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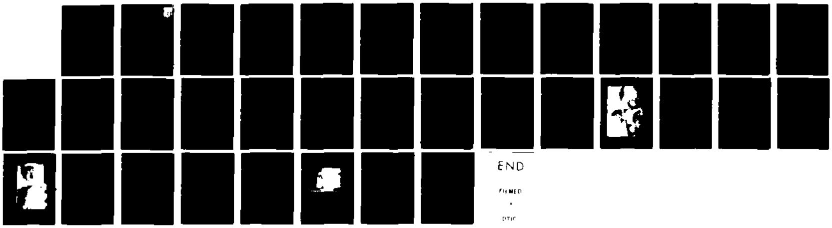

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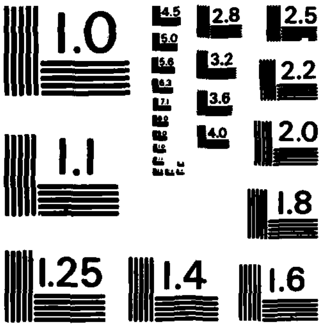
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MECHANICAL PROPERTY DATA ON P/M ALUMINUM X7091-T7E69 EXTRUSION

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OCTOBER 1982

Interim Report for Period August 1981-July 1982

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FOR THE COMMANDER:

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFWAL-TR-82-4161	2. GOVT ACCESSION NO. AD-A121875	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MECHANICAL PROPERTY DATA ON P/M ALUMINUM X7091-T7E69 EXTRUSION		5. TYPE OF REPORT & PERIOD COVERED Interim Technical Report August 1981-July 1982
		6. PERFORMING ORG. REPORT NUMBER UDR-TR-82-99
7. AUTHOR(s) John J. Ruschau Scott K. Jarvis, 1 Lt. USAF		8. CONTRACT OR GRANT NUMBER(s) F33615-82-C-5039
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Dayton Research Institute 300 College Park Avenue Dayton, Ohio 45469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2421-03-18
11. CONTROLLING OFFICE NAME AND ADDRESS Materials Laboratory (AFWAL/MLSA) Air Force Wright Aeronautical Laboratories (AFSC) Wright-Patterson AFB, Ohio 45433		12. REPORT DATE October 1982
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Powder-Metallurgy
7091-T7E69
Extrusion
Aluminum
Notched Fatigue
Fracture
Fatigue Crack Growth
Stress Corrosion

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

A mechanical property investigation was performed on aluminum X7091-T7E69 extrusion, a recently developed alloy produced using powder-metallurgy technology. Properties examined were tensile and compression, smooth and notched fatigue, fracture, fatigue crack growth, and stress corrosion cracking. For notched fatigue investigations, stress concentration factors as high as 10 were examined.

(continued on reverse side)

20. Abstract (Concluded)

Test results indicate the material is a high strength, high toughness aluminum alloy. Smooth and notched fatigue properties are superior to conventionally produced aluminum alloys intended for similar usage throughout the range of stress concentrations examined. Though the fracture toughness and notched fatigue properties are outstanding, the fatigue crack growth rate properties are below those of other 7000 series wrought aluminum alloys. Precracked specimens loaded in a 3.5% NaCl environment indicate there is no sensitivity to stress corrosion cracking under such conditions.

PREFACE

This interim technical report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-82-C-5039, "Quick Reaction Evaluation of Materials," with the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

This effort was conducted during the period of August 1981 to July 1982. The authors, Mr. John J. Ruschau and Lt. Scott K. Jarvis, wish to extend special recognition to Mr. Richard Marton and Mr. John Eblin of the University of Dayton who were responsible for all the mechanical testing performed.

This report was submitted by the authors in September 1982.

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SECTION I
INTRODUCTION

This investigation was performed to determine mechanical property data for aluminum X7091-T7E69 extrusion, a newly developed alloy produced via powder metallurgy (P/M) methods. Such P/M aluminum alloys are purported to possess superior mechanical and physical properties compared to products produced by conventional cast and wrought ingot technology. Properties examined in this effort are tensile, compression, fracture, smooth and notched fatigue, fatigue crack growth, and stress corrosion cracking. Tensile and crack growth properties are established at room temperature and 250°F (121°C).

The investigation described herein is a preliminary effort to an ongoing P/M aluminum round-robin test program, also being sponsored by the Air Force. Test material examined in this effort was purchased independent of the latter program. All results of the subsequent round-robin test program will be thoroughly documented in a technical report to be authored at program completion.

SECTION II

MATERIAL AND SPECIMENS

The test material was provided by the producer, the Aluminum Company of America (ALCOA), in the form of three extruded bars approximately 1.5 x 4.5 x 24 inches long (38 x 114 x 610 mm). All the bars were from the same lot (#G79666A1) and were further identified with individual numbers, -20, -21, and -22. A chemical composition was determined for one of the bars with the following results obtained:

CHEMICAL COMPOSITION OF TEST MATERIAL X7091
[LOT-G79666A1]

Wt. %

Zn	Mg	Cu	Co	Si	Fe	B	Mn	Cr	Ti	Al
6.4	2.2	1.4	0.4	0.04	0.054	0.012	<0.001	<0.02	<0.01	Balance

These compositional results are in reasonable agreement with the producer's specifications for P/M alloy 7091. Because of equipment limitations, the silicon content could not be determined with sufficient accuracy and thus should not be regarded as certain. The amount of cobalt present, which serves as a grain refiner, is in larger quantities than is ordinarily possible with aluminum alloys produced by ingot metallurgy. The material was furnished in the T7E69 temper which is a solution heat-treatment, stress relieved by stretching, and artificially aged (slightly overaged) to yield the highest strength condition available for this product form.

Photomicrographs were obtained from one of the bars and are presented in Figure 1. This material is a very fine grain alloy, with no appreciable inclusions or porosity observed.

Tensile specimens were machined from the longitudinal and transverse orientations of the test material in the configuration shown in Figure 2. Compression samples were similarly machined from both the longitudinal and transverse directions, machined to the configuration shown in Figure 3.

