MEA - 2557

DOT 3AL-6351 T6 Alloy Cylinder Rupture Evaluation Tests for Mechanical Strength and Fracture Toughness

Prepared by:

F.J. Loss
J.D. Aadland

Materials Engineering Associates, Inc.
9700-B M.L. King, Jr. Hwy
Lanham, MD 20706-1837

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U.S. Dept. of Transportation
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1.0 OBJECTIVE

Several ruptures have occurred in DOT 3AL cylinders made from aluminum alloy 6351-T6. The purpose of this project was to investigate the strength and fracture toughness behavior of a ruptured cylinder made from 6351-T6 aluminum alloy. Materials Engineering Associates (MEA) characterized fracture toughness, tension and microhardness properties from ruptured cylinder material.

2.0 TEST MATRIX

Two pieces of ruptured tank material were furnished by DOT as illustrated in Fig. 1 and 2. From one piece, four compact specimens for fracture toughness tests and two tension specimens were cut as illustrated in Fig. 3. Microhardness samples were prepared from the second piece.

3.0 TENSION TESTS

The machining drawing for the tension specimens is presented in Fig. 4. Two tests were performed at room temperature in accordance with ASTM Standard E8, "Test Methods for Testing of Metallic Materials." Stress vs. strain plots for the tests are presented in Fig. 5 and 6. The engineering test results from the tension tests are given in Table 1.

Table 1 Tension Test Results

Specimen ID	Yield Stress (ksi)	Ultimate Stress (ksi)	Reduction of Area (%)	Elongation[a] (%)
11A82-4	43.6	50.1	39.3	11.2
11A82-5	44.8	50.5	38.0	12.3

[a] 0.904 in. gage length

4.0 FRACTURE TOUGHNESS TESTS

Four compact fracture toughness C(T) specimens were prepared in accordance with Fig. 7. Two specimens (11A82-2 and 11A82-3) included 20% side grooves (10% per side) which were machined after the specimens were fatigue precracked. The remaining two specimens did not have side grooves. As can be seen in Fig. 3, the specimens were oriented so that the fracture plane was radial and outward from the threaded neck region of the cylinder so as to simulate the observed fracture behavior.

The specimens were tested at room temperature in accordance with ASTM Standard E813, "Test Method for J_{IC}, A Measure of Fracture Toughness", or ASTM Standard E399, "Test Method for Plane-Strain Fracture Toughness of Metallic Materials". Fatigue precracking was performed with a maximum stress intensity of ~ 8 ksi $\sqrt{in}$.

Table 2 includes the data required by ASTM E813 or E399 for the J-deformation or K analyses. Table 3 is a summary of the results. Detailed test data are presented in the Appendix.

J-R curves were produced by the two specimens that had no side grooves (Specimens 11A82-1 and 11A82-6). However, the crack extension from these specimens was "tunneled" thereby making valid tests impossible. On the other hand, the two specimens that were side grooved (Specimens 11A82-2 and 11A82-3) exhibited no apparent crack extension (and therefore no J-R curve behavior) before failing in a brittle manner.

The load vs. displacement records for Specimens 11A82-2 and 11A82-3 are quite linear (illustrated in the Appendix) and resulted in K_Q values of approximately 25 ksi $\sqrt{in}$. While the load vs. displacement record for these two tests was sufficiently linear for the E399 test validity requirement, the specimen thickness was insufficient to meet the validity condition:

$$B > 2.5 (K_Q/\sigma_{ys})^2 \qquad (1)$$

where B and σ_{ys} are the thickness and yield stress, respectively.

It should be noted that the inclusion of side grooves changed a ductile behavior of slow stable growth (Specimens 11A82-1 and 11A82-6) to a brittle behavior (Specimens 11A82-2 and 11A82-5). This suggests that the material is notch-sensitive.

5.0 MICROHARDNESS TESTS

A microhardness (Vikers Brale) survey was performed at two locations from a failed tank as indicated in Fig. 2. Section 1 is in the neck region of the tank where the fracture originated. Section 2 is in the cylindrical section of the tank wall removed from the fracture origin. The objective of the hardness survey was to determine the presence of differences in hardness near the region of fracture which might suggest a root cause of the fracture.

The results of the microhardness surveys from regions 1 and 2 are presented in Fig. 8 and 9 respectively. Careful examination of the hardness surveys does not reveal any significant differences between the two regions. Therefore, hardness does not appear to be a significant diagnostic tool regarding the cause of failure.

