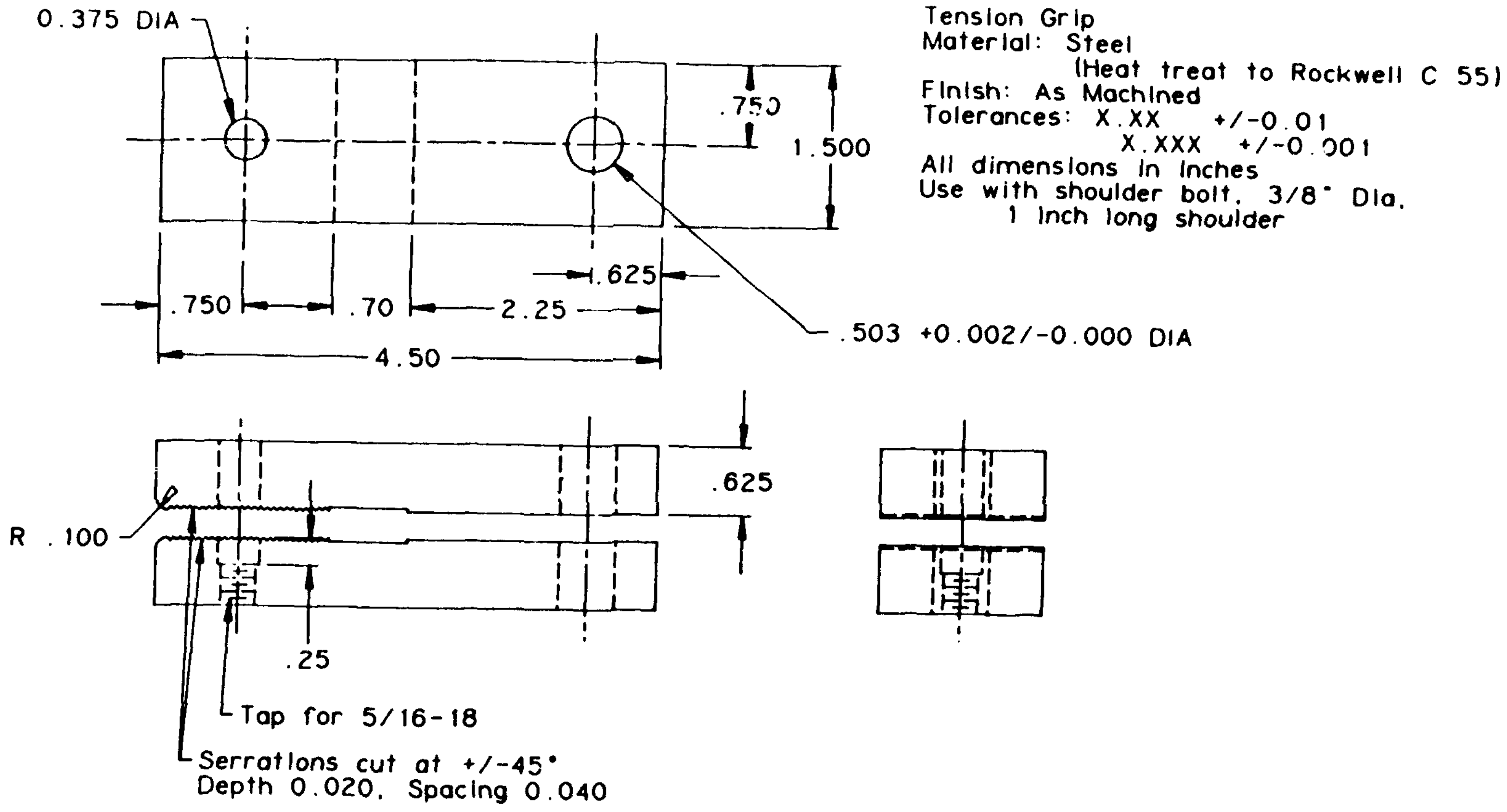


Figure 12. Test Grip.

SECTION 8

TEST RESULTS/DISCUSSION

The results of the residual strength testing of the tensile dogbone specimens and the rectangular specimens with holes are shown in Table 7. Typical stress-strain curves for the dogbone specimens are shown in Figure 13. Typical load displacement curves for the rectangular specimens are shown in Figure 14. In contrast with Tayebi and Agrawal[18], the reduction in effective breaking stress was minimal for the tensile/residual strength specimens. Elongation was markedly reduced for specimens with holes. There was minimal variation in tensile residual strength between the hole designs. No tensile residual strength testing was conducted for Group 3specimens. Group 3 specimens were not tested as there were only a limited number available, and those were dedicated to fatigue testing.

The results of the fatigue testing are summarized in Tables 8, 9, and 10. A composite plot of all of the fatigue data is shown in Figure 15. Plots for each of the individual specimen designs are shown in Figures 16-24. The maximum stress reported on the tables and graphs is gross stress, not net stress.

Fatigue testing of the dogbone specimens produced some unusual results in the 8.5 ksi down to the 5.5 ksi region. In this region, the life (cycles to failure) is nearly constant and may even be slightly shorter for some of the lower stresses. In addition, the majority of the specimens in this region did not fail in the gage length. The shape of the S-N curve for the dogbone specimens is similar to those reported for polycarbonate from References 14 and 16. It was suspected that the cause of the unusual shape of the S-N curve and the failures outside of the gage length for the dogbone specimens was residual surface compressive stresses which were caused by the extrusion process. Cracks tended to initiate at the specimen edges and propagate within the specimen. Cracks which initiated at a corner also tended to propagate within the specimen and were retarded at the surface (indicating significant residual surface compressive stresses). A limited number of specimens were annealed and tested. As was expected, annealing resulted in shorter fatigue lives, the vertical portion of the S-N curve disappeared, and the specimens all failed within the gage length.

TABLE 7

TENSILE RESIDUAL STRENGTH TEST RESULTS

HOLE DESIGN	AVERAGE NET FAILURE STRESS (KSI)	STANDARD DEVIATION	AVERAGE GROSS FAILURE STRESS (KSI)	STANDARD DEVIATION
NO HOLE*	9.68	0.12	9.68	0.12
ANNEALED	10.7		10.7	
#1	9.57	0.06	7.98	0.05
#2	9.57	0.07	7.98	0.06
#3	NO SPECIMENS TESTED			
#4	9.46	0.07	7.89	0.06
#5	9.48	0.09	7.9	0.07
#6	9.48	0.04	7.9	0.03
#7	9.5	0.05	7.92	0.05
#8	9.59	0.02	7.99	0.02
ANNEALED	10.28		8.57	