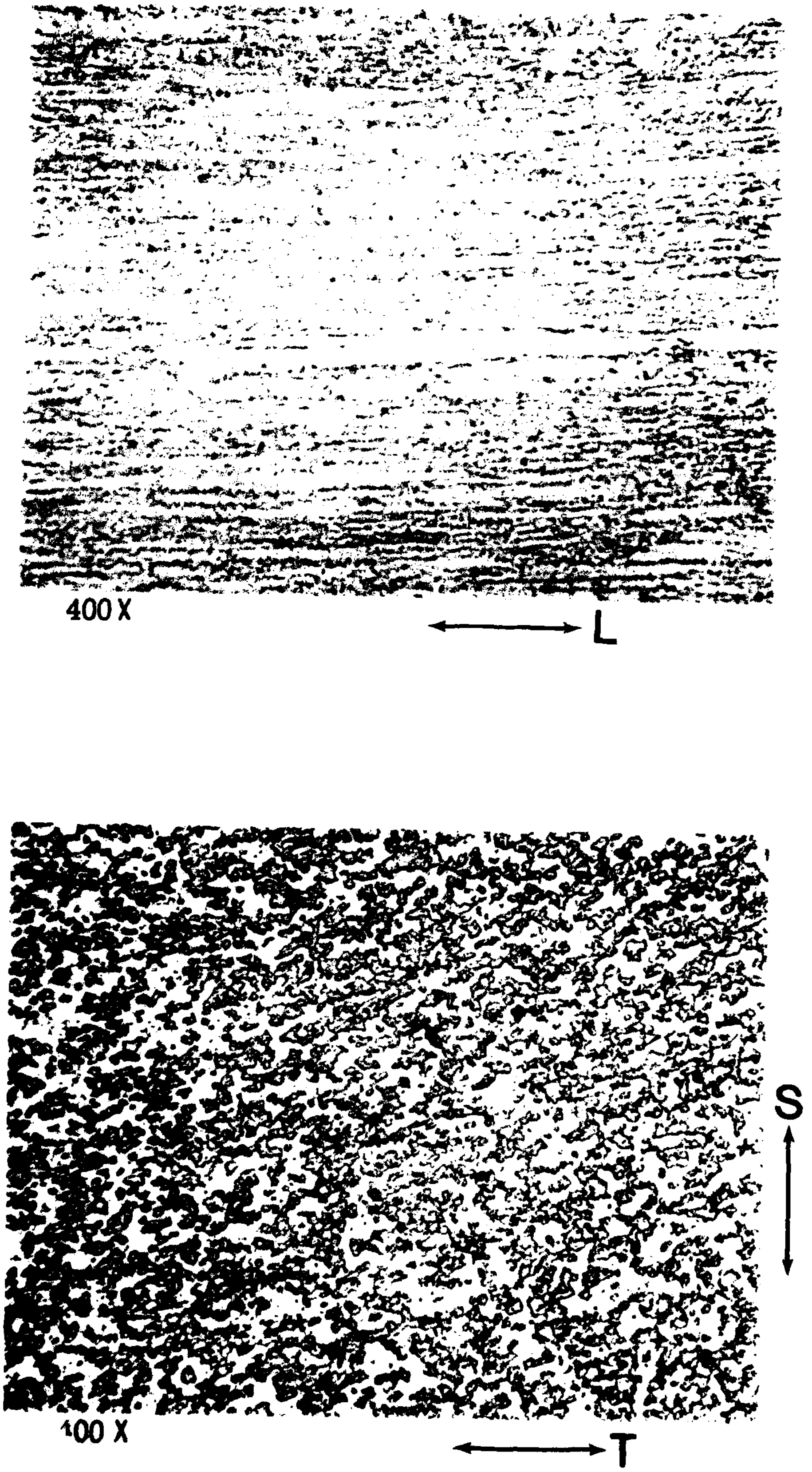


Figure 1. Photomicrographs of X7091-T7E69 Extrusion.

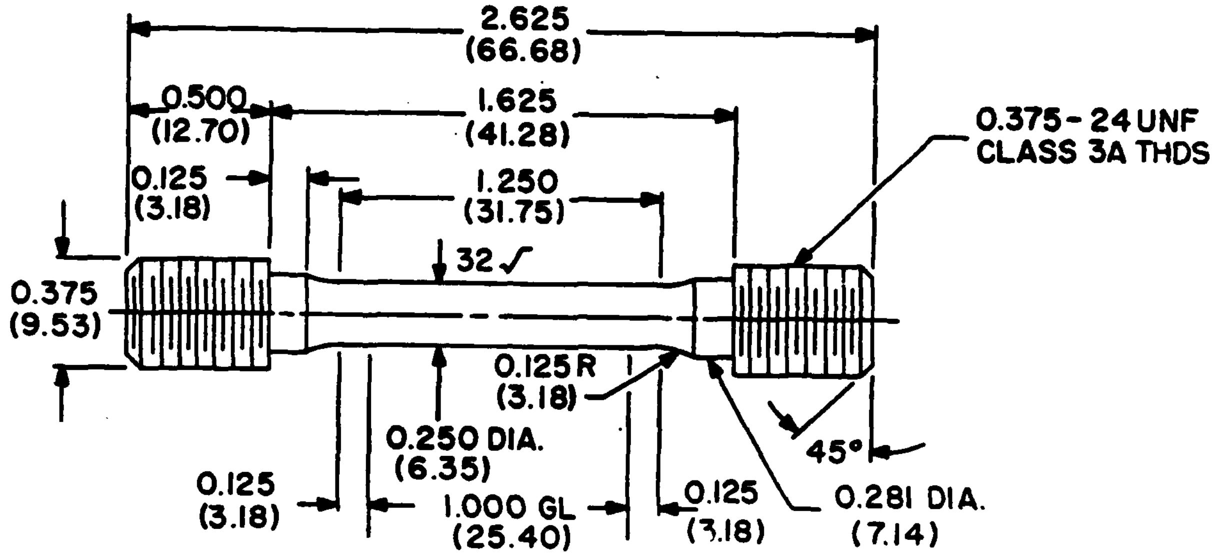


Figure 2. Tensile Specimen Geometry.

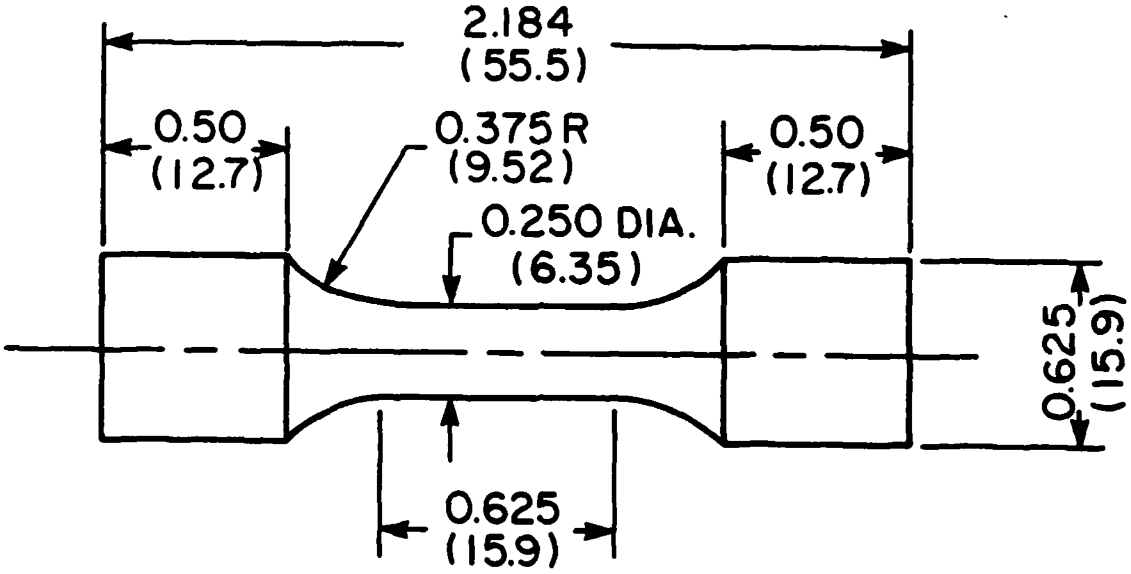


Figure 3. Compression Specimen Geometry.

Smooth and notched fatigue samples were machined from the longitudinal orientation to the dimensions shown in Figures 4 and 5, respectively. The smooth specimens were final surface finished using 6 μm diamond paste, polished in the longitudinal direction. Each sample was examined at 40X to insure no circumferential scratches. The notched fatigue samples were polished in the notched vicinity using similar polishing compound on a string to obtain a good surface finish. Final notch geometry was examined using a 100X Shadow-graph.

Fracture specimens were machined in both the L-T and T-L crack plane orientations, as defined in the ASTM "Standard Terminology Relating to Fracture Testing," E616. Specimens were machined in two thicknesses, 0.75 inch (19 mm) and 1.50 inch (38.1 mm). Dimensions are shown in Figure 6.

Stress corrosion cracking specimens were machined from the L-T orientation only, and machined to the same dimensions as the 0.75 inch (19 mm) thick fracture specimens (Figure 6).

Constant amplitude fatigue crack growth rate samples were machined from both the L-T and T-L directions of the test material. Specimen dimensions are likewise presented in Figure 6.