Table 2 -- Fracture Toughness Data Summary

Specimen ID	Yield Strength	Ultimate Strength	Flow[a] Stress	Thickness B	Depth W	Initial[b]		Final		Delta a_m[c]	Delta a_p[d] Delta a_m	Temp	ASTM Analysis		
						a_o/W	W-a_o	a_f/W	K_{max} precracking				E 813-87 J_{Qc}[f]	E 813-87 K_{JQ}[g]	E 399-90 K_Q
	(ksi)	(ksi)	(ksi)	(inch)	(inch)		(inch)		(ksi-in$^{1/2}$)	(inch)	(inch)	(°F)	(in-lb/in^2)	(ksi-in$^{1/2}$)	(ksi-in$^{1/2}$)
11A82.1	44.2	50.2	47.2	.503	1.001	.509	.491	.660	8.1	.151	.066	74	76.8	27.7	N/A
11A82.2[e]	44.2	50.2	47.2	.499	1.000	.513	.487	.513	8.1	.000	N/A	74	N/A	N/A	24.1
11A82.3[e]	44.2	50.2	47.2	.504	1.000	.518	.482	.518	8.5	.000	N/A	74	N/A	N/A	25.7
11A82.6	44.2	50.2	47.2	.496	1.002	.535	.464	.789	6.6	.253	.065	74	74.1	27.2	N/A

[a] Flow stress calculated using: Flow stress = (Yield + Ultimate) / 2.
[b] Based on measured initial crack length a_o by ASTM E 813 procedure.
[c] Measured crack extension by ASTM E 813 procedure.
[d] Difference between the measured and the elastic compliance predicted crack extension.
[e] Specimens side grooved 20%, e.g., 10% of the specimen thickness on each side.
[f] ASTM E 813 analysis uses the deformation theory formulation of the J integral.
[g] Quasi-elastic fracture toughness K_{Jc} calculated using the relationship $K_{Jc} = (E\ J_{Ic})^{1/2}$.

Table 3 -- Fracture Toughness Data from ASTM E 813 Analysis

Specimen ID	J_Q	K_{JQ}[b] / K_Q		T[c]
	ASTM[a] E 813-87	ASTM E 813-87	ASTM E 399-90	ASTM E 813-87
	(in-lb/in2)	(ksi-$in^{1/2}$)		
11A82.1	76.8	27.7	N/A	7.2
11A82.2	N/A	N/A	24.1	N/A
11A82.3	N/A	N/A	25.7	N/A
11A82.6	74.1	27.2	N/A	10.1

[a] Power law curve fit intersection, J-deformation, E 813-87 J equation data

[b] $K_{JQ} = (J_Q E)^{1/2}$

[c] Tearing Modulus T calculated between exclusion lines using $T = E / \sigma_f \, dJ/da$; E = Young's Modulus