* YIELD STRESS REPORTED FOR SPECIMENS WITHOUT HOLES

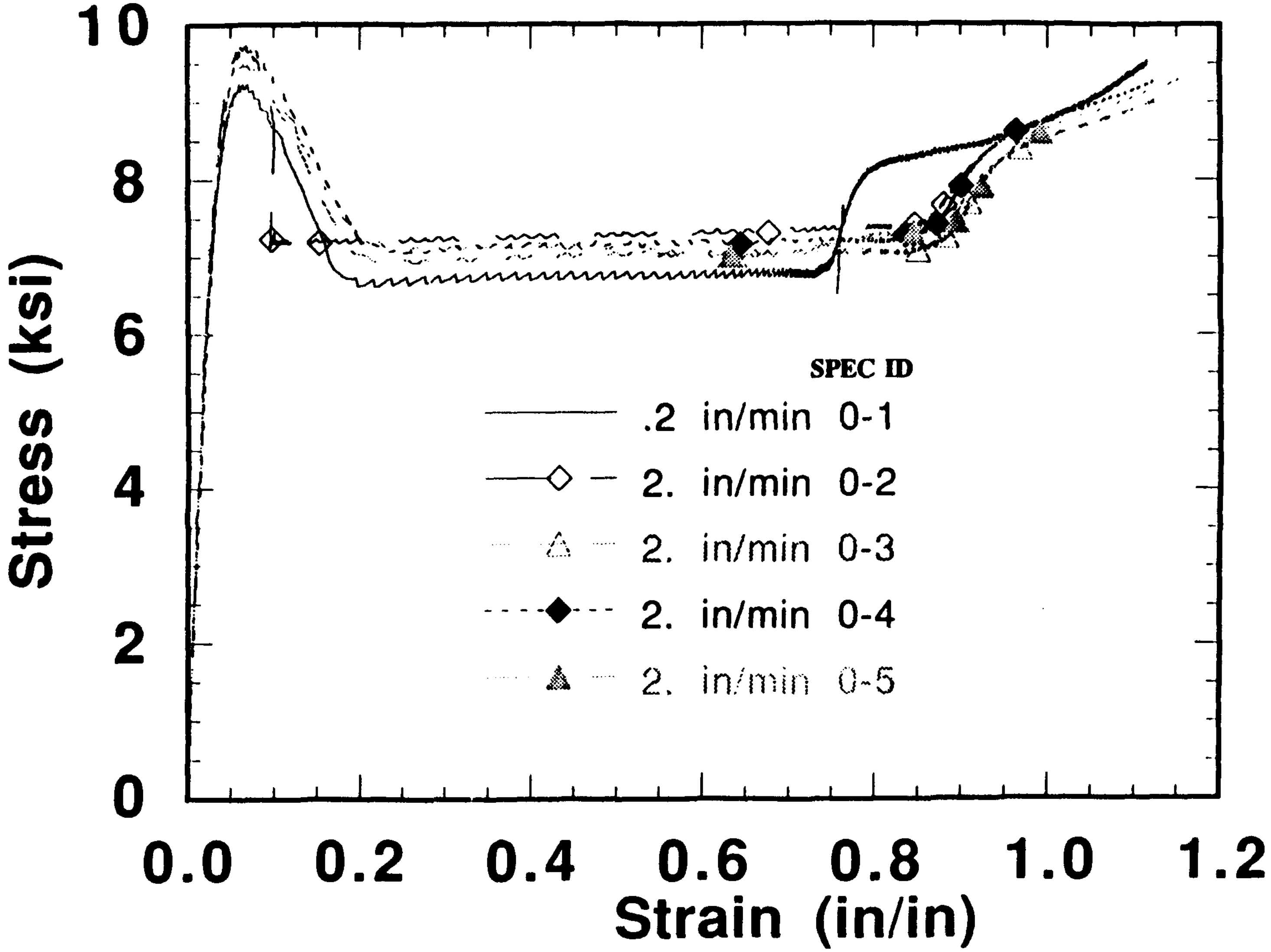


Figure 13. Typical Stress Strain Curves for Tensile Dogbone Specimens.

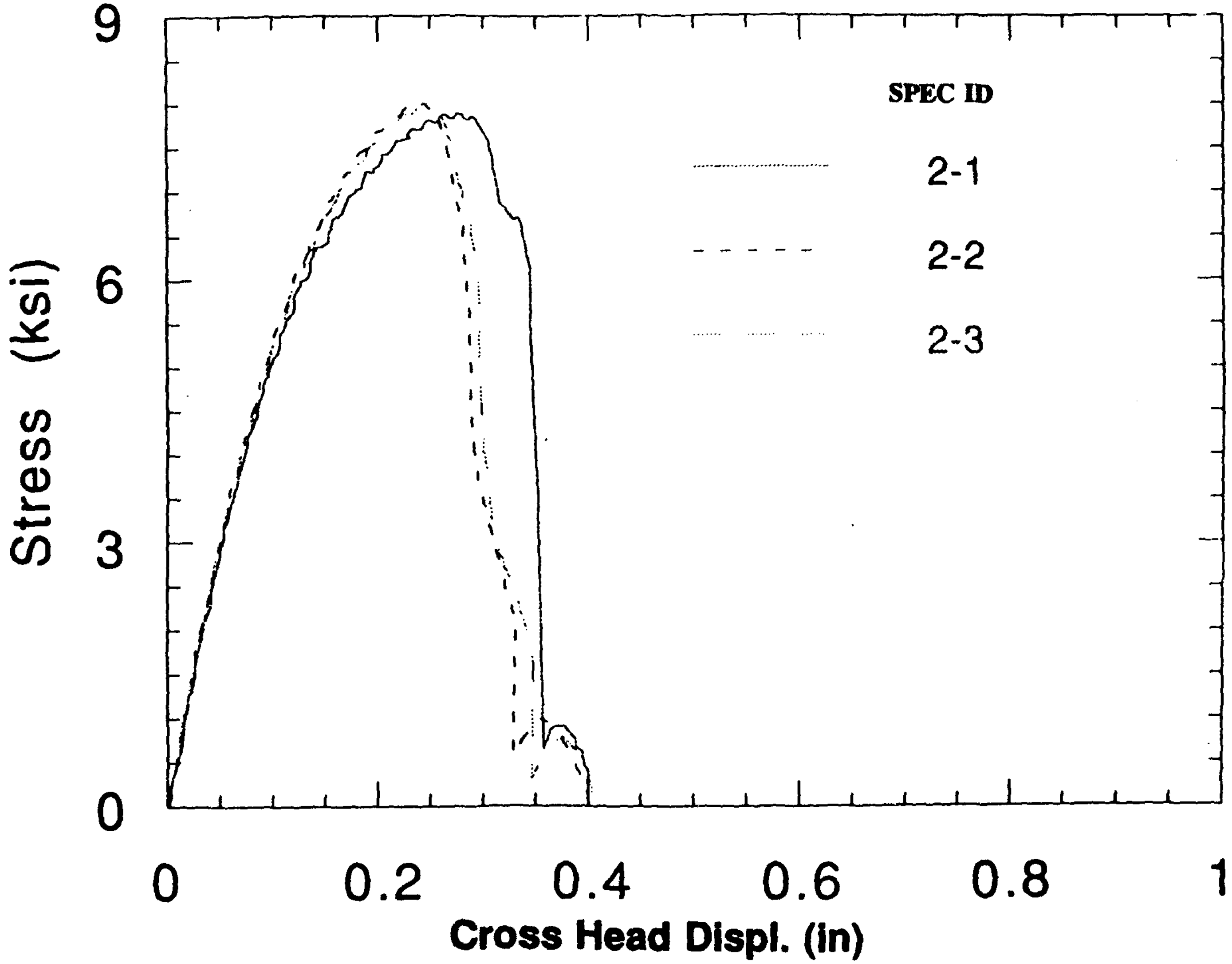


Figure 14. Typical Load Displacement Curves for Tensile Residual Strength Specimens with Holes.