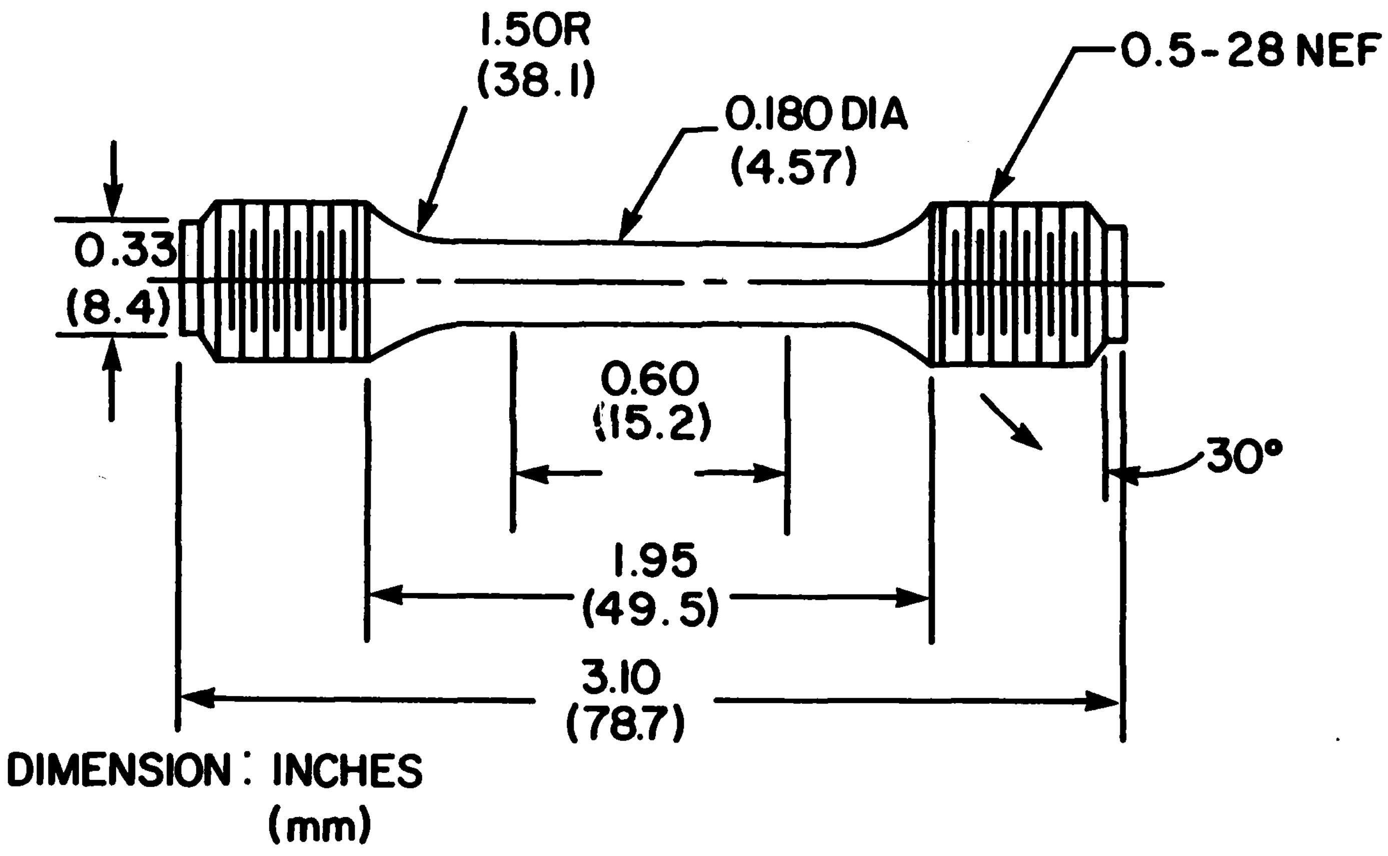
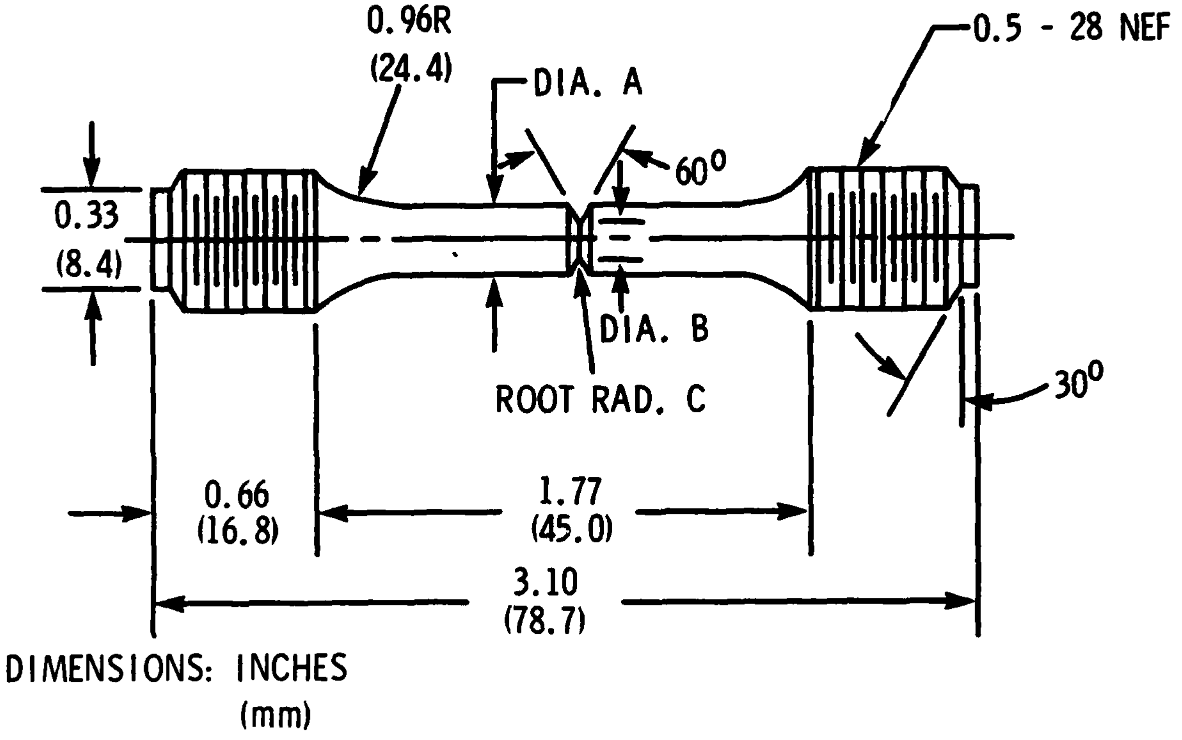
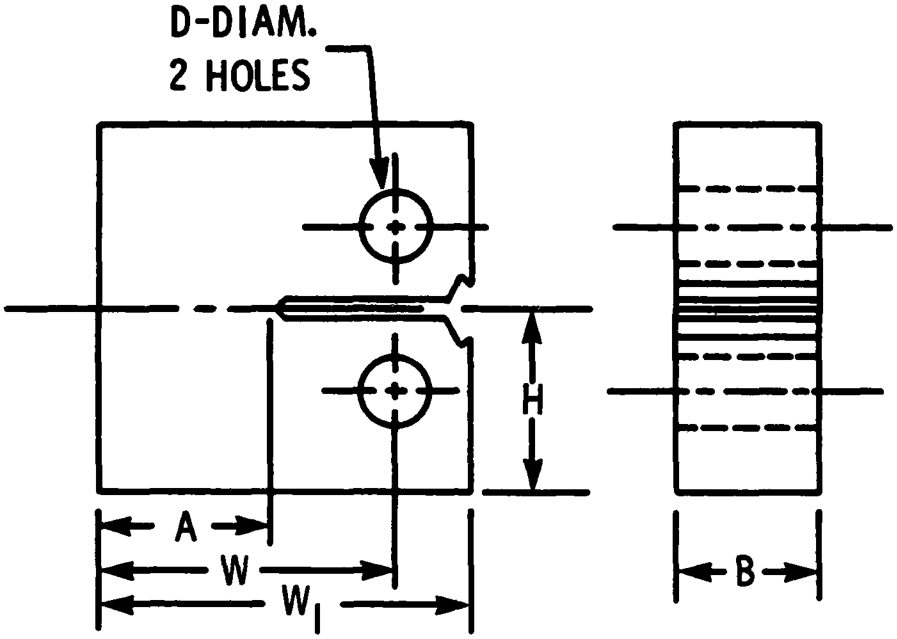


Figure 4. Smooth Fatigue Specimen Geometry.



STRESS CONCENTRATION	A	B	C
$K_T = 3$	0.250 (6.35)	0.215 (5.46)	0.0075 (0.190)
$K_T = 5$	0.312 (7.92)	0.218 (5.54)	0.0035 (0.089)
$K_T = 10$	0.375 (9.52)	0.278 (7.06)	0.0010 (0.025)

Figure 5. Notched Fatigue Specimen Geometries.



SPECIMEN TYPE	A	W	W_1	B	H	D
FRACTURE AND CORROSION	0.90 (22.9)	1.50 (38.1)	1.88 (47.8)	0.75 (19.0)	0.90 (22.9)	0.38 (9.6)
	1.75 (44.4)	3.00 (76.2)	3.75 (95.2)	1.50 (38.1)	1.80 (45.7)	0.75 (19.0)
CRACK GROWTH	1.00 (25.4)	1.50 (38.1)	1.88 (47.8)	0.37 (9.4)	0.90 (22.9)	0.38 (9.6)

*ALL DIMENSIONS IN INCHES
(mm)

Figure 6. Compact Type Specimen Geometries.

