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EVALUATION OF THE MECHANICAL PROPERTIES OF 2091 AND 8090 ALLOYS

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A 2091 plate and 8090-T651 extrusion were evaluated in this study and compared with 2024. Tensile, compression, axial fatigue, and fracture toughness tests were performed on 2091. Tensile tests were performed on 8090.

Alloy 2091-T3 has a higher tensile strength, yield strength, percent elongation and modulus than 2024-T3. Alloy 8090-T651 exhibits a higher tensile strength and yield strength than that of 2024-T6. However, 8090 does not exhibit any improvement in ductility or stiffness to that of 2024-T6.

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INTRODUCTION

This investigation was performed as part of an ongoing evaluation program by the Naval Air Development Center on advanced aluminum-lithium alloys. The Navy has considerable interest in aluminum-lithium alloys for aerospace applications. It is well known that the addition of lithium to aluminum decreases the density and increases the modulus of aluminum alloys.[1] Due to these properties there may be significant weight savings achieved by using aluminum-lithium alloys in aircraft structure.

The objective of this study was to evaluate the mechanical properties of two aluminum-lithium alloys, 2091-T351 and 8090-T651. Both of these alloys are being considered as medium strength replacements for 2024. 8090 is desirable because it exhibits a lower density with improved static strength properties than those of 2024. Direct replacement of 2024 with 8090 would result in a 10% weight reduction because of the lower density.[2] 2091 is attractive because it exhibits a lower density with improved strength, toughness and ductility than that of 2024. Keywords: aluminum alloys, lithium alloys; Ductility; tensile strength; (KT)

EXPERIMENTAL PROCEDURE

Alloy Information

The alloys examined in this investigation were made by Cegedur-Pechiney, France. They were provided to the Naval Air Development Center through a cooperative test program with Air Force Wright Aeronautical Laboratories. The product forms included alloy 2091, 0.42 inch thick plate and alloy 8090, tee-extrusion (3in X 2.5in X 0.19in). The 2091 was received in the T351 condition. This is a medium strength condition which involves solution heat treatment, cold work and natural aging. The 8090 was received in a the T651 condition. This is a peak aged condition which involves solution heat treatment and artificial aging.

Microsturctural Examination

The microstructures were examined optically using a Nikon Epiphot-TME metallograph. Kellers etch was used to bring out the grain structure. Alloy 2091 was examined in the longitudinal, transverse and short transverse directions. Alloy 8090 was examined in the longitudinal direction.

Mechanical Properties

Tensile Tests:

The 2091 plate was machined into standard 0.252" diameter tensile specimens (longitudinal and transverse). The 8090 extrusion was machined into flat longitudinal tensile specimens. The tensile tests were performed according to ASTM specification B557 on an MTS closed loop servohydraulic machine. Strain rates of $4.0X10^{-4}$/sec and $3.0X10^{-4}$/sec were used for alloys 8090 and 2091, respectively.

Compression Tests:

The 2091 plate was machined into compression specimens (longitudinal and transverse). The compression tests were performed according to ASTM specification E9 on an MTS system. A strain rate of $5X10^{-4}$/sec was used.

Fatigue Tests:

Alloy 2091 was machined into axial fatigue specimens (K_t=1) from the longitudinal direction. The fatigue tests were performed according to ASTM specification E466. They were run in tension-tension on a Krause fatigue machine using a ratio of minimum to maximum load of 0.1 (R=0.1).

Fracture Toughness Tests:

Alloy 2091 was machined into compact tension specimens from the LT/L direction. The fracture toughness tests were performed according to ASTM specification E399. These tests were ran on an MTS machine using a loading rate of 1.01 MPa $m^{1/2}$/sec. The fracture toughness specimens were not a valid geometry for calculating K_{1c} values. Also, Pm/Pq was greater than 1.1. Thus, K_q values and strength ratios were calculated.

Fractography

The fracture surfaces of the 2091 and 8090 tensile samples and the exterior surfaces of the 2091 compression samples were examined with an Amray SEM model 1000B. Macrophotographs of the fracture toughness samples were taken with a Polaroid MP-3 Land camera.

RESULTS AND DISCUSSION

Alloy Information

Macrophotographs of the as received material are shown in Figure 1. The material of both product forms, the plate and the extrusion, was uniform in appearance. There were not any significant flaws or porosity evident.

The compositions from the wet chemical analysis are given in Table I. Alloy 2091 contained a relatively high amount of lithium. However, both alloys were within the standard composition limits for the alloy designations.

Microstructural Examination

The microstructure of the 2091-T351 plate is shown in Figure 2. The plate displayed a grain structure in which the longest dimension of the grains was aligned with the rolling direction of the plate. The average grain size was 50μm X 700μm X 1100μm. The grain structure of the 8090-T651 extrusion is shown in Figure 3. The 8090 extrusion had a smaller grain size and a different shape than that of the 2091 plate. The average grain size of the 8090 extrusion was 6μm X 15μm X 15μm. The smallest grain dimension was in the short transverse direction.

Mechanical Properties

Tensile Properties:

The 2091-T351 plate (Table II) displayed higher tensile strength (T.S.), yield strength (Y.S.), Young's modulus (E) and percent elongation (%e) compared with 2024-T351 plate for both testing directions. Specifically, the tensile strength of 2091 was 22 MPa higher than that of 2024 in the longitudinal direction and 13 MPa higher in the transverse direction. The yield strength for 2091 was 41 MPa higher in the longitudinal direction and 43 MPa higher in the transverse direction. The Young's modulus was 2 GPa higher in the longitudinal direction and 3 GPa higher in the transverse direction.