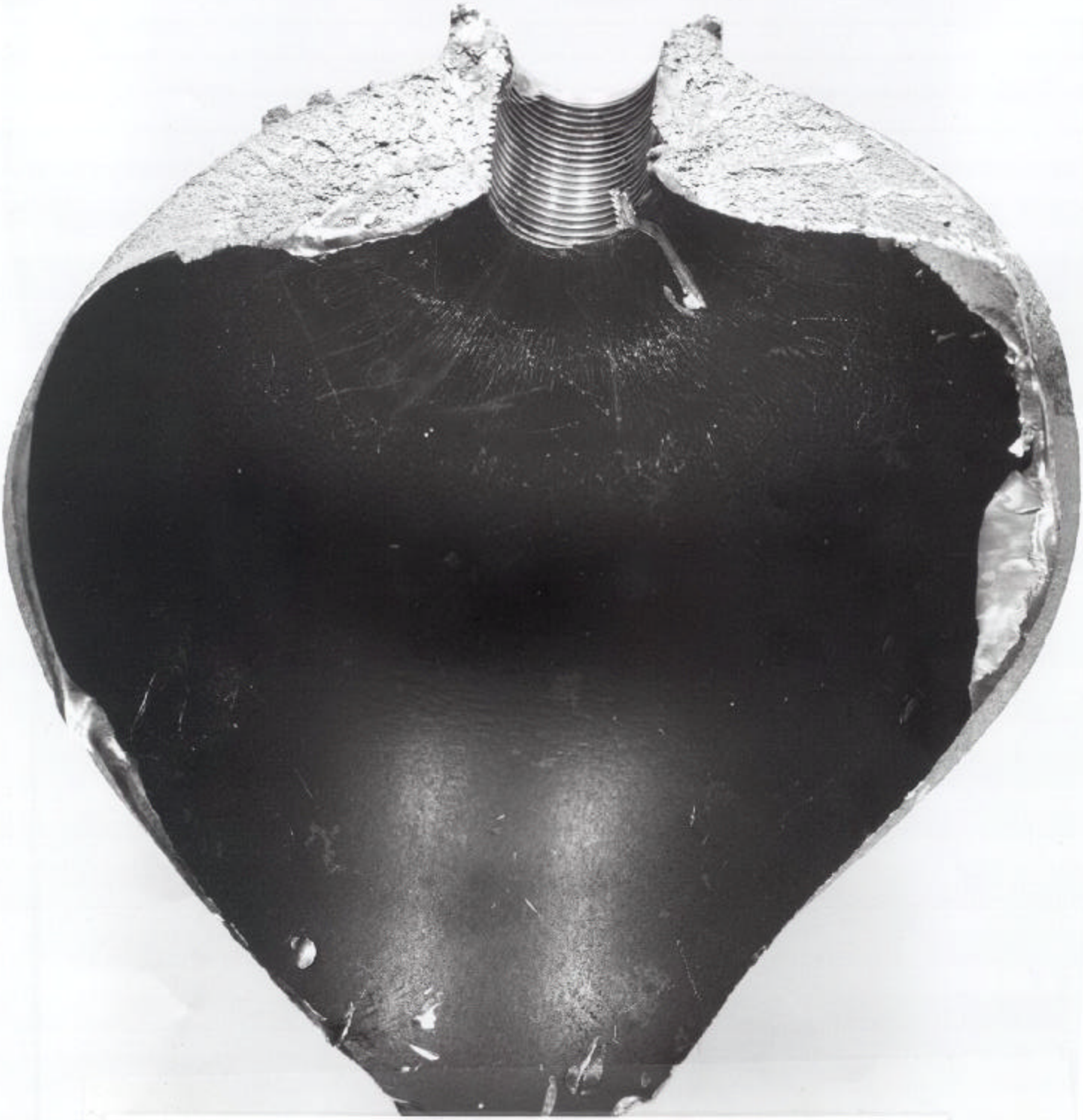


Fig. 1 Piece of failed 6351-T6 aluminum cylinder used to obtain fracture toughness and tension specimens.

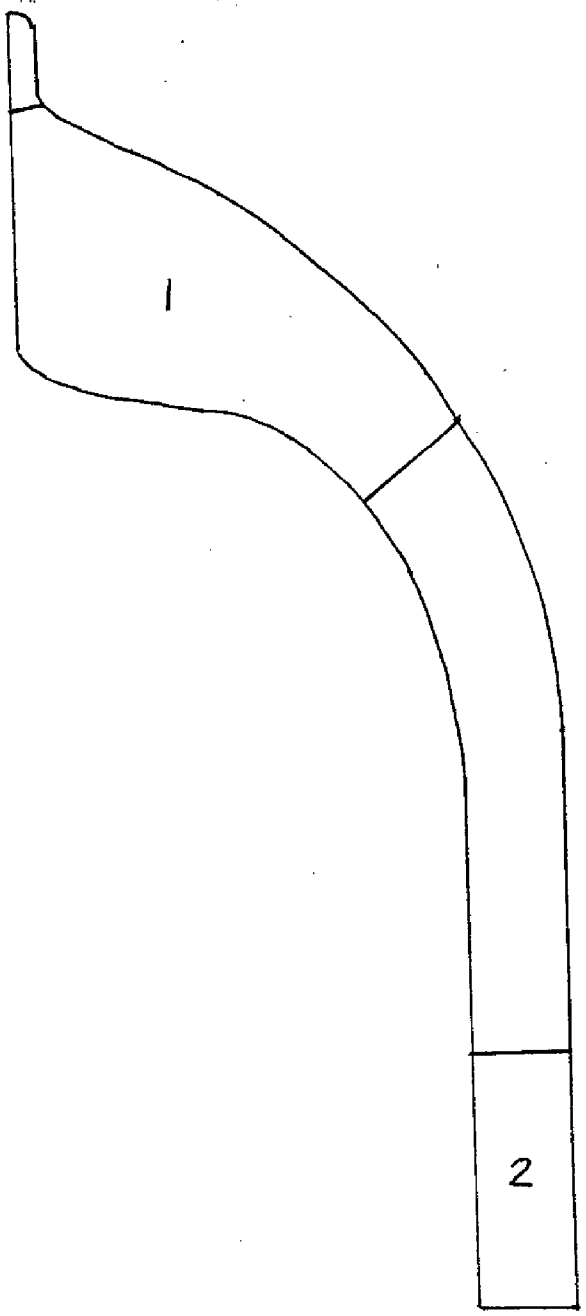


Fig. 2 Piece of failed 6351-T6 aluminum cylinder used to obtain samples No. 1 and 2 for microhardness tests. The piece is shown as actual size (~ 3/8 in. thick).