SECTION III
PROCEDURES

Tensile testing was performed at both room temperature and 250°F (121°C) in a 10 KIP (45 kN) Instron tensile testing machine, equipped with an environmental chamber for elevated temperature testing. A 1-inch (25 mm) Instron extensometer was used to obtain strain measurements. Procedures outlined in the ASTM Standard for "Tension Testing of Metallic Materials," E-8, were followed.

Compression testing was similarly performed on a 10 KIP (45 kN) Instron machine, using procedures described in ASTM Standard for "Compression Testing of Metallic Materials at Room Temperature," E9. A subpress was used to insure unidirectional loading conditions. Strain measurements were obtained using a 0.5 inch (13 mm) MTS extensometer.

Smooth and notched fatigue testing was accomplished using a 25 KIP (111 kN) MTS servo-hydraulic fatigue testing machine. All tests were performed in lab air, using an R-ratio of 0.1 at a frequency of 20 Hz. Procedures were followed in accordance with the ASTM Standard for "Constant Amplitude Axial Fatigue Tests of Metallic Materials," E466.

All fracture testing was accomplished using a 60 KIP (267 kN) Tinius-Olsen tensile testing machine. Specimens were carefully precracked using an MTS servo-hydraulic fatigue testing machine. Testing procedures, described in the ASTM Standard for "Plane-Strain Fracture Toughness Testing," E399, were carefully followed.

Precracked compact-type specimens were used to establish this material's sensitivity to stress corrosion cracking. Specimens were loaded to various initial stress intensities in a 3.5% NaCl solution with time to failure recorded. Air was bubbled through the solution for the test duration to supply oxygen to the corrosion medium as well as to insure a homogeneous test solution. Distilled water was added to replace that which was lost to evaporation, with the entire solution replaced after 1,000 hours of test. Tests which did not yield failures were terminated after 2,000 hours, after which the specimens were broken open and examined for crack growth.

Constant-amplitude fatigue crack growth rate testing was accomplished using a 20 KIP (89 kN) maximum MTS servo-hydraulic fatigue machine. A sinusoidal waveform was applied at 20 Hz, using an R-ratio of 0.1 for all tests. Crack length was visually monitored using a 10X traveling microscope with digital readout. Procedures were applied and data reduced in accordance with the ASTM Standard for "Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle," E647. The seven-point incremental polynomial method was employed over the secant method for the determination of growth rates.

SECTION IV
RESULTS

The average tensile and compression properties obtained are presented in Table 1. Strength and ductility properties are superior to the majority of conventionally produced structural aluminum alloys, though strength levels are slightly below both the manufacturer's claim and reference data for X7091-T7E69.[1] Properties are nearly identical in both longitudinal and transverse directions. The increased test temperature of 250°F (121°C) caused a loss in ultimate tensile strength of 16%, with a 12% decrease in yield strength.

Typical stress-strain curves for room temperature and 250°F (121°C) tensile tests are presented in Figure 7. Stress-strain response for both longitudinal and transverse directions appeared similar at both test temperatures; consequently, only longitudinal specimen data are presented. Typical room temperature compression stress-strain curves for both longitudinal and transverse directions are illustrated in Figure 8.

Fracture results are presented in Table 2 for both L-T and T-L orientations. Due to the apparent high toughness and limited material thickness, only one valid K_{IC} value was obtained for the nine specimens tested, that being a T-L oriented specimen with a critical toughness of 46.4 $KSI\sqrt{in}$ (51.0 $MPa\sqrt{m}$). Results listed in Table 2 indicate this material is an extremely tough aluminum alloy, with possibly greater toughness in the L-T orientation than in the T-L orientation. Fracture appearances for all the invalid specimens was consistently irregular, as shown in Figure 9, for specimens #LT-1B and #20-K4. In all the invalid cases, rapid fracture occurred on approximately a 45° plane relative to the precrack plane. Fracture appearance of the one valid specimen, #TL-1B, was a more traditional flat fracture with minimal shear lip formation, as shown in Figure 9.

TABLE 1

AVERAGE TENSILE PROPERTIES OF ALUMINUM X7091-T7E69 EXTRUSION

Properties	Temperature, °F(°C)	
	70 (21)	250 (121)
UTS, L[(a)] KSI (MPa)	81.3 (560)	67.6 (466)
UTS, T KSI (MPa)	81.1 (559)	66.0 (455)
TYS, L[(a)] KSI (MPa)	75.4 (520)	66.2 (456)
TYS, T KSI (MPa)	73.7 (508)	65.0 (448)
% elong. in 1 in.(25 mm) G.L., L[(a)]	12	18
% elong. in 1 in.(25 mm) G.L., T	13	18
% Reduction in Area, L[(a)]	37	45
% Reduction in Area, T	37	52
CYS, L KSI (MPa)	73.0 (503)	--
CYS, T KSI (MPa)	75.2 (518)	--

(a) Average of six tests, all others average of three tests.

TABLE 2

INDIVIDUAL FRACTURE RESULTS FOR ALUMINUM X7091-T7E69 EXTRUSION

Specimen I.D.	Orientation	Nom. Thickness in (mm)	K_Q KSI $\sqrt{in}$ (MPa $\sqrt{m}$)	Valid K_{IC}?	Invalid K_{IC} Criteria	
					$2.5(\frac{K_Q}{YS})^2$	P_{MAX}/P_Q
20K4	L-T	0.75 (19)	47.9 (52.6)	No	1.0	1.21
21K4	"	"	52.2 (57.4)	No	1.2	1.09
22K2	"	"	49.8 (54.7)	No	1.1	1.16
22TK1	"	1.5 (38)	68.7 (75.5)	No	2.3	1.02
21TK1	"	"	63.4 (69.7)	No	1.8	1.04
LT1B	"	"	61.4 (67.4)	No	1.7	1.04
22TL1	T-L	0.75 (19)	52.4 (57.1)	No	1.2	1.06
22TL2	"	"	47.2 (54.1)	No	1.1	1.13
TL1B	"	1.5 (38)	46.4 (51.0)	Yes	0.96	1.00