As expected in a rolled plate, due to the elongated grain structure, alloy strength is greatest in the longitudinal direction. However, the plate did not exhibit anisotropy with respect to the Young's modulus. The modulus was equivalent for both testing directions.

The percent elongation for alloy 2091 was 8 percent higher in both testing directions over 2024. Usually aluminum-lithium alloys exhibit low ductility.[3] The presence of a shearable precipitate, such as Al_3Li, promotes poor ductility.[4] The improved percent elongation in 2091 may be due to the presence of other alloying additions.[5]

Tensile properties for 8090-T651 (Table III) were determined only in the longitudinal extrusion direction due to the geometry of the extrusion. The tensile strength and yield strength of 8090-T651 extrusion were higher than that of alloy 2024-T6 plate. Standards for 2024-T6 extrusion were not available, therefore, comparison was made with 2024-T6 plate. The tensile strength of 8090-T651 extrusion was 43 MPa higher than that of 2024-T6 plate. The yield strength of 8090 was 111 MPa higher. The percent elongation was slightly lower, and the Young's modulus was equivalent. The lower percent elongation, which portrays ductility, was expected. However, alloy 8090 was expected to have a higher modulus. The low modulus which was measured may be due to the presence of other precipitate phases such as T2 ($Al_6Cu\ Li_3$) or AlLi.[6]

As expected, the static tensile properties of the 8090-T651 extrusion exceeded those of 8090-T651 plate material which are reported in the literature.[7] Typically static tensile properties from an extrusion exceed those of plate material. The short transverse (ST) properties of 8090 were not evaluated in this investigation due to the geometry of the extrusion. However, they may be of concern. The average short transverse properties of an 8090 forging have been reported in the literature.[8] The ST tensile strength was reported as 387 MPa. The ST yield strength was 322 MPa, and the ST percent elongation was 2%. These properties are reasons for concern when considering alloy 8090 forging, extrusion, or plate for applications where the short transverse properties are critical.

Compression Properties:

The compressive strength results are given in Table IV. The compressive yield strength of 2091-T351 is higher than that of 2024-T351. It is 29 MPa higher in the longitudinal direction and 20 MPa higher in the transverse direction. The ultimate compressive strengths for 2091 are 759 MPa and 744 MPa in the longitudinal and transverse directions, respectively. The compressive yield strength for 2091 was less than half of the ultimate compressive strength. Yielding occurred at a lower strength level in compression than in tension.

The percent compression was 2 percent higher in the longitudinal testing direction than in the transverse direction. This may be due to the geometry of the grain structure relative to the applied load. Note that the longitudinal sample exhibits bending flow lines parallel to the loading axis. The transverse sample does not. (See Figure 4). This is indicative of the grains undergoing micro-buckling in the longitudinal direction. The longitudinal sample yielded more before failure. The fracture surfaces from the compression samples occurred on a 45 degree angle to the loading direction in both samples indicating a shear type fracture.

Fatigue Properties:

The results of the axial fatigue tests of 2091-T351 are shown in figure 5. The threshold limit was approximately 32.5 ksi. After 10^7 cycles at a maximum stress of 32.5 ksi failure did not occur. Fatigue data for 2024-T351 plate was not available for these identical test conditions. However, MIL-HDBK5 data for 2024-T3 sheet were available. 2024 sheet run with K_t=.02 shows lower fatigue strength. 2024 sheet run with K_t=.4 shows a higher fatigue strength. The fatigue data for 2091 plate, K_t=0.1, falls between these two curves. This is to be expected for 2024 sheet with a K_t=0.1. Fatigue behavior of alloy 8090 was not examined in this study. Valid test specimens could not be machined from the extrusion. However, there is concern about rapid fatigue crack growth behavior of 8090 plate expressed in the literature.[9]

Fracture Toughness Results:

Fracture toughness tests were run for alloy 2091-T351. The fracture toughness samples yielded before failure. A fracture surface which typified the specimens is shown in Figure 6. Evidence of yielding is apparent from the jagged nature of the fracture surface. The specimen geometry allowed for calculation of Kq values. The average Kq value was 45 MPa $m^{1/2}$. The strength ratio, which is a ratio of maximum strength to yield strength was an average of 1.2. The pertinent variables for the fracture toughness validity are given in Table V. Fracture toughness values were not determined for 8090 in this study. The available extrusion was too thin. This sample thickness would experience predominantly plane stress upon loading. However, the fracture toughness for 8090-T651 plate has been reported to be comparable to 2024-T651.[6] It is expected that the value for the extruded material would be at least equivalent.

Fractography

Fracture surfaces of alloy 2091 were obtained using a scanning electron microscope. Fracture surfaces from longitudinal and transverse tensile specimens, are shown in figures 7a & 7b. A transgranular 45° shear fracture occurred in both testing directions. The surfaces display shear dimples and slip. Coherent precipitates such as delta prime (Al_3Li) are shearable.[4] Once shearing has begun on a particular glide plane, deformation on that plane is favored, and thus localization of slip occurs. Planar slip is responsible for low ductility in aluminum-lithium alloys.[3]

The fracture surfaces are slightly different for the different testing directions. (Figure 7). Both surfaces display transgranular fracture. However, in the transverse direction, cleavage along the grain boundaries is more pronounced. This is due to the differences in grain structure.