TABLE 8
FATIGUE LIFE (CYCLES TO FAILURE) FOR DOGBONE SPECIMENS

MAXIMUM STRESS (KSI)	GROUP A	GROUP B	GROUP 0	GROUP 9
9.60			50	
9.50			55	
9.50 ANNEALED		2492		
9.25			167	
9.00	179		294 328	406
9.00 ANNEALED	2599			2092
8.75	381		562 613	
8.75 ANNEALED	2126			
8.60			23519	
8.50			34497 24955	
8.40 ANNEALED	2989 1592	2620 2723		1896
8.40	25680	27471 27948		13576
8.00 ANNEALED	2450			2512
8.00	26229		26357 17462	6559 13632
7.50		22650	24984	
7.00	14788		22943	8745
6.50 ANNEALED	5972			
6.00	19909			
5.50		21948		20035
5.00	18877		36885	
5.00 ANNEALED		14352		
4.50	31784			
4.00	50749			53979
3.50	77559			
3.50 ANNEALED	46441			
3.25	52052 121811			
3.00	1029773*			

* DID NOT FAIL

TABLE 9
FATIGUE LIFE (CYCLES TO FAILURE) FOR SPECIMENS WITH HOLES

MAXIMUM STRESS (KSI)	GROUP 1	GROUP 2	GROUP 3.1	GROUP 4	GROUP 5	GROUP 6	GROUP 7	GROUP 8
9.00								6
8.75								6
8.00								12
7.25	61	59	49	59				
7.00	110 117	105 127		109 111	59 52	94	74 93	82
6.50	305	355	181	256	210	366	224	
6.00	1243 1128	973 1081	488	944 854	503 889	1518 2454	627 678	646
5.75					1205			
5.50					2127			
5.20					8885			
5.00	12799 15401	4405 17378	12495	7640 6064	11418 7033	8559 13928	13558 13258	8242
5.00 ANNEALED						4791		
4.00	28497 26379	26597 25416	28253 12999	36524 34167	8981 8846	50223 55530*	19665 32448	26588
4.00 ANNEALED								2616
3.50								24584
3.25								18602
3.00	32754 33902	26707 28899	17003 28690	35663 56994	9843 13097	141096 108904	24458 19940	18019
2.00	44695 55041	35347 31842	35917	83374 42919	17901 16317	237339 209995	41913 34949	34749
2.00 ANNEALED	35140	27869						20706 20294
1.75								53007
1.50								87199
1.25	385392	480254**		170132 251978	95522	691669**	106074	152297 122455
1.00		858350**		713271**				

* DID NOT FAIL THROUGH HOLE
** DID NOT FAIL

TABLE 10
FATIGUE LIFE (CYCLES TO FAILURE) FOR SHOT PEENED SPECIMENS

SHOT SIZE	MI-70-H	MI-70-H	MI-70-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H	MI-170-H
AIR PRESSURE (PSI)	10	20	70	5	10	20	30	40	80
ALMEN INTENSITY	4.4N	7.4N	7.4A*	2.0N	4.6N	8.7N	4.3A	5.2A	7.5A
GROUP NUMBER	3.6	3.8	3.1	3.5	3.3	3.2	3.9	3.4	3.7
MAXIMUM STRESS (PSI)									
7.25			49						
6.50			181						
6.00			488						
5.00			12495						
4.00			28253 12999						
3.00			17003 28690						
2.00	28369 41094	31604 30120	35917	28843 17420	36273 36632	32595 31840	29386 27227	29288 32891	43879 42574

*MEASUREMENT UNCERTAIN

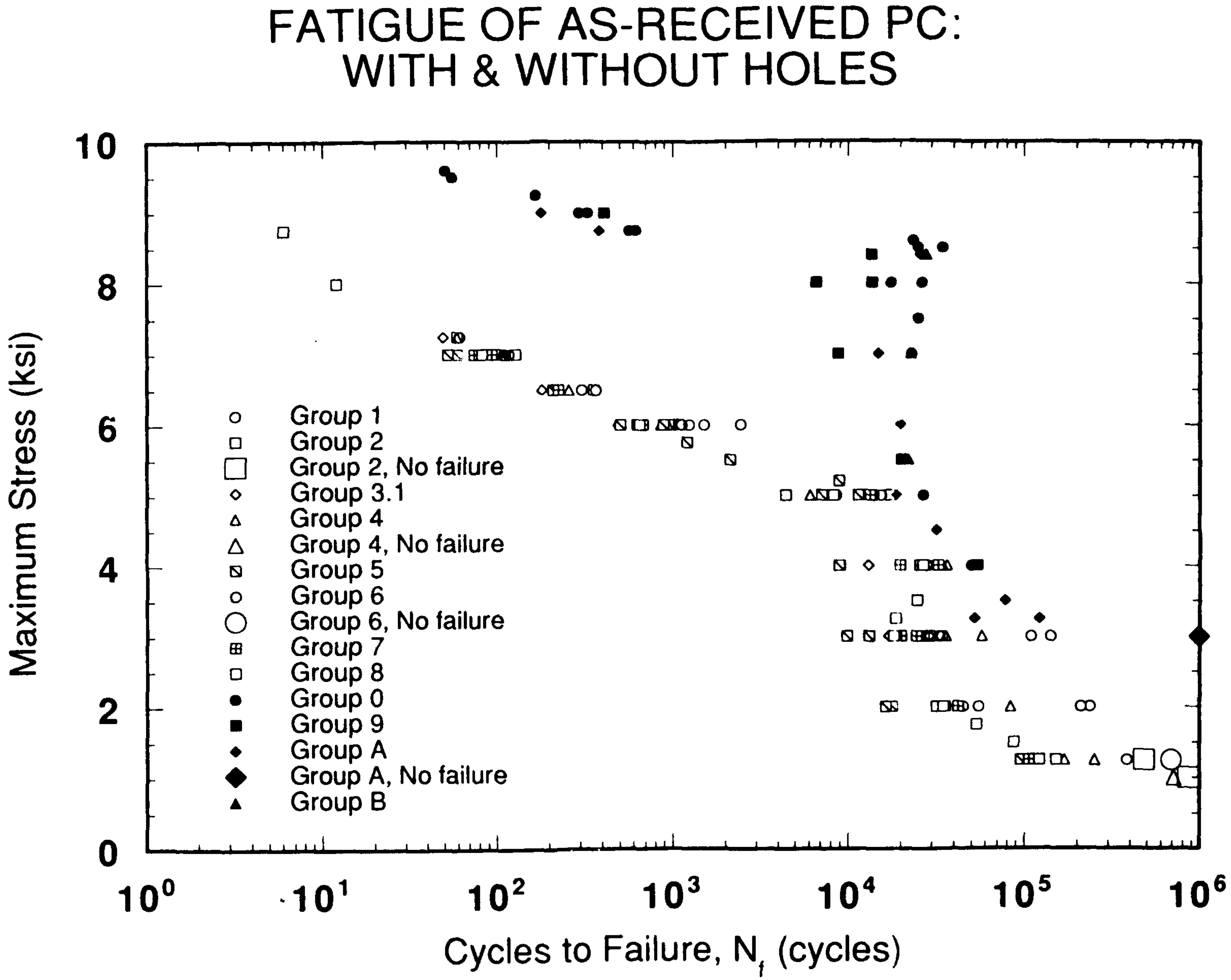


Figure 15. Fatigue of As-Received PC: With and Without Holes.