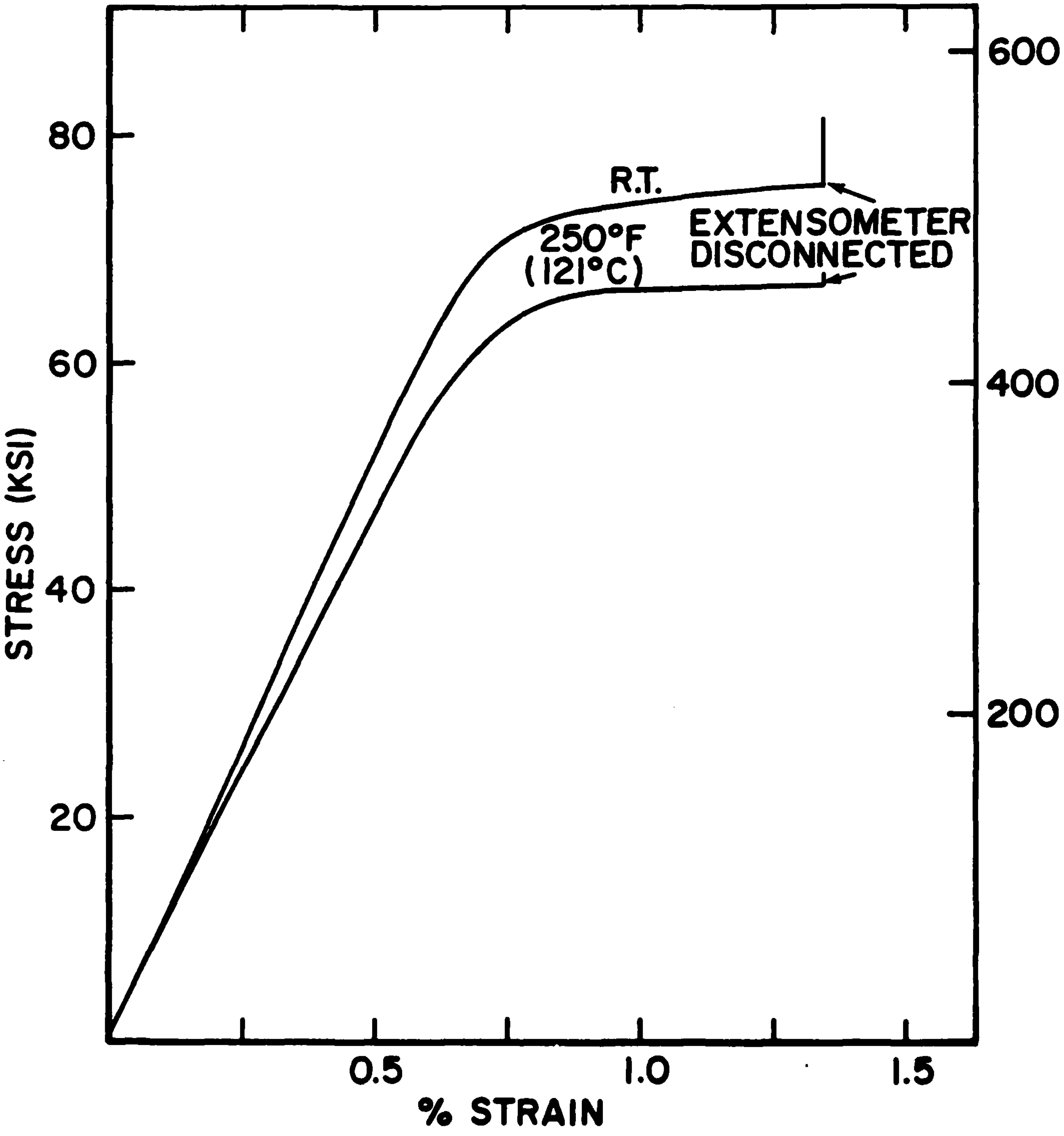


Figure 7. Typical σ-ε Tensile Curves for X7091-T7E69 at Room Temperature and 250°F (121°C).

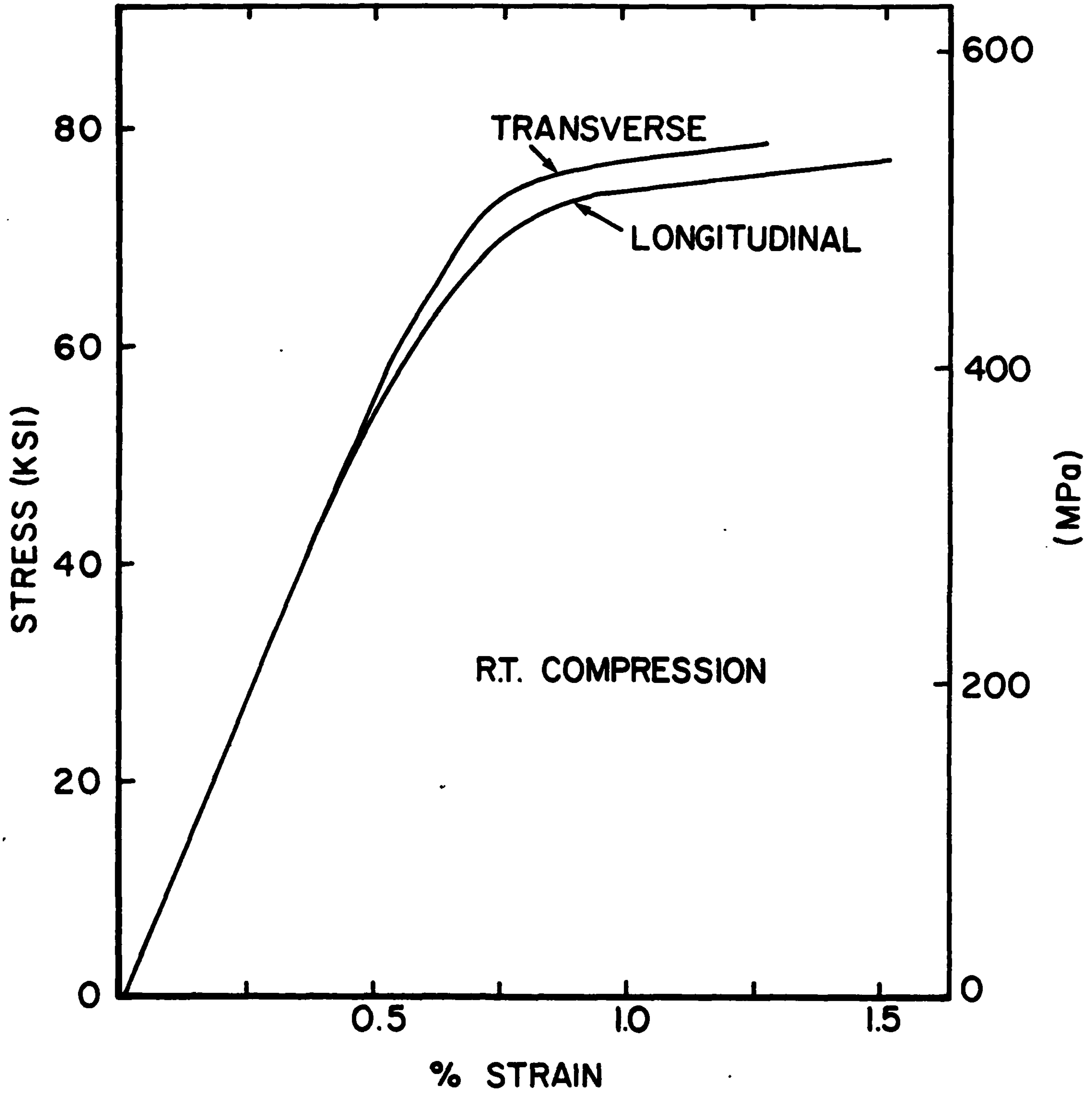


Figure 8. Typical σ-ε Compression Curves for X7091-T7E69 for Both Longitudinal and Transverse Orientations.

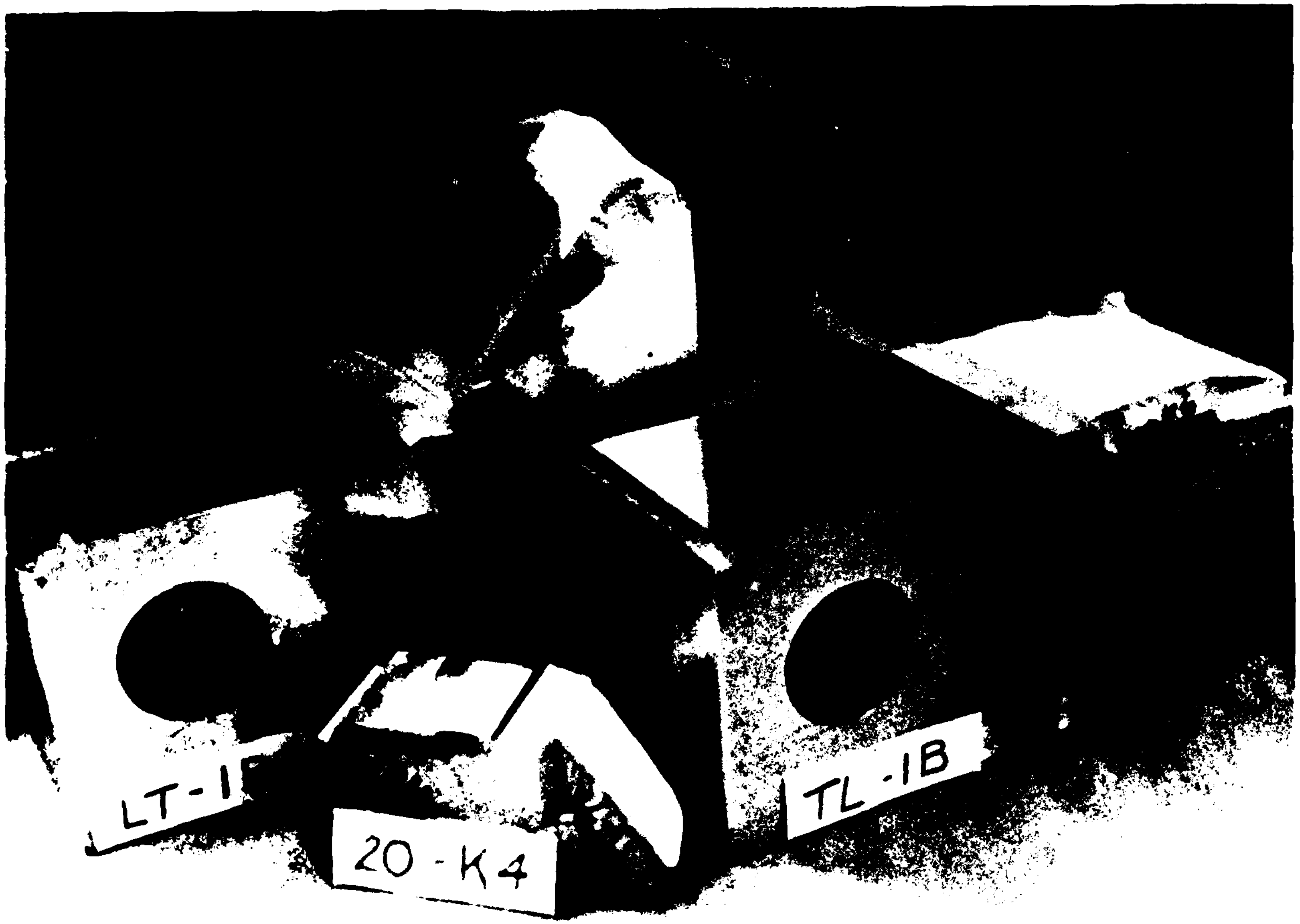


Figure 9. Fracture Appearance for X7091-T7E69 Toughness Specimens.