The fracture surfaces for alloy 8090 longitudinal tensile specimen, are shown in Figure 8. The fracture surface was 45 degree to the loading axis in 8090 also, due to the shearable nature of the delta prime. Intergranular fracture is evident. This is probably due to grain boundary precipitation during aging to the T6 condition.

CONCLUSIONS

1. Alloy 2091-T351 has higher tensile strength than 2024-T351, and it exhibits an improved yield strength, percent elongation and modulus. Alloy 2091-T351 exhibits comparable fatigue life to 2024-T3.

2. Alloy 8090-T651 exhibits higher tensile strength and yield strength than alloy 2024-T6. However, 8090 exhibits lower ductility and no improvement in stiffness compared to 2024 in the T6 condition.

RECOMMENDATIONS

Alloy 2091-T351 is competitive with alloy 2024-T351 for aerospace applications. The advantages of alloy 2091 over 2024 are a lower density with improved strength, ductility and stiffness. Further evaluation is needed for applications where the short transverse properties and fracture toughness are critical.

Alloy 8090-T651 extrusion has improved tensile properties to alloy 2024-T6 plate. The advantages of 8090 over 2024 are a lower density with improved static strength. However, data in the current literature indicates that alloy 8090 is not appropriate for applications where the short transverse properties or fatigue crack growth rates are critical. Further evaluation is recommended for applications where the short transverse properties and/or fatigue crack growth rates are critical.

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TABLE I CHEMICAL COMPOSITIONS (wt%)

ALLOY	Li	Cu	Mg	Si	Fe	Mn	Zr	Al
# 2091	1.7-2.3	1.8-2.5	1.1 1.9	.2	.3	.10	.04-.16	balance
+ 2091	2.30	2.00	1.50	.05	.015	.10	.12	balance
# 8090	2.1 2.7	1.1 1.6	.08-1.4	.10	.15	.05	.04-.16	balance
+ 8090	2.41	1.20	.70	.04	.016	.10	.15	balance
* 2024	-	4.40	1.50	-	.200	.60	-	balance

+ Wet Chemical Analysis

* "ASM Databook", 1979 Metal Progress vol.116, no.1.

Acceptable composition range, Aluminum Association 1988

TABLE II. TENSILE DATA
2091, 0.42 inch plate
2024, 0.5 inch plate

ALLOY	2091-T351	*2024-T351	2091-T351	*2024-T351.
Testing Direction	Longitudinal	Longitudinal	Transverse	Transverse
Y.S. (MPa)	387	345	346	303
U.T.S (MPa)	470	448	461	448
% ELONGATION	16	8	16	8
MODULUS, E (GPa)	76	74	77	74

* MIL-Handbook V data, p.3-69, 1 June 1987

TABLE III.

TENSILE DATA
8090 and 2024

ALLOY	8090-T651	*2024-T42	*2424-T62
Product form	Extrusion	Extrusion	Plate
Testing Direction	Longitudinal	Longitudinal	Longitudinal
Y.S. (MPa)	488	262	345
U.T.S. (MPa)	552	393	441
% Elongation	3	12	5
Modulus, E (GPa)	72	74	72

* MIL-Handbook V data, p.3-70,3-71, 3-79, 1 June 1987.

TABLE IV

COMPRESSION TEST RESULTS

ALLOY	Compression Y.S.(MPa)	Compression T.S.(MPa)	%Compression
2091-T351			
Longitudinal	311	759	30
Transverse	344	744	28
*2024-T351			
Longitudinal	283	-	
Transverse	324	-	

* MIL-Handbook V data, p.3-69, 1 June 1987.

TABLE V FRACTURE TOUGHNESS

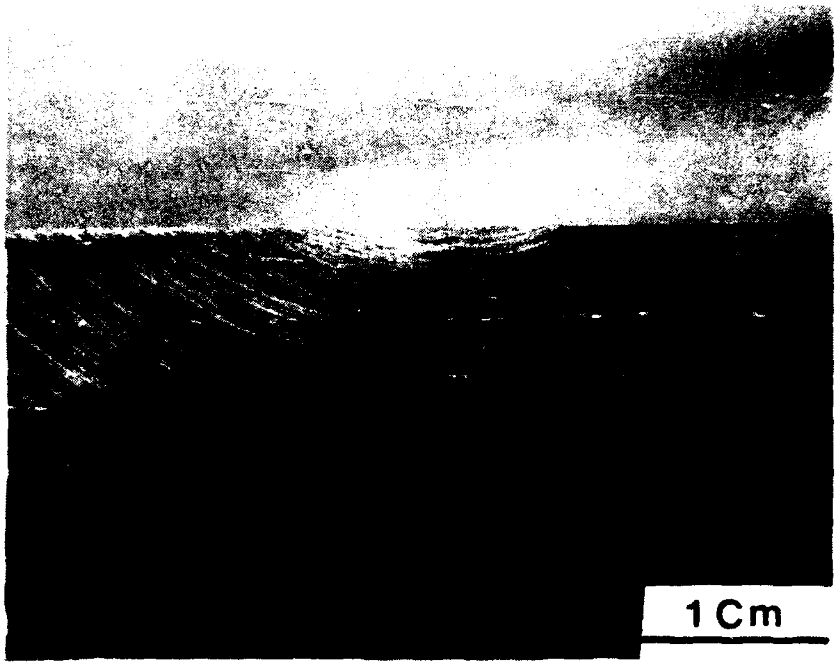
ALLOY	Pm/Pq	Rsc	Kq (MPa $m^{1/2}$)
2091-T351			
LT	1.17	1.2	44.6