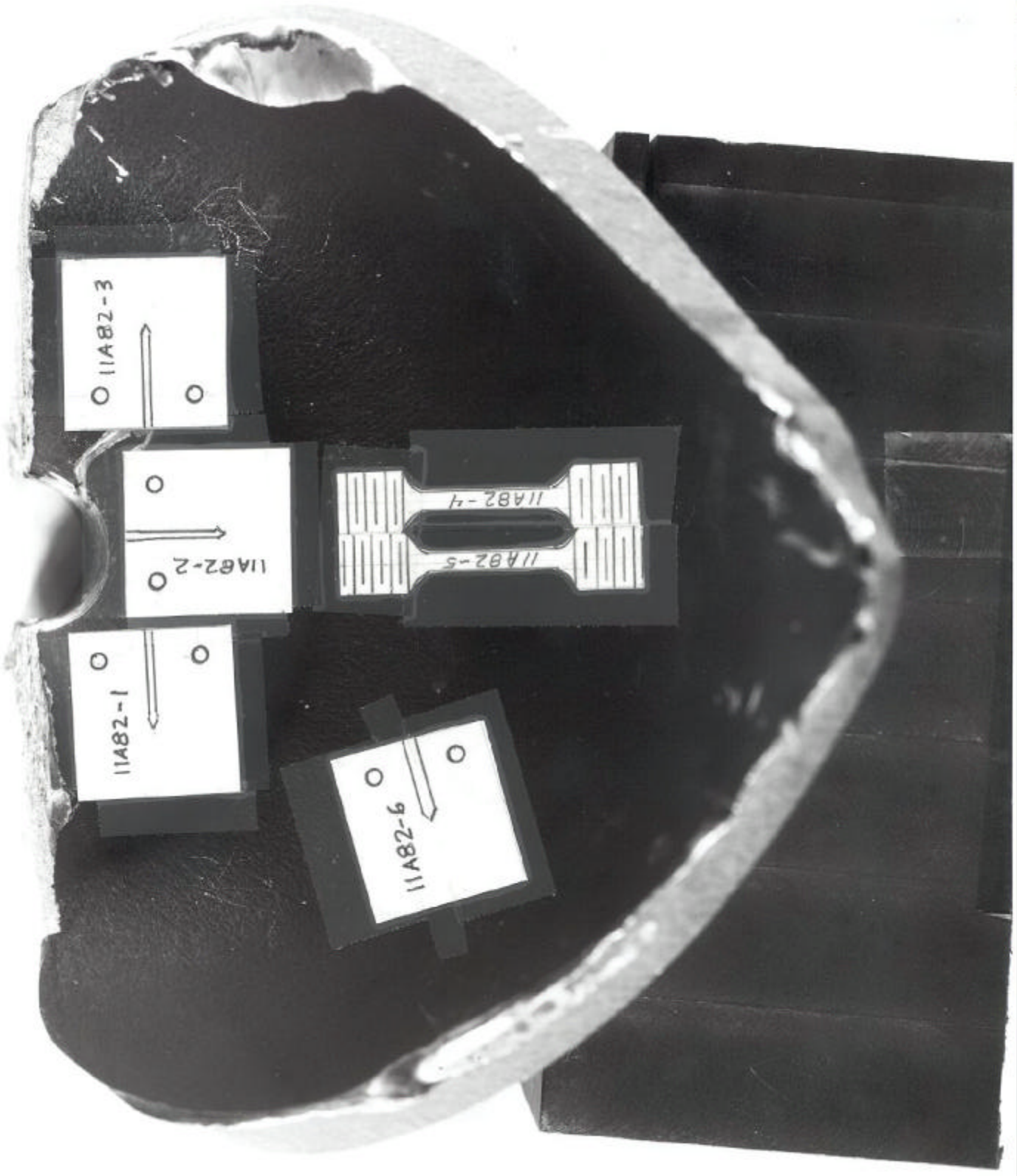


Fig. 3 Location of fracture mechanics and tension test specimens