Fatigue crack growth rate results obtained at both room temperature and 250°F (121°C) are presented in Figure 10 for L-T oriented specimens, and Figure 11 for T-L oriented specimens. The data shown for the L-T oriented specimens reflect the results of two specimens at each test temperature; the T-L data represent a single specimen at each temperature. Also furnished are reference data on similar material,[1] along with data for aluminum 7050-T73651 plate,[2] a comparable wrought alloy in terms of strength and toughness. Crack growth rate data obtained in this effort are in excellent agreement with the referenced data on similar material. Results show a marked reduction in fatigue crack growth resistance for aluminum 7091 over conventionally produced aluminum 7050 for both orientations examined. Loss in crack growth resistance is greatest at the lower stress intensity ranges while diminishing at the higher stress intensity ranges. The increased test temperature did not appear to alter crack growth rate properties. Though not plotted together (for the sake of clarity), crack growth properties are identical for the T-L and L-T orientations at both temperatures examined.

A final observation worth noting is that though the fatigue cracked region of the crack growth specimens appeared smooth and "clean", the rapid fracture portion of several specimens yielded evidence of numerous point defects or dispersoids. One example of such is illustrated in the photograph presented in Figure 12. An EDAX investigation of several such particles revealed only aluminum present, indicating the particles are most likely aluminum oxide. Though the crack growth sample shown probably possessed the most number of visually discernable dispersoids, nearly all the compact type specimens tested yielded some evidence of such inclusions in the rapid fracture region.

The results of smooth and notched round bar fatigue tests are presented in Figure 13. Results indicate that for an endurance limit defined at 10 million cycles, the fatigue strength at R=0.1 is estimated as 48, 25, 17, and 10 KSI (331, 172, 117, and 69 MPa, respectively) for stress concentrations of 1, 2.8,

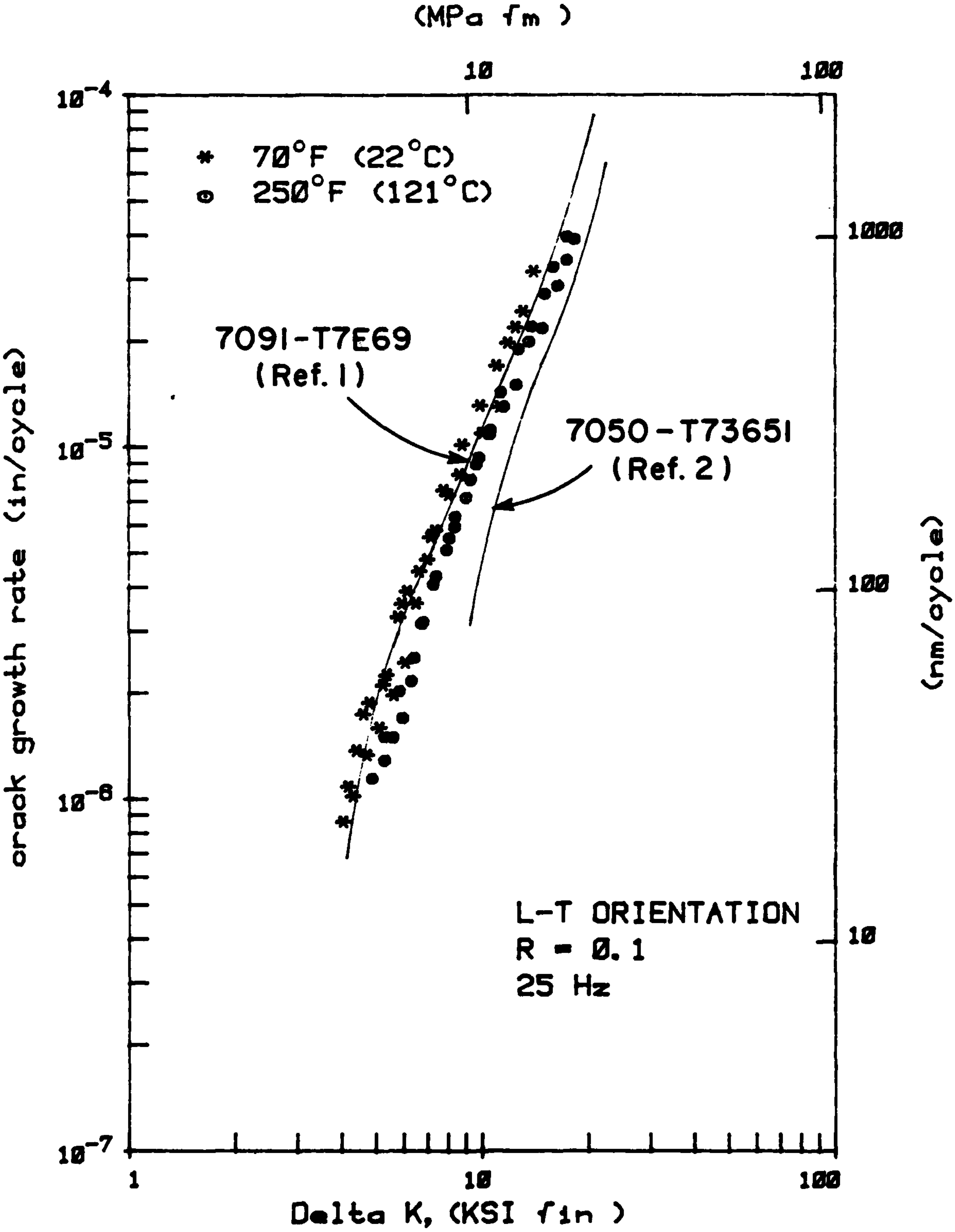


Figure 10. Fatigue Crack Growth Rate Data for 7091-T7E69 Extrusion, L-T Orientation.