P_m - Maximum Load sustained

P_q - Calculated offset load

R_{sc} - Strength Ratio, $R_{sc} = (2P_m(2W+a))/(B(W-a)2\ _{ys})$

a)



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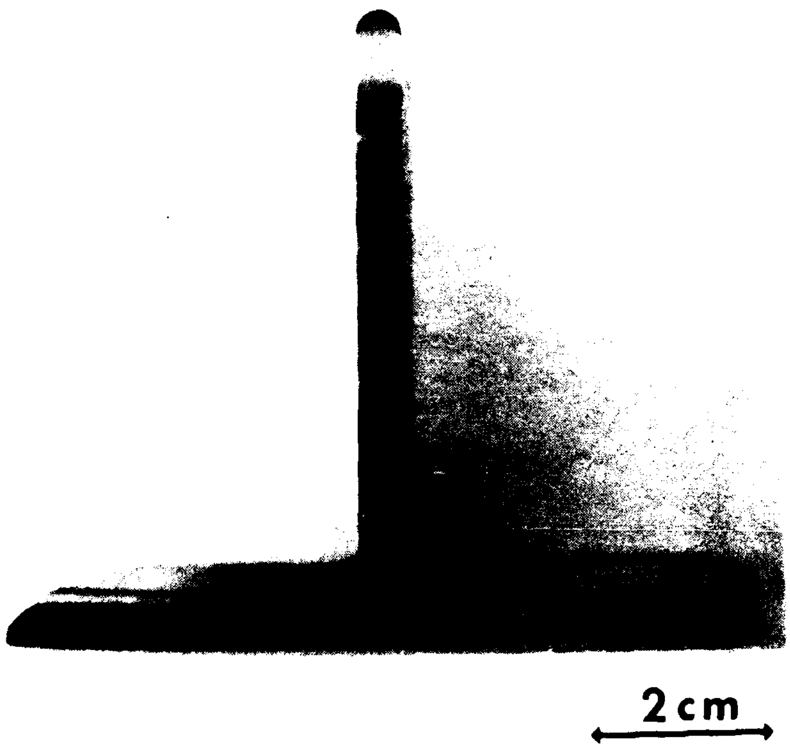