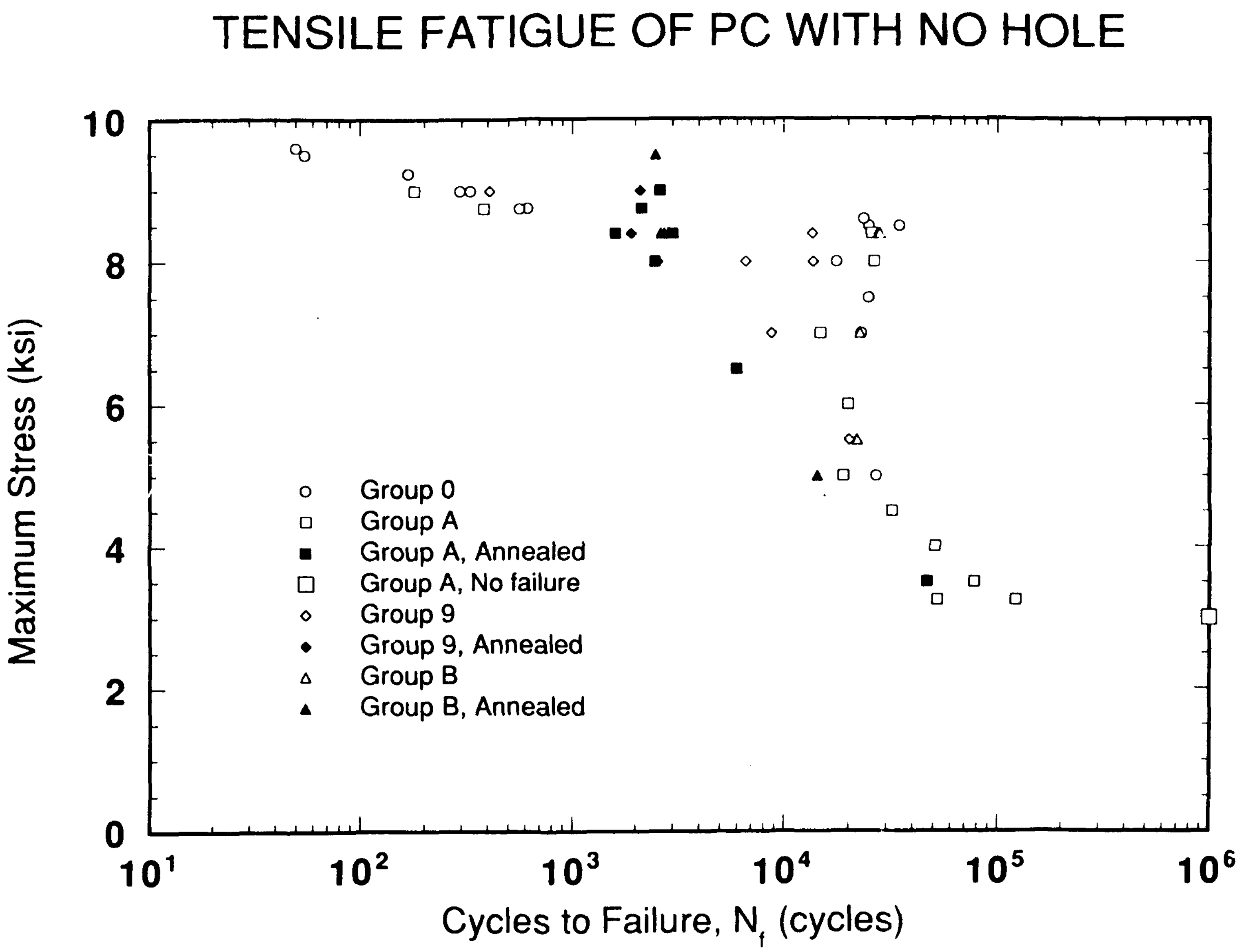


Figure 16. Tensile Fatigue of PC with No Hole.

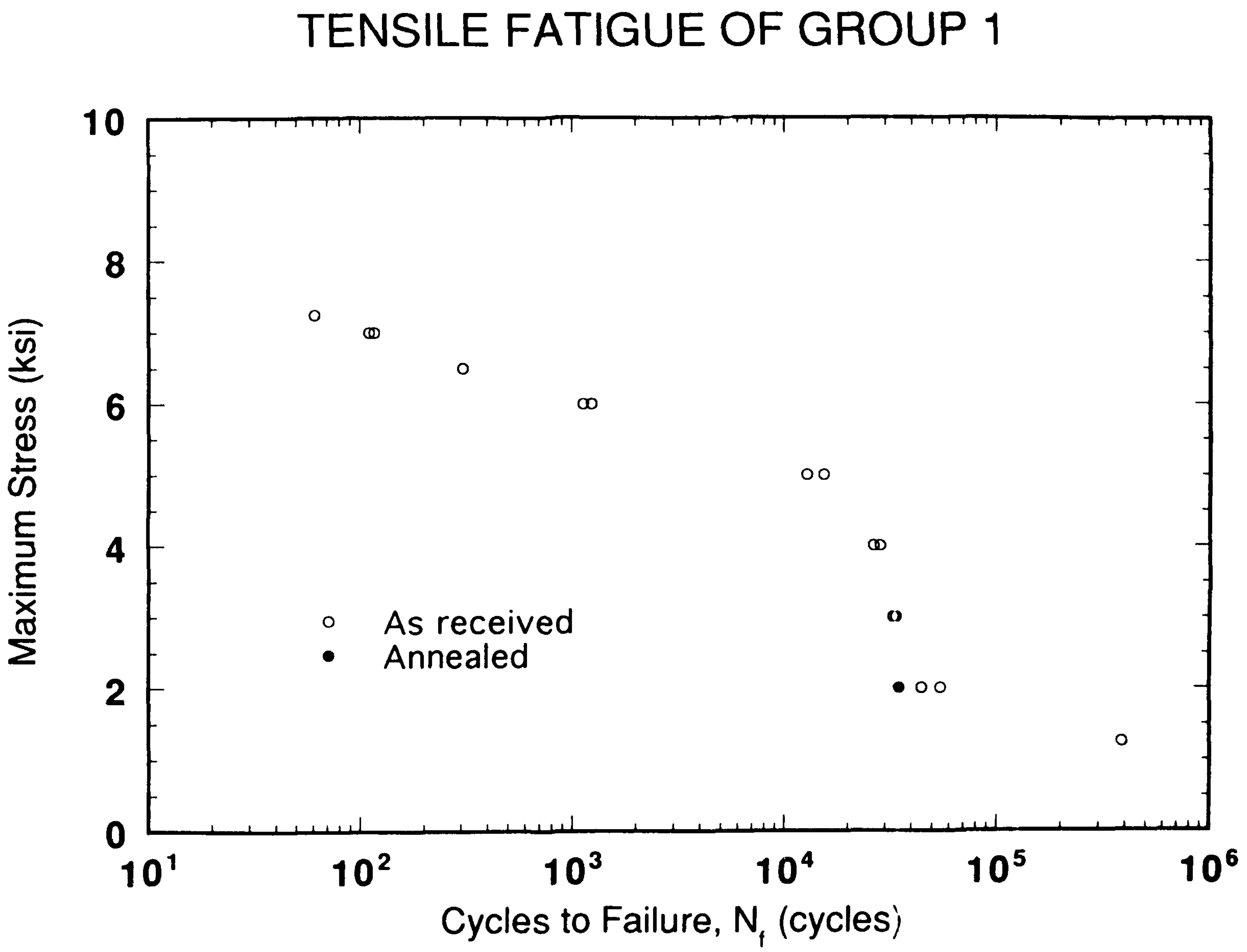


Figure 17. Tensile Fatigue of Group 1 Specimens With Holes.