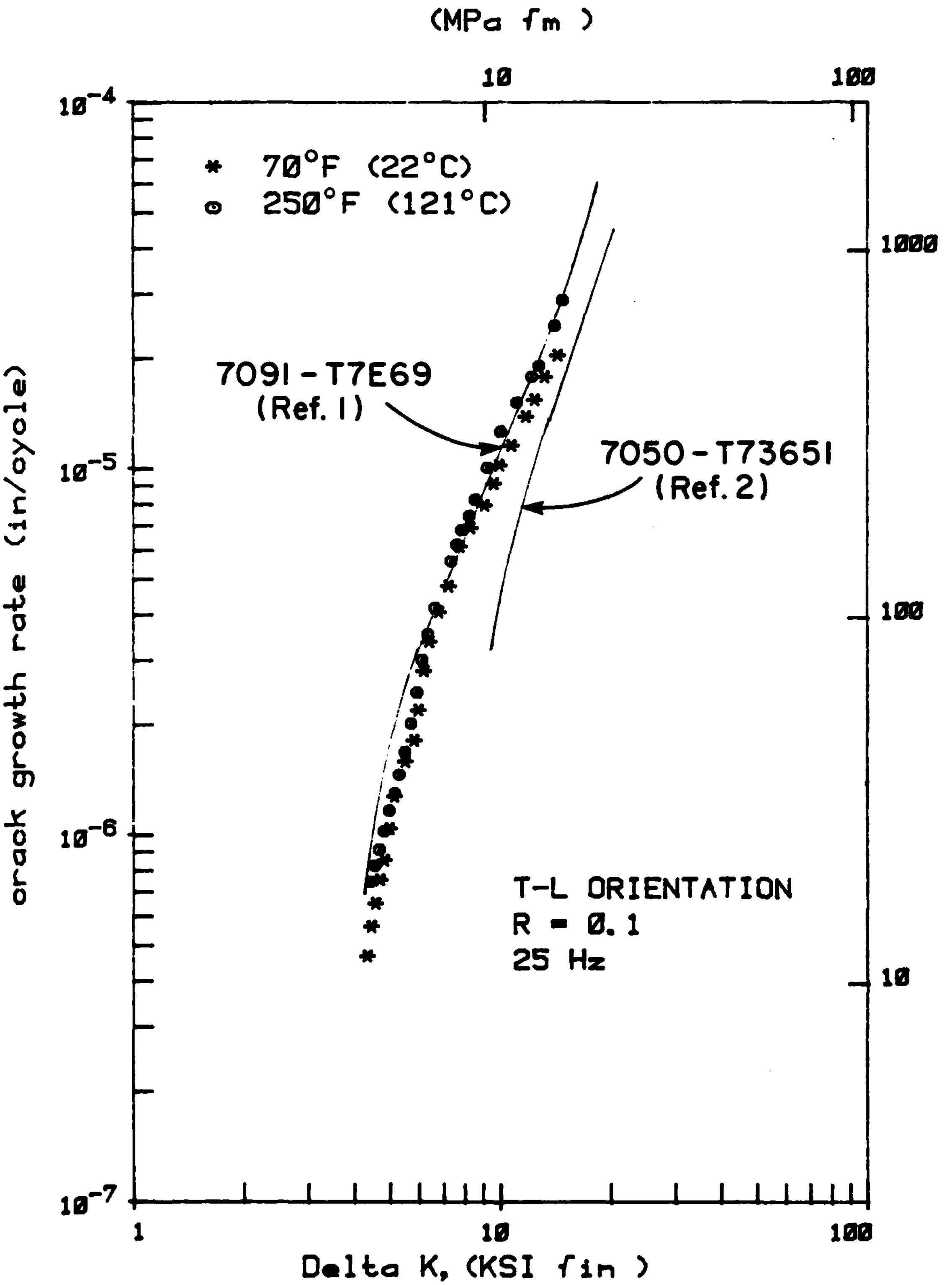


Figure 11. Fatigue Crack Growth Rate Data for 7091-T7E69 Extrusion, T-L Orientation.

Figure 12. Fracture Face of 7091-T7E69 Crack Growth Specimen.

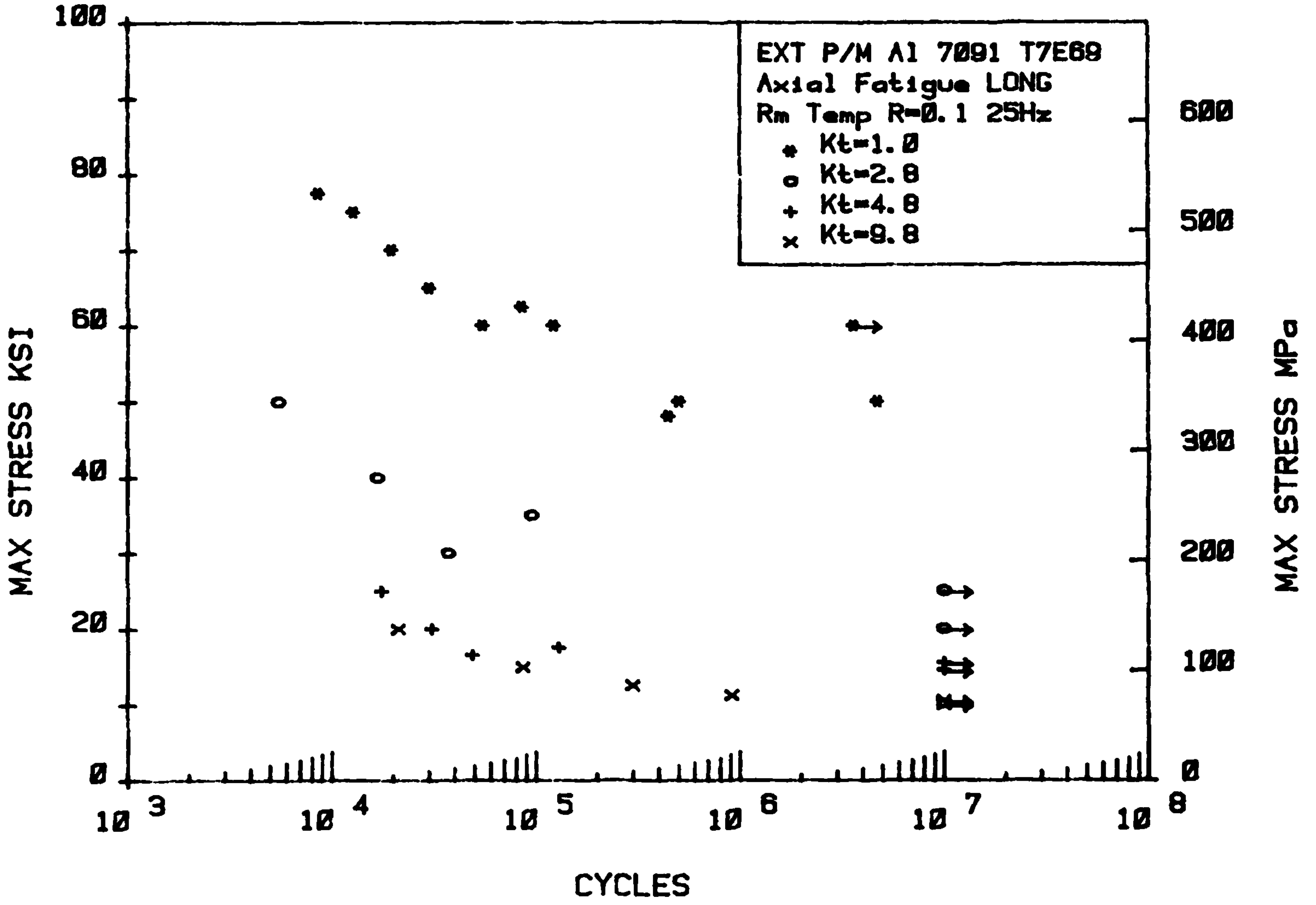


Figure 13. Smooth and Notched Fatigue Data for 7091-T7E69 Extrusion.

4.8, and 9.8, respectively. Despite the fact that the crack growth specimens revealed numerous inclusions present in the material, all fatigue failures originated at the surface with only one exception, that being a single smooth fatigue sample which failed at an internal defect. The resultant life, however, was in agreement with the other smooth fatigue data, indicating no appreciable loss in fatigue resistance due to such a point defect. The data shown in Figure 13 for 7091-T7E69 extruded material show a marked improvement in fatigue resistance over conventionally processed aluminum alloys.

To better assess the relative notched fatigue behavior of this alloy, the endurance stress was normalized with respect to yield strength and plotted versus stress concentration factor, K_t, as illustrated in Figure 14. Also plotted are similar data for aluminum alloys 7075-T6 and 2024-T3.[3] Results show each data set, as plotted on log-log axes, appears linear, with endurance stress decreasing with increasing stress concentration as expected. The important fact to point out, however, is that the data for 7091 appear linear throughout the range of stress concentrations investigated; there is no value or "threshold" of K_t where the notch fatigue behavior suddenly improves or decreases at a noticeably different rate with increasing stress concentrations. It has been suggested that because the smooth fatigue resistance of 7091 was superior to conventional aluminums while the crack growth resistance was inferior, there might appear a transition point in notched fatigue data where the improvement in fatigue properties suddenly decreased. No such transition point was discovered in this investigation. In fact, the relative notched fatigue behavior is superior or equal to the other aluminum alloys presented for the range of stress concentrations given.