Figure 1. Macrophotographs a) 2091 Plate
b) 8090 Extrusion

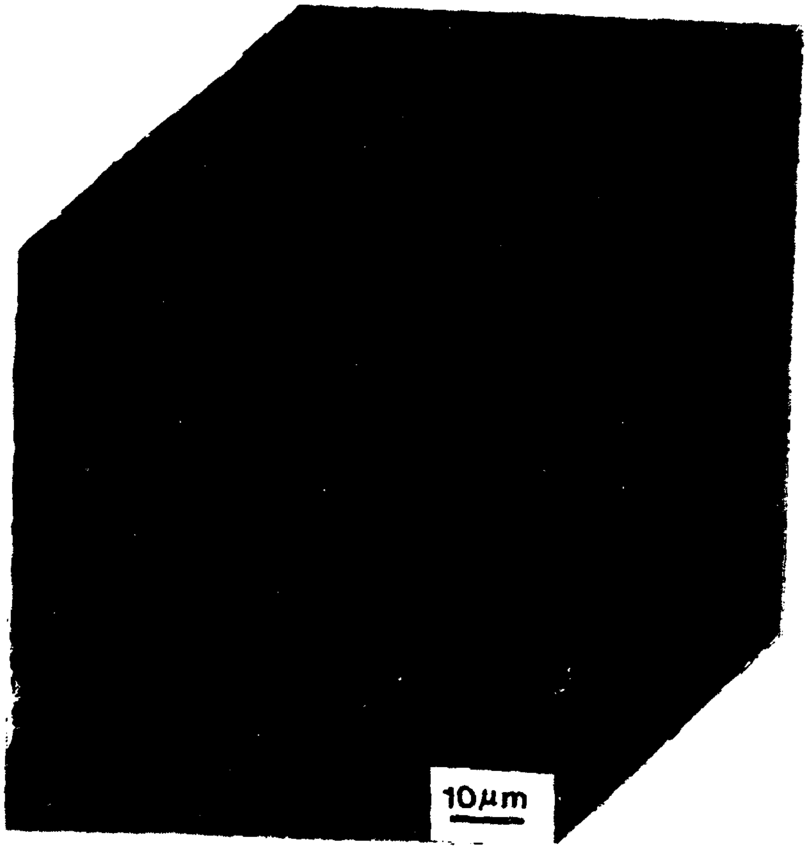


Figure 2. Grain structure of 2091 plate
Etched with Keller's reagent

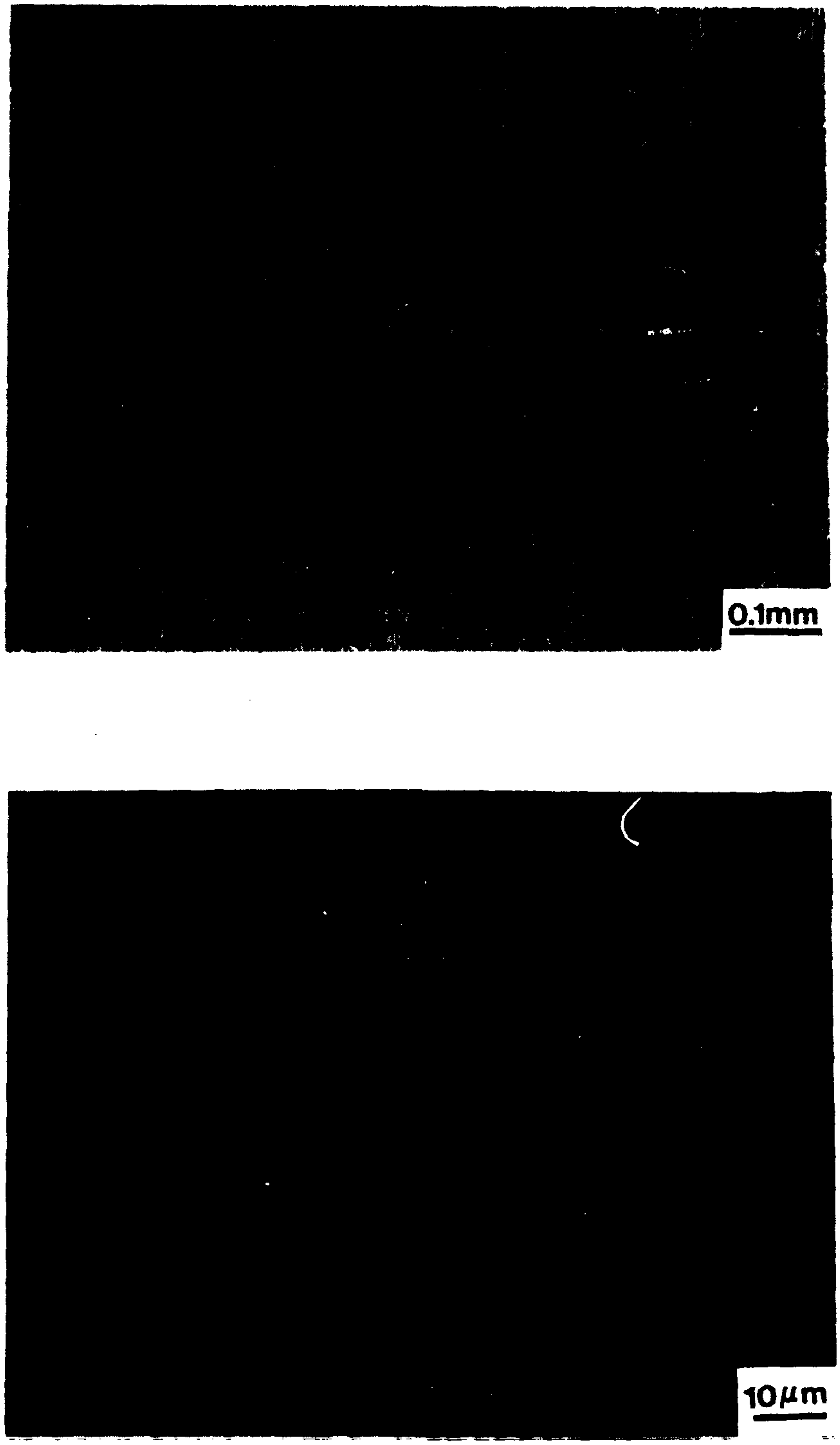
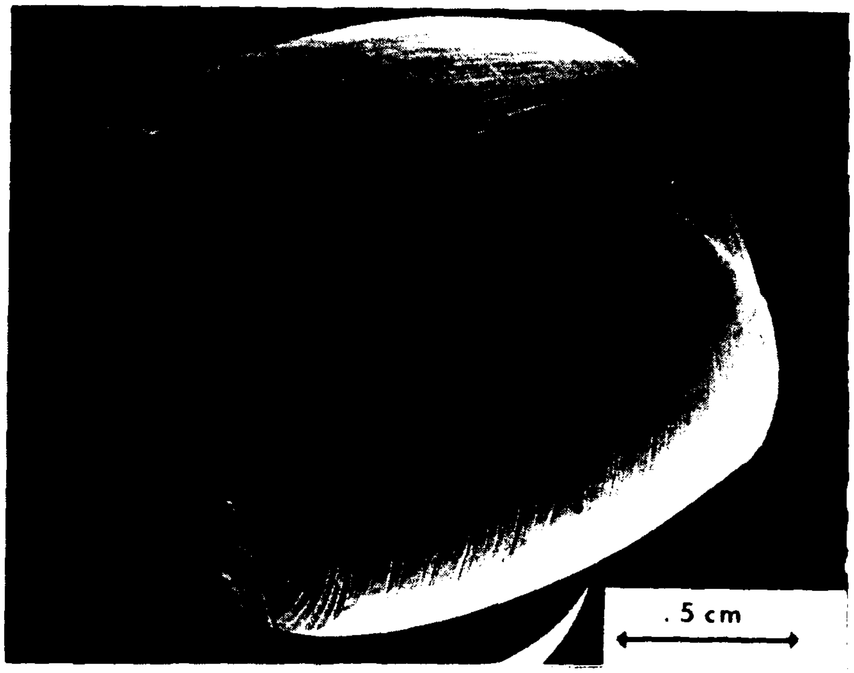