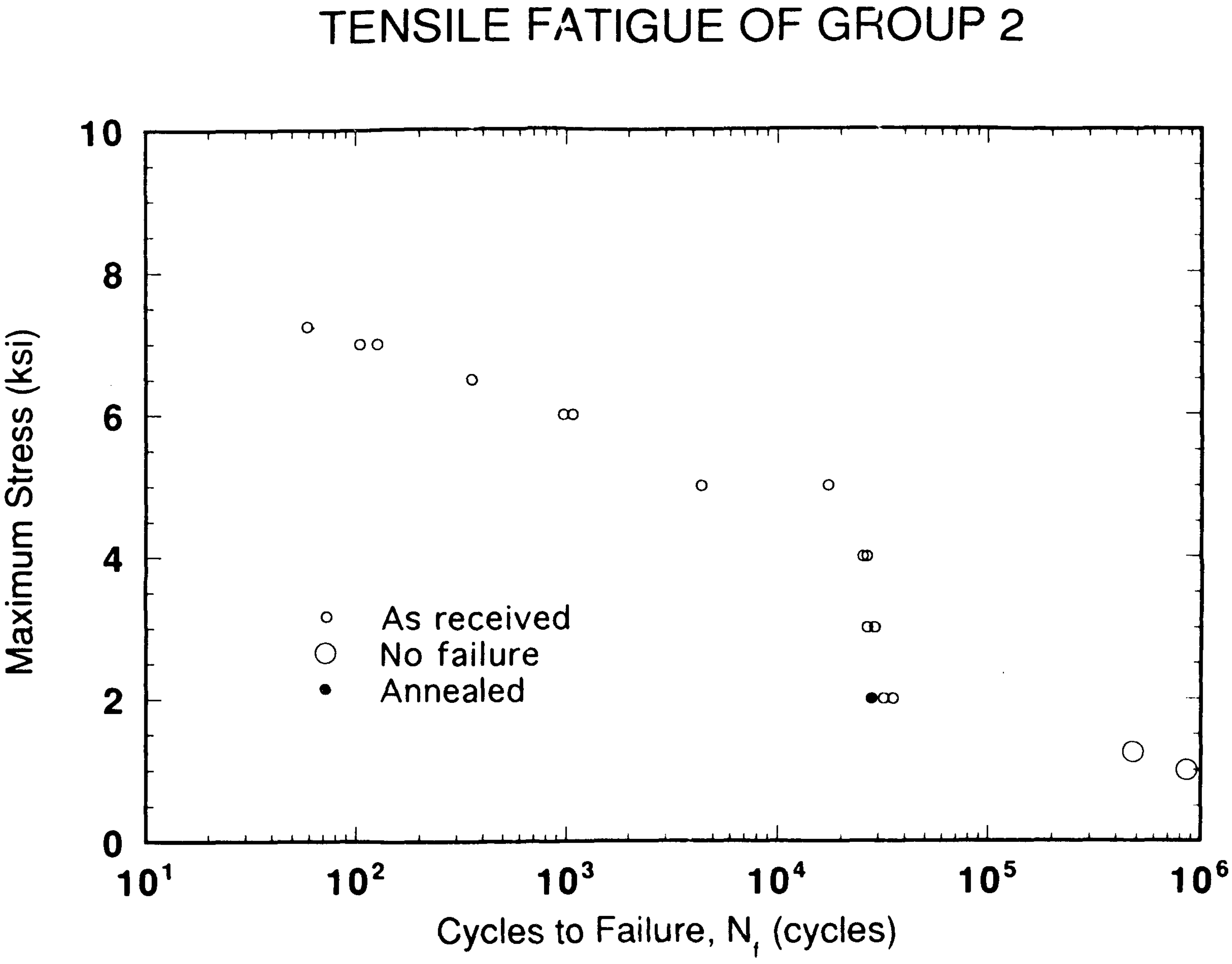


Figure 18. Tensile Fatigue of Group 2 Specimens With Holes.

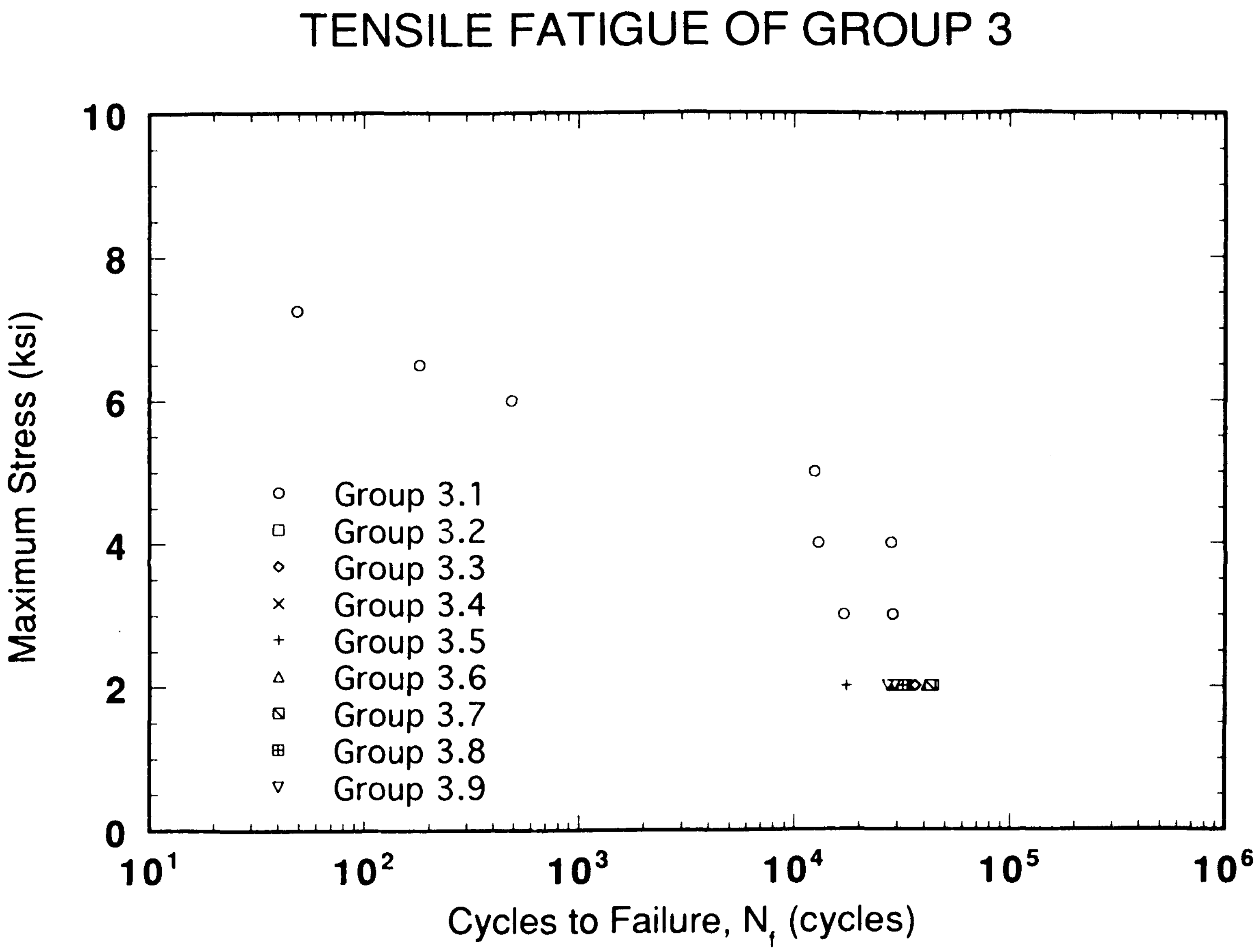


Figure 19. Tensile Fatigue of Group 3 Specimens With Holes.