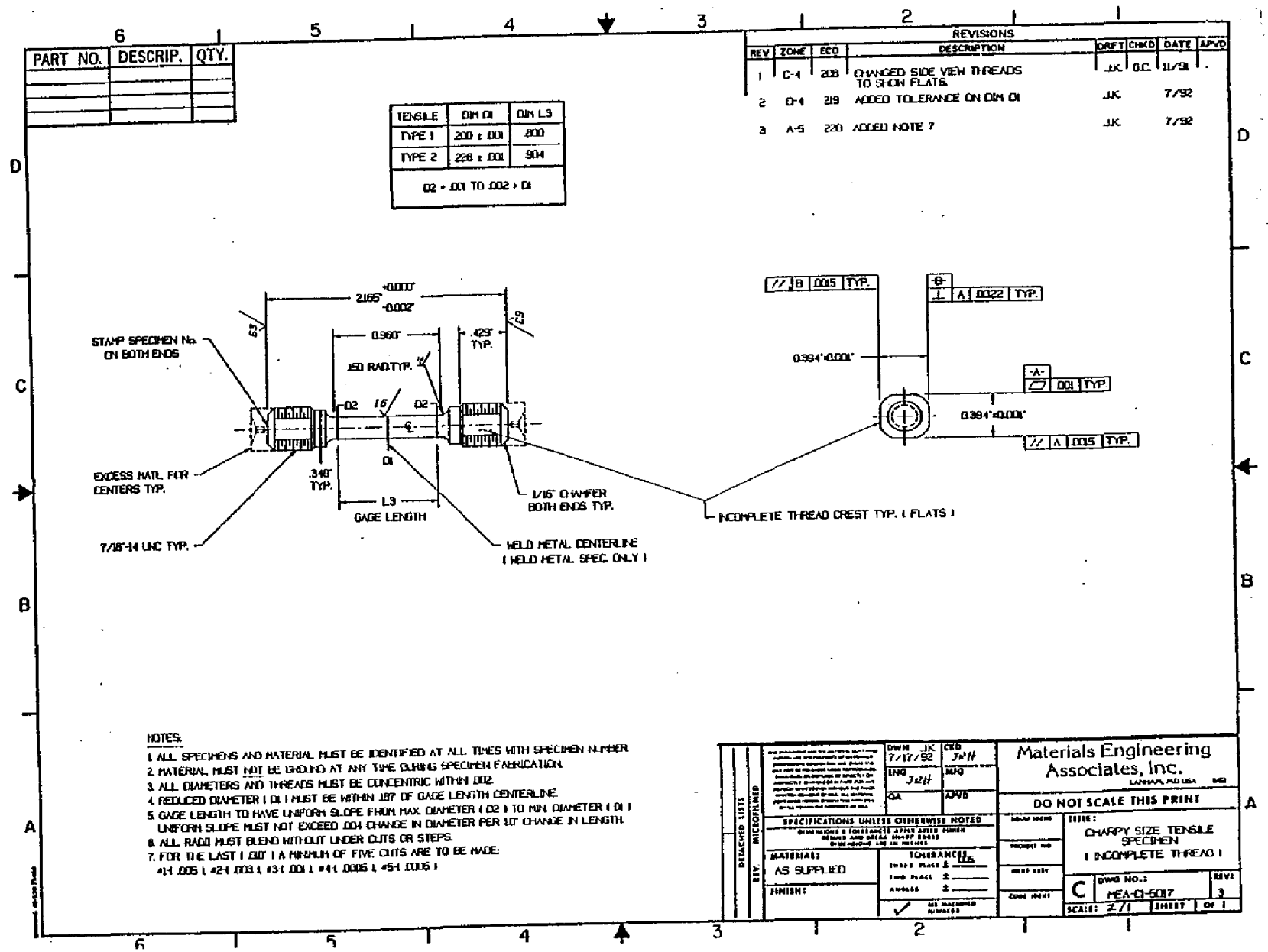
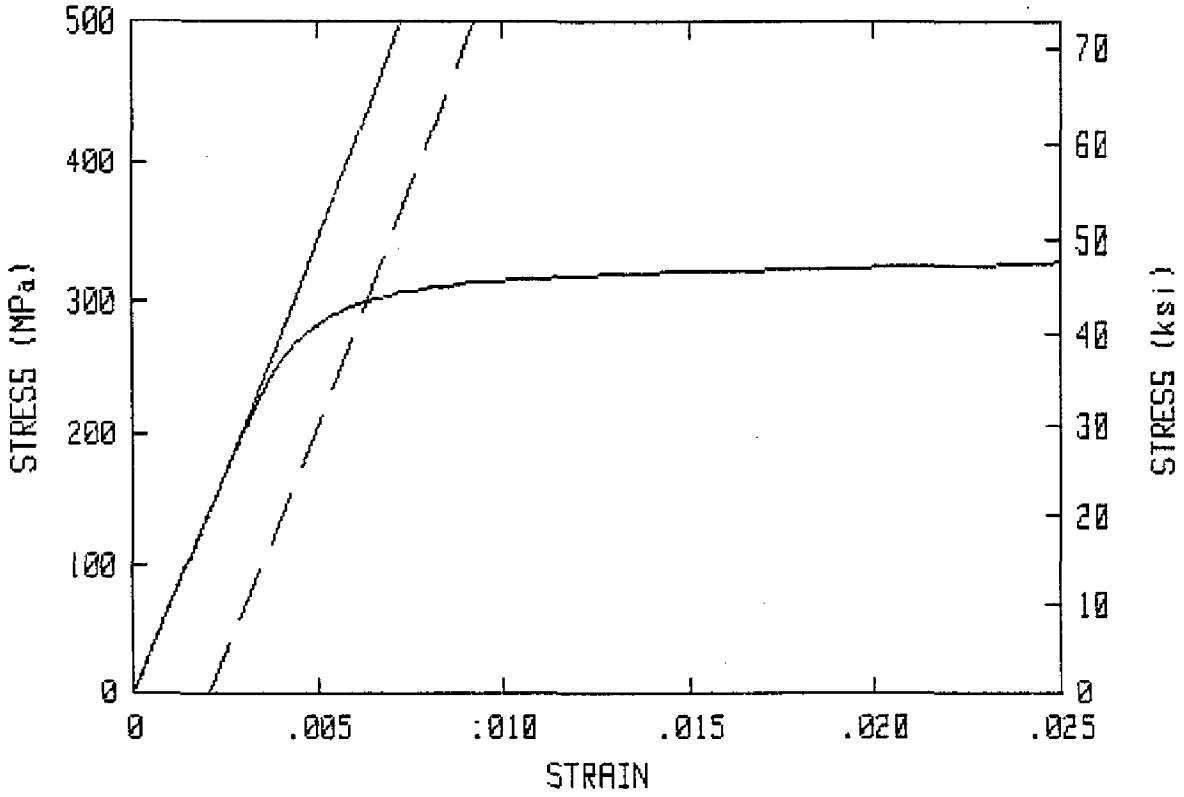