Figure 3. Grain Structure 8090, Extrusion
Etched with Keller's Reagent

a)



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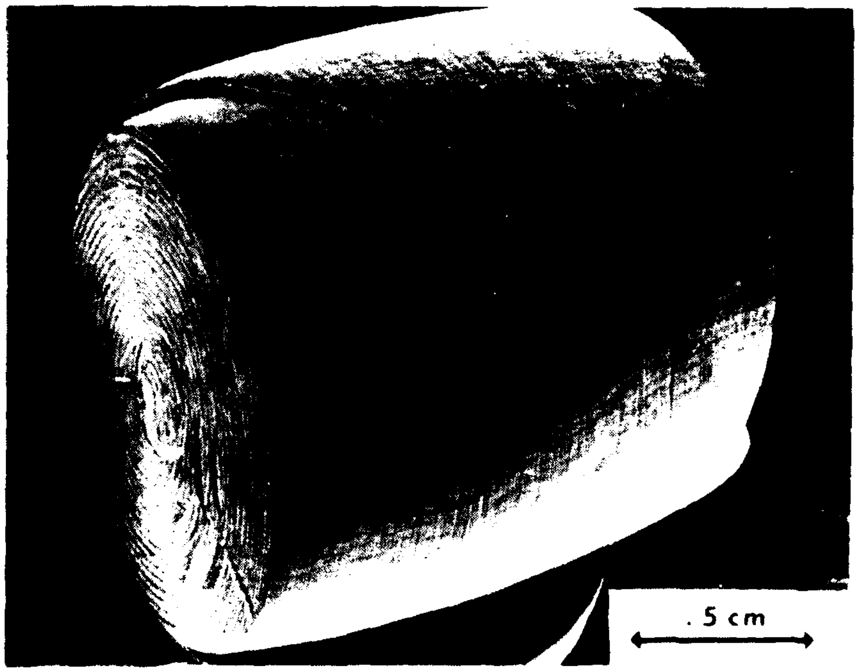