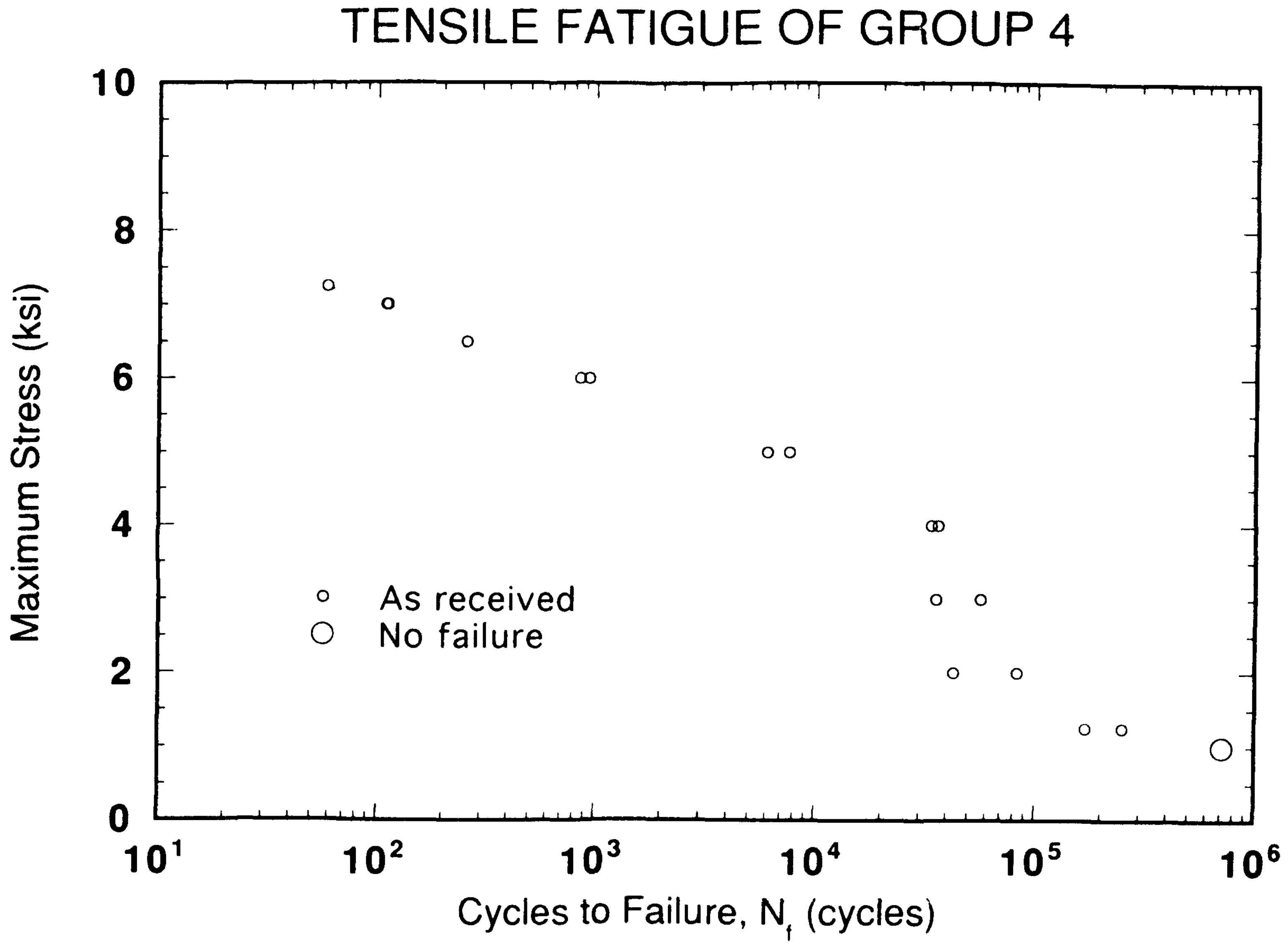


Figure 20. Tensile Fatigue of Group 4 Specimens With Holes.

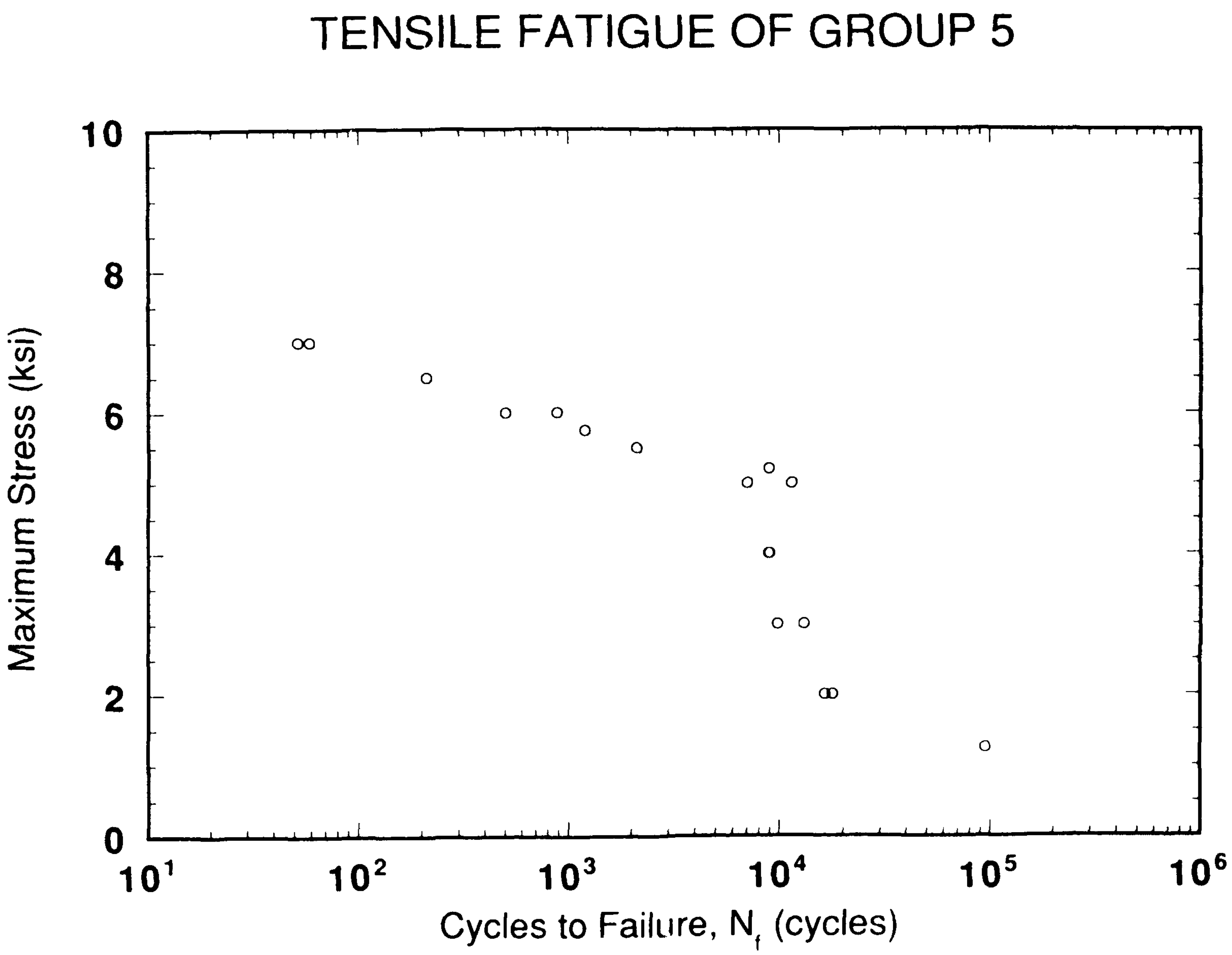


Figure 21. Tensile Fatigue of Group 5 Specimens With Holes.