Fig. 4 Tension test specimen

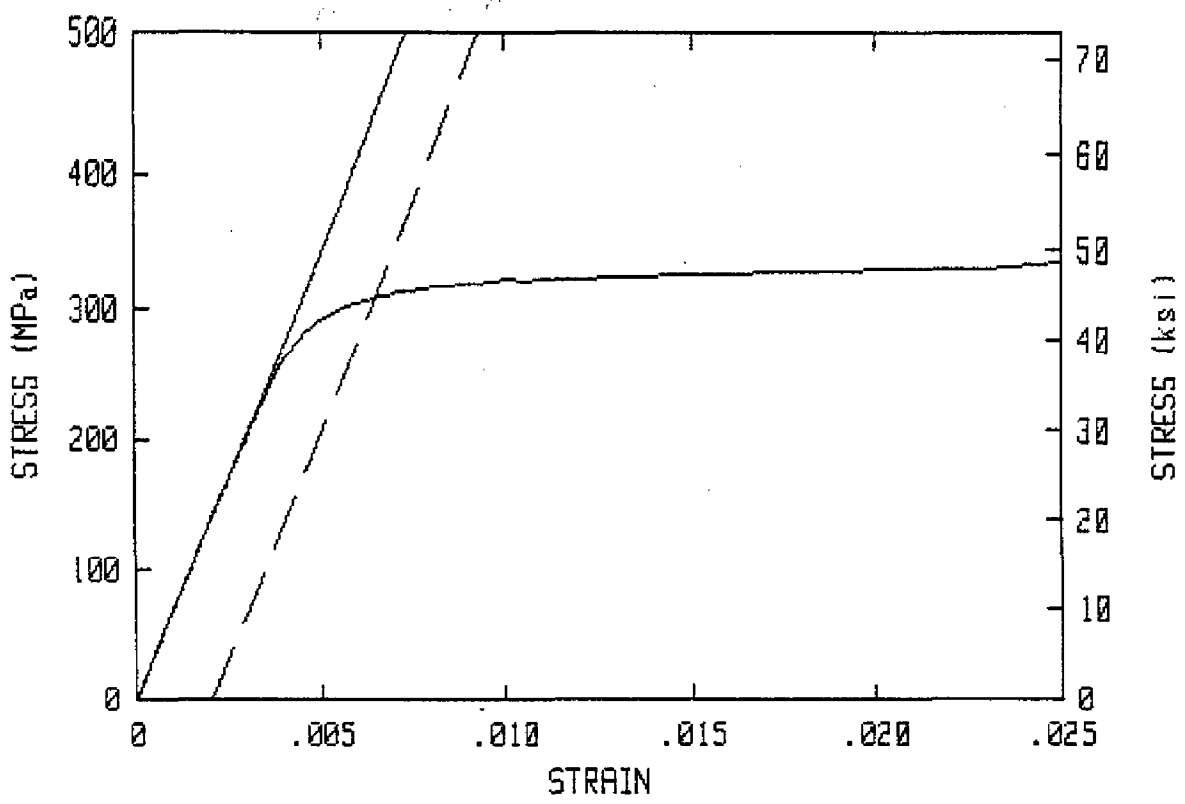


Engr. Stress-Strain Data

Specimen : 4

Young's Modulus = 10.01E6 psi
Ymod Fit Range = 7.25 to 21.76 ksi
0.2% Yield Strength = 43.55 ksi
Ultimate Strength = 50.09 ksi
Elastic Testing Rate = 53.80 ksi/min

Fig. 5 Stress vs. strain behavior for tension specimen no. 11A82-4.



Engr. Stress-Strain Data

Specimen : 5

Young's Modulus = 9.92E6 psi
Ymod Fit Range = 7.25 to 21.76 ksi
0.2% Yield Strength = 44.75 ksi
Ultimate Strength = 50.53 ksi
Elastic Testing Rate = 55.33 ksi/min