Figure 4. Compression Samples 2091
a) Longitudinal
b) Transverse

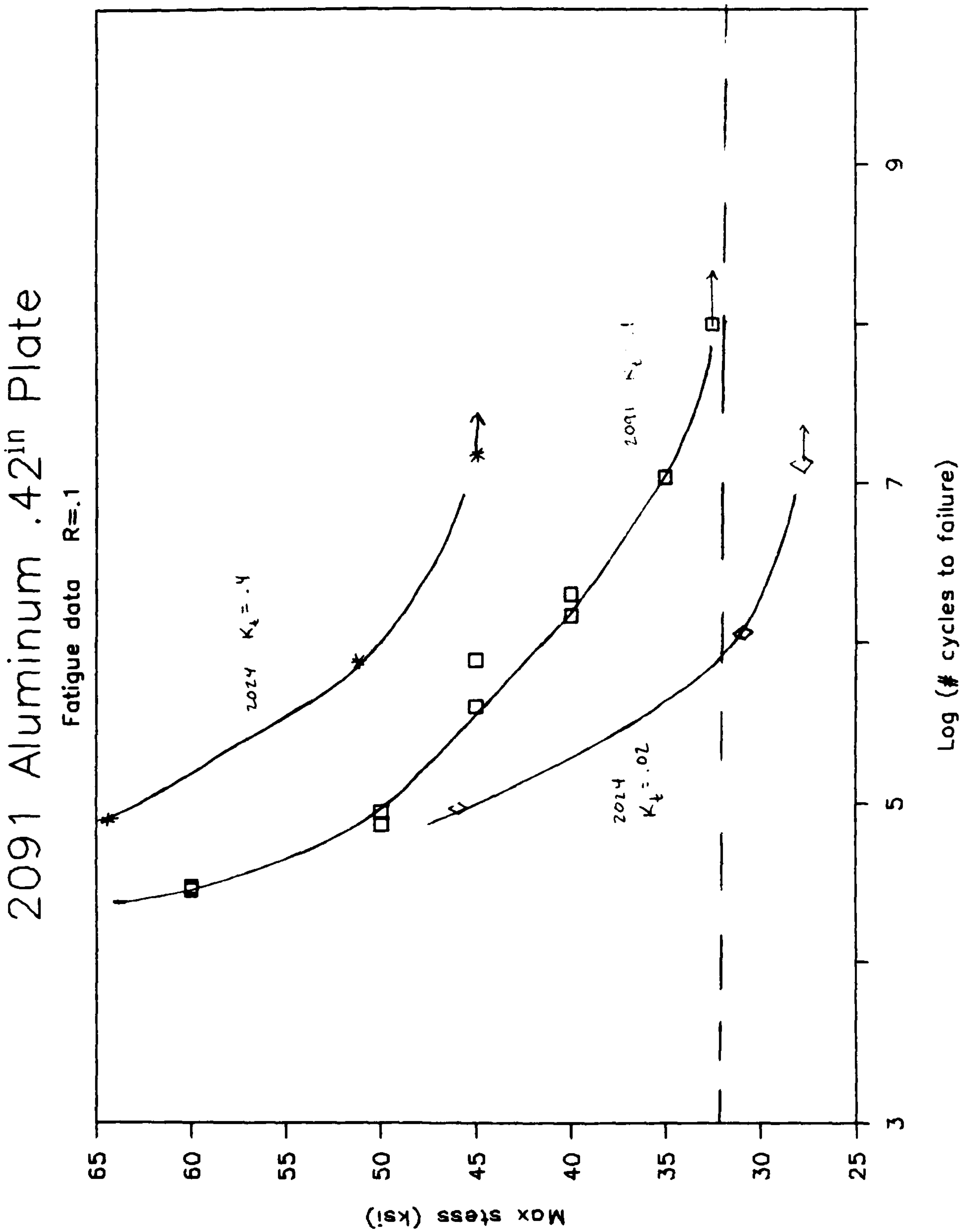


Figure 5 Fatigue Data, Alloy 2091, 0.42^{in} plate

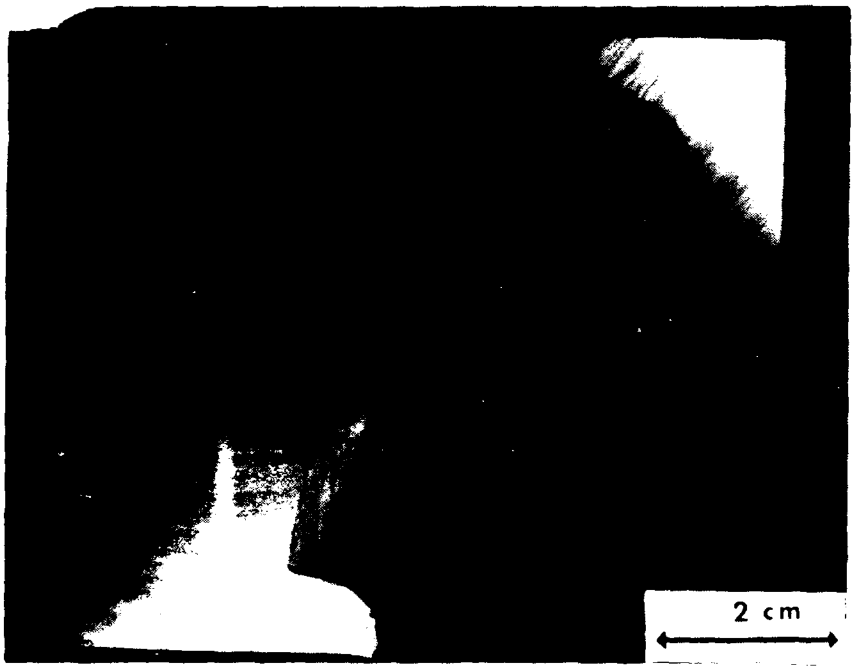


Figure 6 Macrophotograph Compact Tension, Sample 2091

7a)