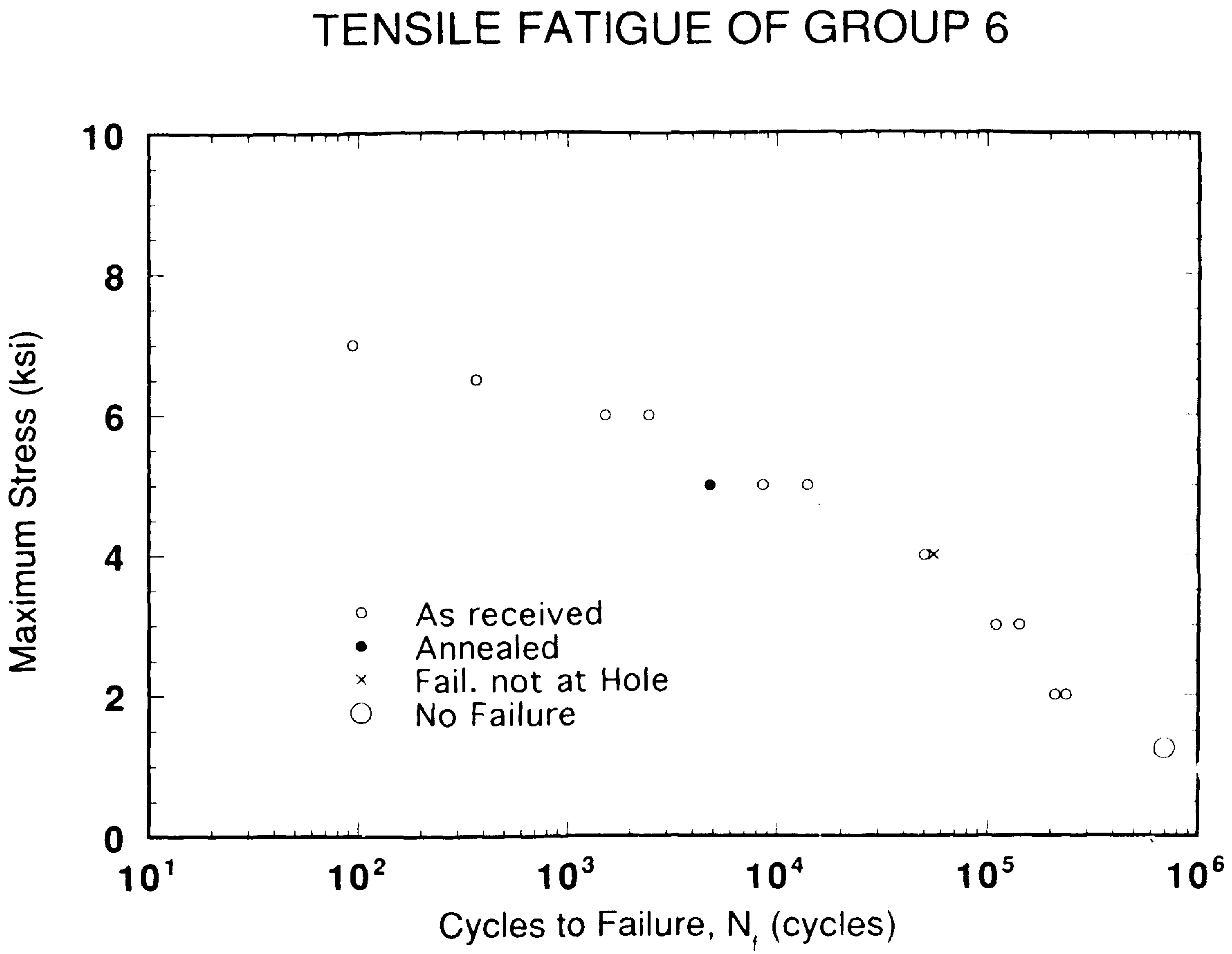


Figure 22. Tensile Fatigue of Group 6 Specimens With Holes.

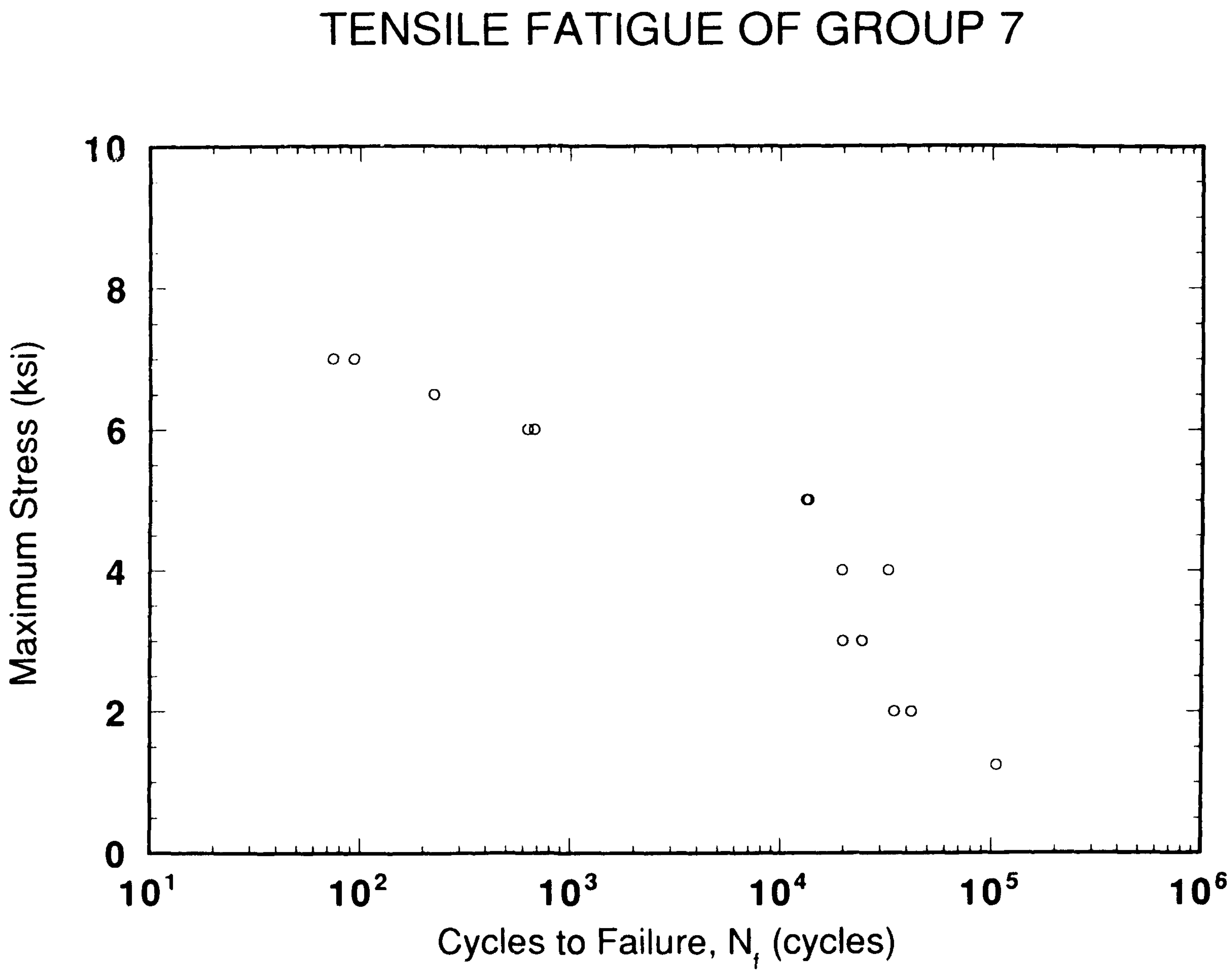


Figure 23. Tensile Fatigue of Group 7 Specimens With Holes.