Fig. 6 Stress vs. strain behavior for tension specimen no. 11A82-5

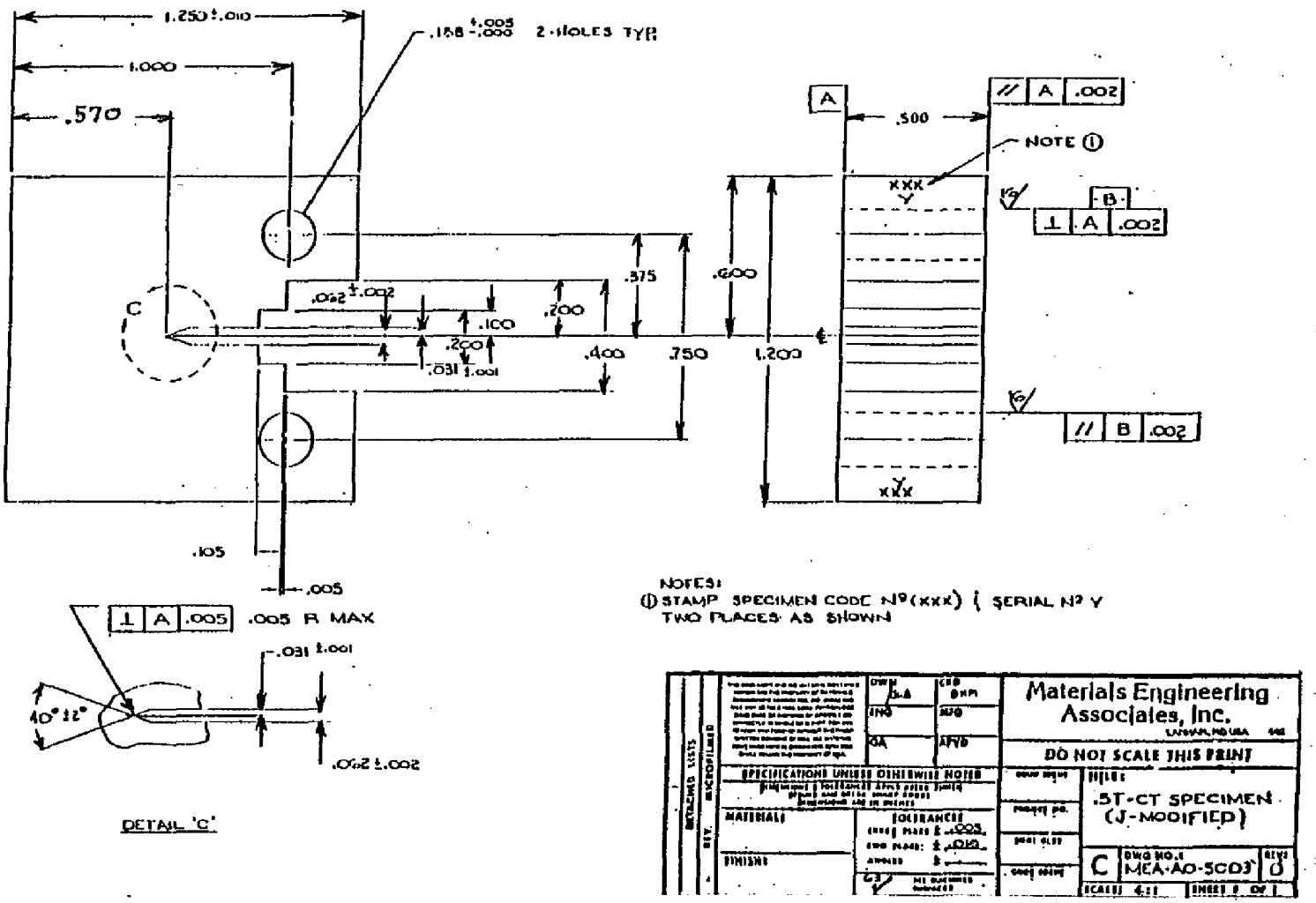


Fig. 7 Compact fracture toughness specimen design