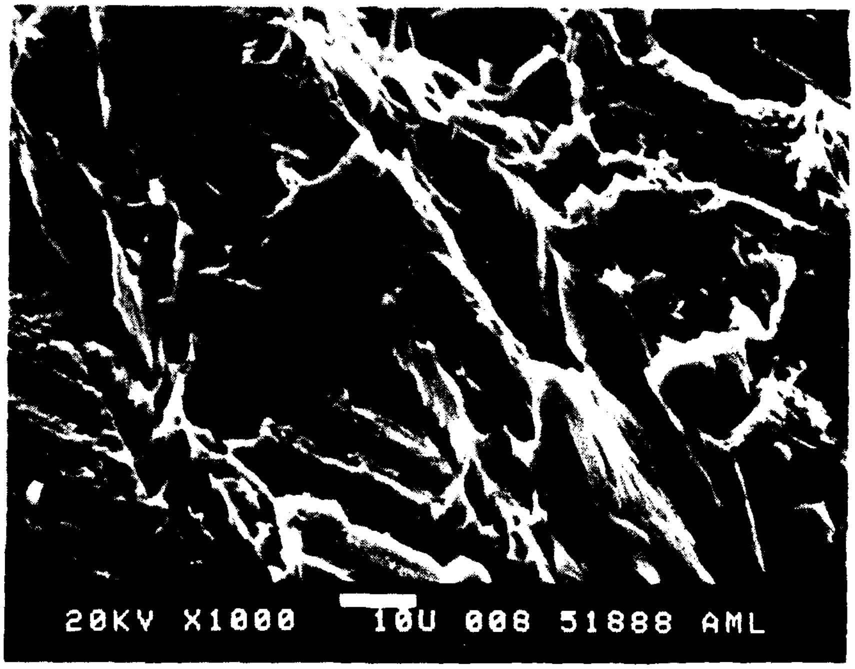
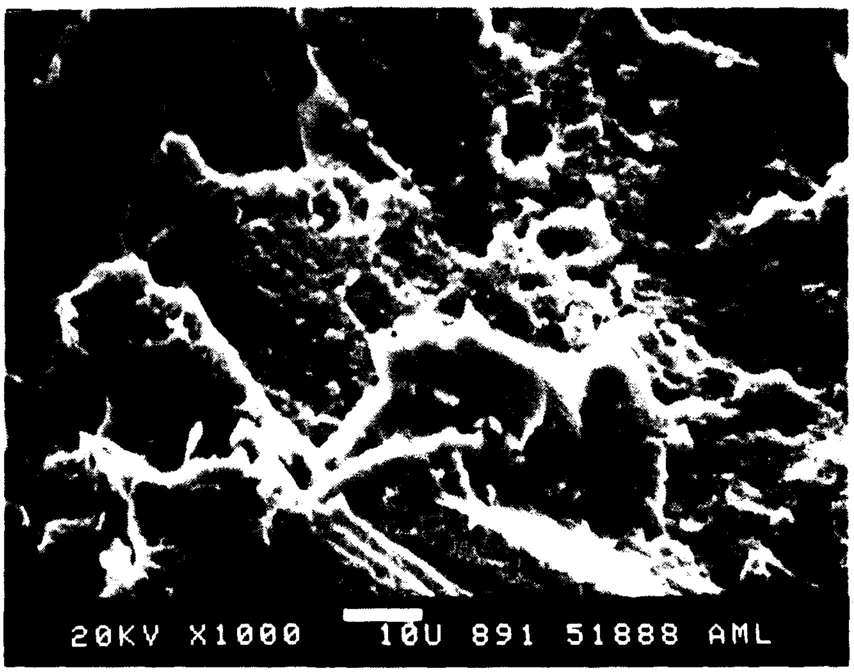
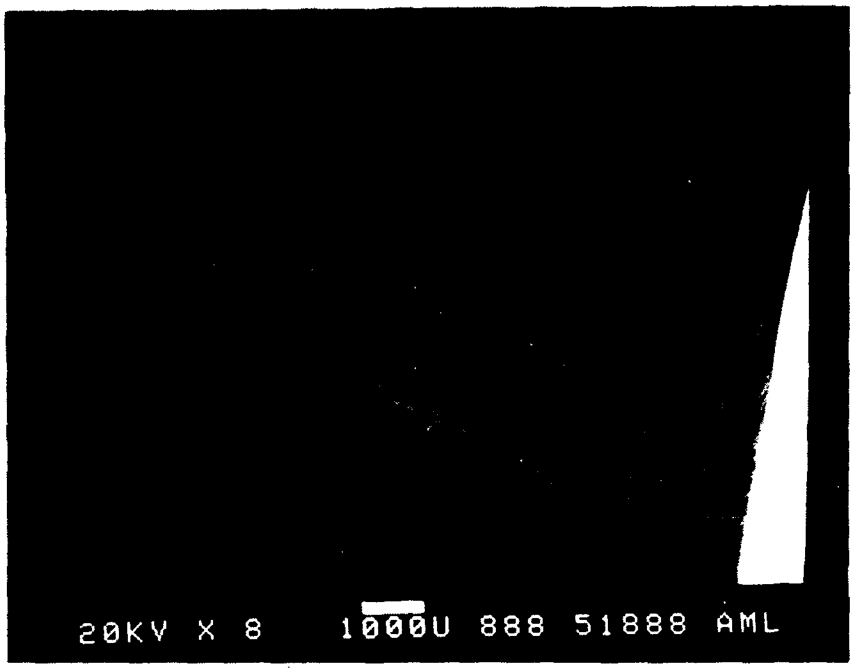


Figure 7 Fracture Surfaces, 2091
a) Longitudinal
b) Transverse

7b)





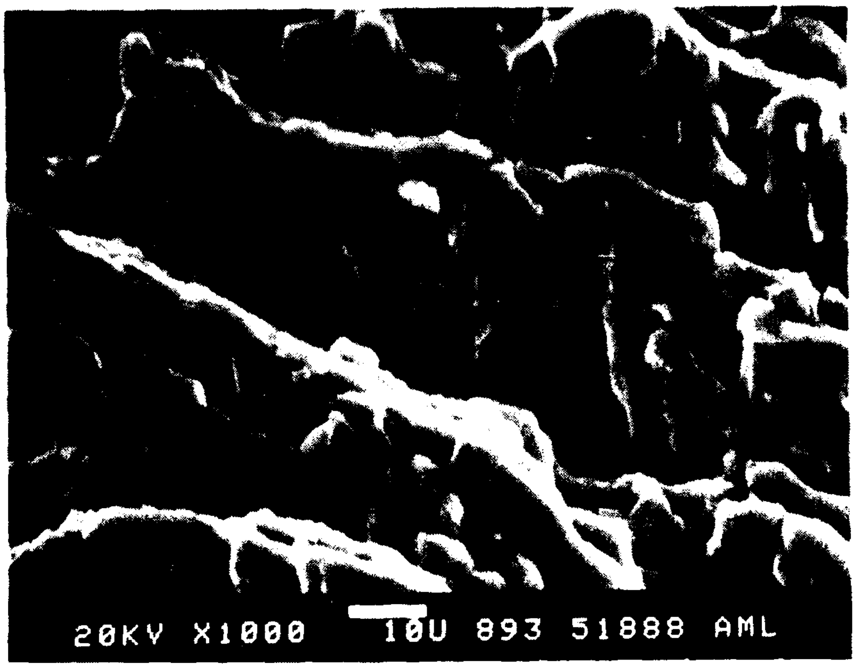


Figure 8 Fracture Surfaces, 8090
Longitudinal

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