Results of stress corrosion cracking tests performed indicate no sensitivity for specimens in a 3.5% NaCl environment when loaded at stress intensities ranging from 12 to 41 KSI$\sqrt{\text{in}}$ (13 to 45 MPa$\sqrt{\text{m}}$). There was no evidence of any appreciable

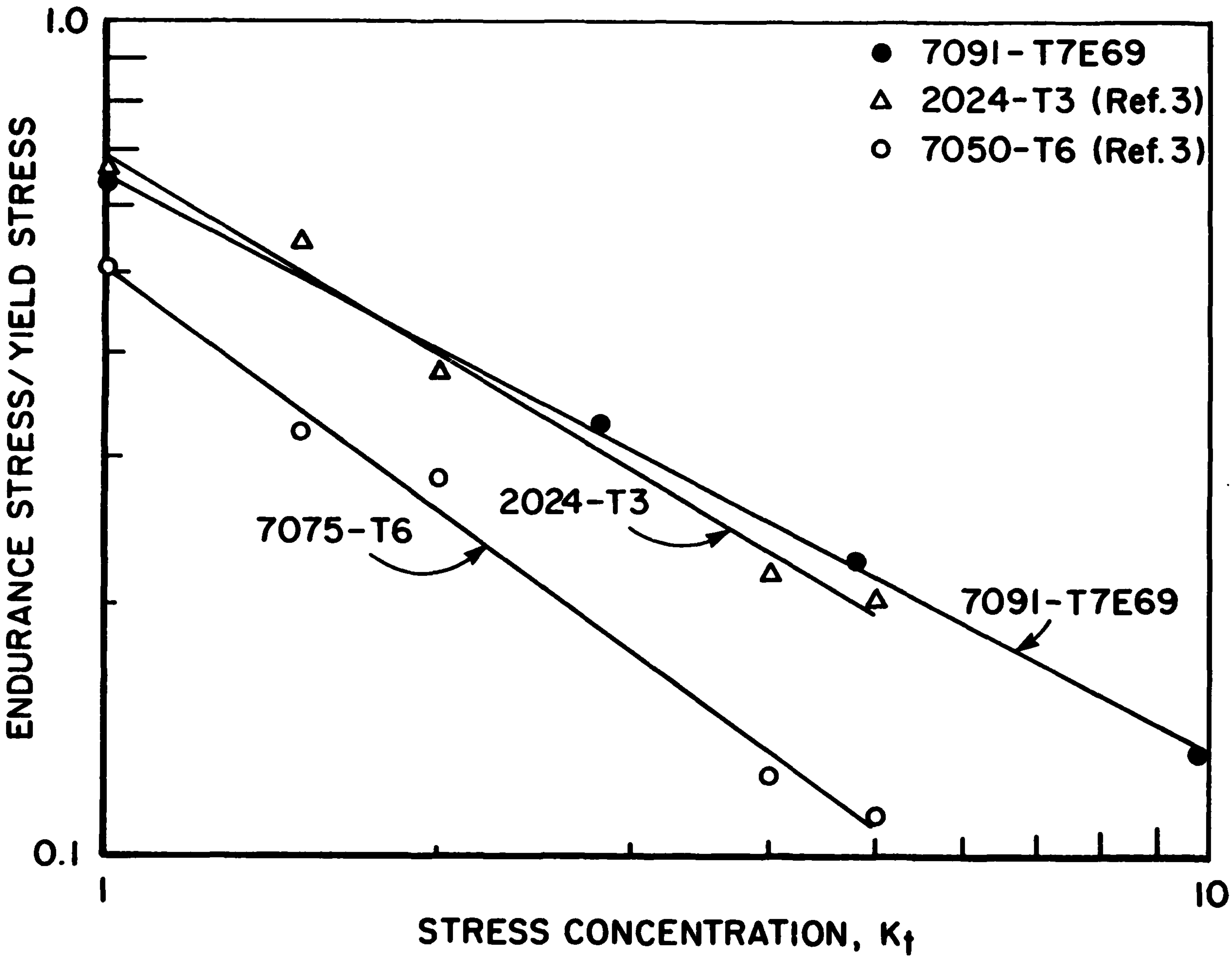


Figure 14. Normalized Endurance Stress (Defined as 10 million Cycles) versus Stress Concentration for X7091-T7E69.

pitting on any of the samples after 2,000 hours in the test solution, only a slight uniform corrosion on each exposed surface. A photograph of a typical specimen, broke open after test for examination, is shown in Figure 15. The cross-section of samples loaded at the higher stress intensities did not reveal any discernable crack extension or crack branching due to the combined effects of stress and environment.

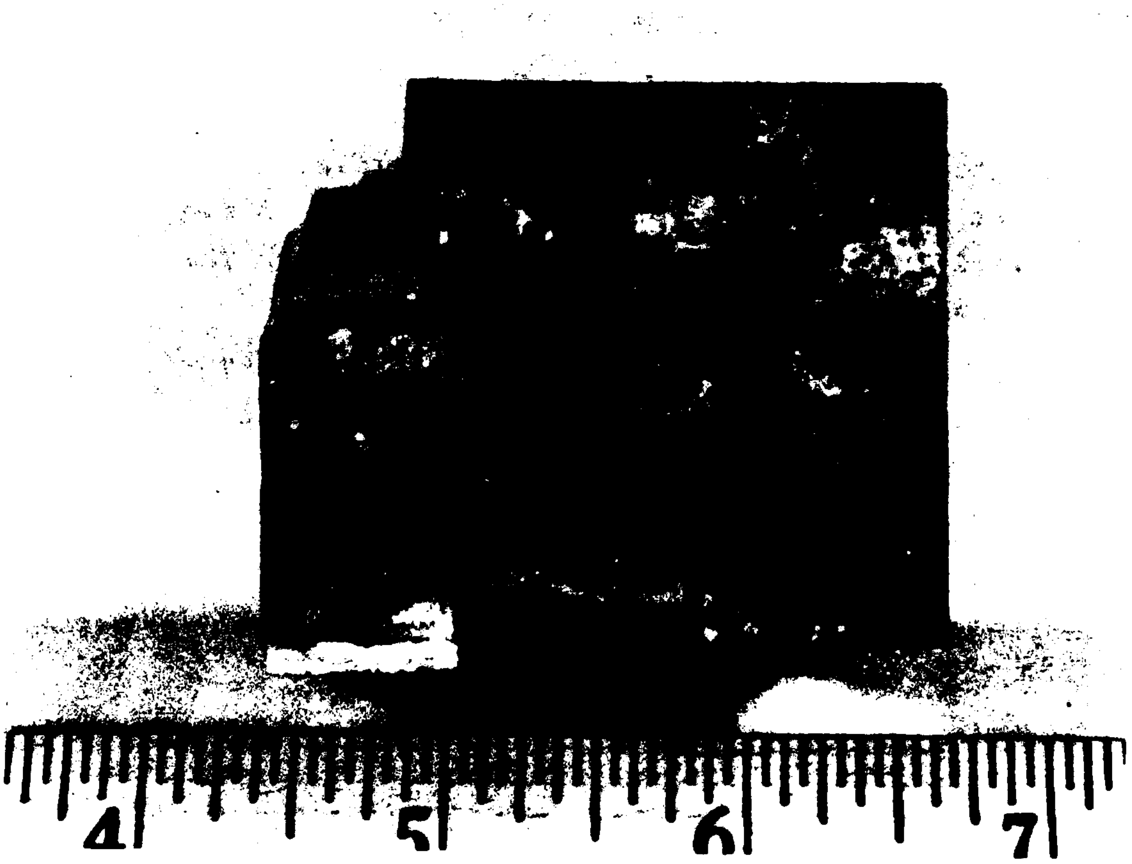


Figure 15. Typical Stress Corrosion Test Specimen After 2,000 Hours in NaCl Solution.

SECTION V
CONCLUSIONS

The following conclusions are based on test results from three extruded bars of aluminum X7091-T7E69.

1. The material possesses an outstanding combination of strength and toughness. Tensile properties exceed those of most conventionally produced aluminums. A single valid critical fracture toughness value (K_{IC}) which was obtained was 46.4 $KSI\sqrt{in}$ (50 $MPa\sqrt{m}$).
2. Smooth and notched fatigue properties of 7091-T7E69 are superior to similar usage wrought aluminum alloys. Stress concentration factors up to 10 did not reveal any discrepancies in the superior notched fatigue performance.
3. In contrast to the above, fatigue crack growth rate properties are consistently inferior to similar 7000 wrought aluminum alloys.
4. The material is insensitive to stress corrosion cracking when loaded in a 3.5% NaCl environment at stress intensities ranging from 12 to 41 $KSI\sqrt{in}$ (13 to 45 $MPa\sqrt{m}$).

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