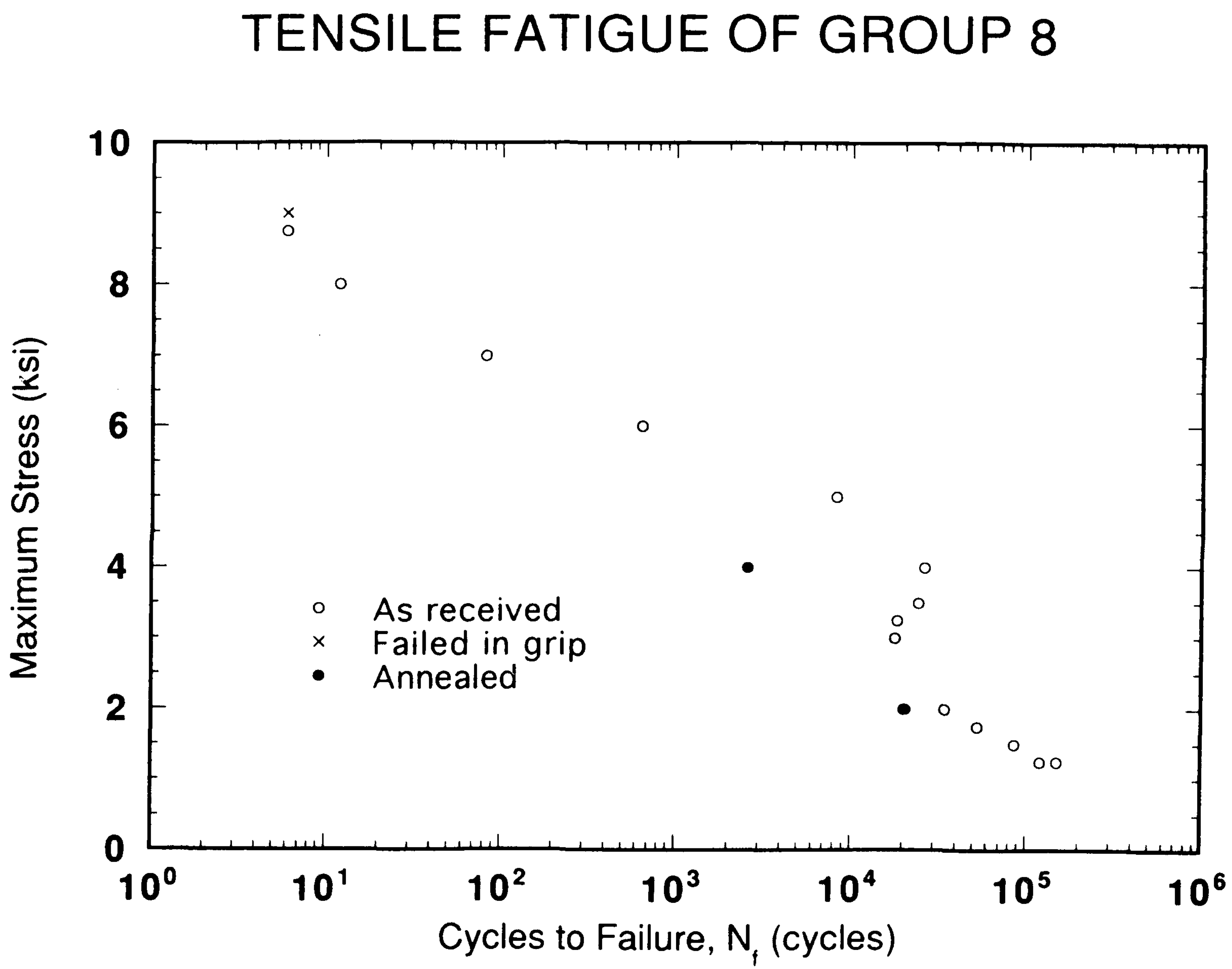


Figure 24. Tensile Fatigue of Group 8 Specimens With Holes.

The hole fabrication/treatment techniques evaluated in this program are listed below in order of fatigue performance, with the high cycle fatigue at 1.25 ksi maximum stress as the criteria, and the best technique listed first.

(1) Group 6 - Cold working
(2) Group 2 - Step drilling
(3) Group 1 - Drilling with new drill, one step
(4) Group 4 - PPG Hole Drilling
(5) Group 8 - Hand drilling
(6) Group 7 - Radiused entry and exit
(7) Group 5 - Polishing with toluene

Group 3, the shot peened holes, are not included as no specimens were tested at 1.25 ksi. Group 3 would most likely perform similarly to Groups 1, 4, and 8. Examination of the shot peened results in Table 10 indicates that higher intensities and pressures may result in better fatigue performance. Higher intensities and pressures would be expected to result in higher and/or deeper induced residual stress in the vicinity of the hole. The results of the fatigue testing of shot peened specimens seems to indicate that at low pressures and intensities, shot peening results in some degradation due to roughening of the hole surface. With increased pressure and intensities, this roughening increases with minimal cold working, resulting in continued decrease of fatigue properties. Eventually, this trend changes and fatigue life starts to improve with increased pressure and intensity as the induced favorable residual compressive stresses start to overcome the degradation induced by increased surface roughness. In addition, surface roughness most likely peaks out a some point, and does not increase with additional shot peening (this is a hypothesis based on the author's experiences with salt blasting of plastics and no testing was conducted in this program to confirm this). Group 7, with radiused hole entry and exit, did not perform well, it appears that removal of the extra material to create the radius decreases fatigue life. Polishing with toluene, as with group 5, did not perform well. Careful hole drilling appears to be a much safer way of obtaining good surface finish than chemical polishing after drilling. Based on these test results, a carefully machined hole which is cold worked, Group 6, has a fatigue life of 2 to as much as 6 times the fatigue life of a hand drilled hole. This represents a considerable improvement.

It is important to note that depending on the stress level chosen to evaluate the different techniques, the ranking would change. None of the techniques chosen were optimized, and optimization could easily change the ranking. Also, testing more specimens at each stress level would result in improved definition of individual S-N curves, resulting in more exact discrimination between different hole fabrication/treatment techniques.

The effects of surface finish on fatigue life can not easily be discerned from this testing. As noted in Section 3, surface finish is only one factor influencing fatigue, residual strength, etc. The hole fabrication/treatment techniques evaluated in this report did not concentrate on surface finish alone. Comparing specimen groups with drilled holes (and no other post-fabrication treatment), Groups 2, 1, 4, and 8 have increasing surface roughness, with Group 2 holes being the smoothest and Group 8 the roughest, and Groups 2, 1, 4, and 8 have decreasing fatigue life, with Group 2 having the longest lives, and Group 8 the shortest. There does appear to be a correlation between surface roughness and fatigue life for specimens which were drilled (with no other post-fabrication treatment), with the smoother holes having the longest lives.

SECTION 9

CONCLUSIONS/SUMMARY

A number of different potential hole fabrication/treatment techniques were identified. Eight of these were chosen for tensile residual strength and tensile-tensile fatigue evaluation in this program. The differences in tensile residual strength for the specimens with holes were minimal. While no attempt was made to optimize the hole fabrication/treatment techniques, there was a fair amount of spread in fatigue performance for the techniques chosen for evaluation. Fatigue life varied by as much as a factor of 10 between the best technique, cold working, and the worst, chemical polishing. In addition to cold working, optimized hole drilling and shot peening also show promise for improvements in fatigue life. Based on limited testing, there is a correlation between surface roughness and fatigue life for specimens which were drilled (with no other post-fabrication treatment), with smoother holes having longer lives.

It should be noted that the results of this program apply to extruded polycarbonate and open (unloaded) holes. Indications are, from the limited number of annealed specimens which were tested, that annealing decreases fatigue life by eliminating favorable residual surface compressive stresses. The effect of annealing on tensile residual strength was not evaluated in this program; annealing might result in greater differences in residual strength between the different hole fabrication/treatments. Also, specimens with lug-loaded holes may show marked differences from the results reported herein. Evaluation of some of the parameters affecting hole performance, evaluation of the hole fabrication/treatment techniques identified herein for lug-loaded holes, optimization of some of the techniques identified herein for open holes, and evaluation of some of the identified candidate techniques for improving hole performance (which were not chosen for evaluation in this program) are areas for additional research.

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