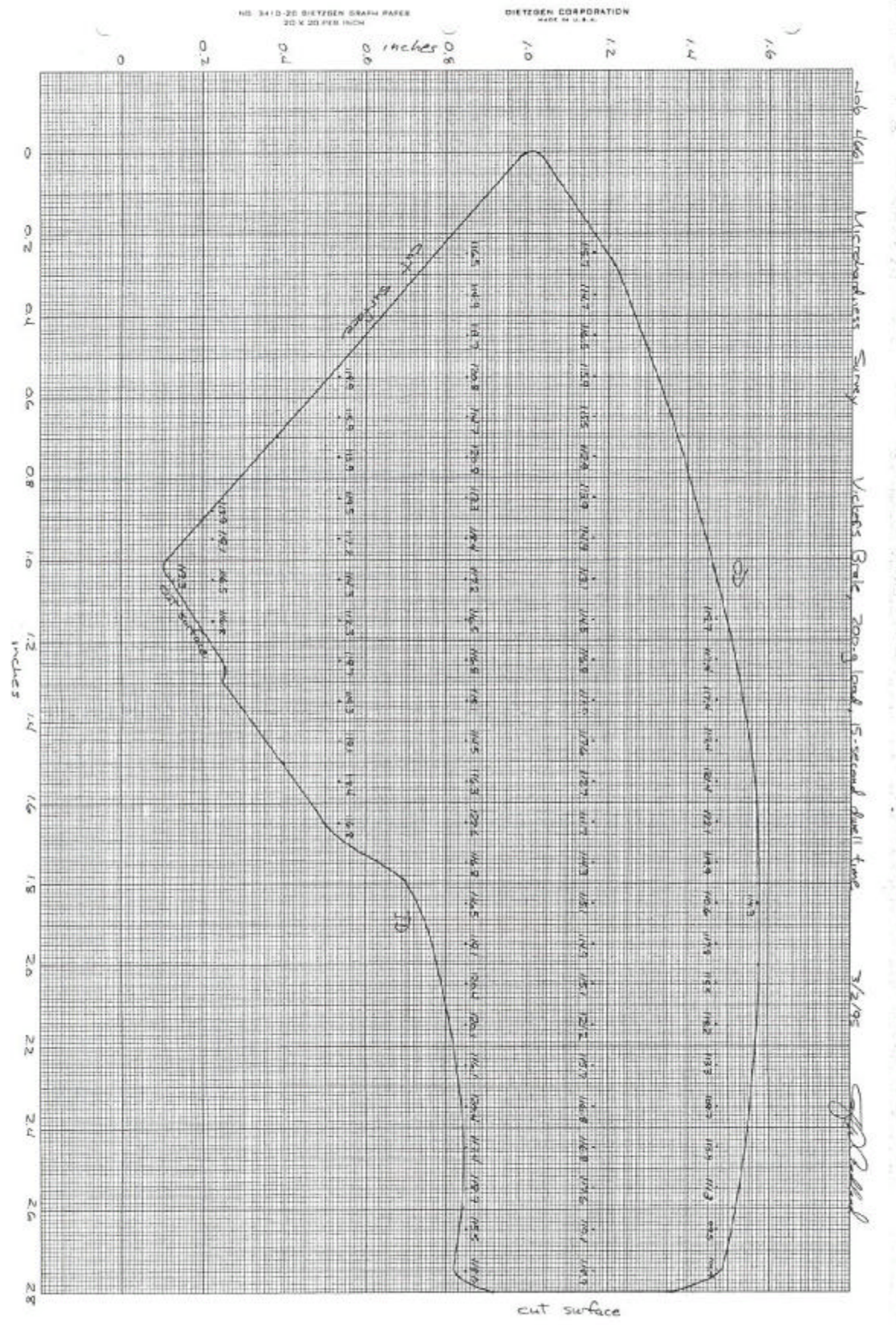


Fig. 8 Microhardness survey from Piece 1 (Fig. 2)

Job 4661 - US DOT
Microhardness Survey
Baseline
Vickers Brale
200 g load, 15 sec dwell time

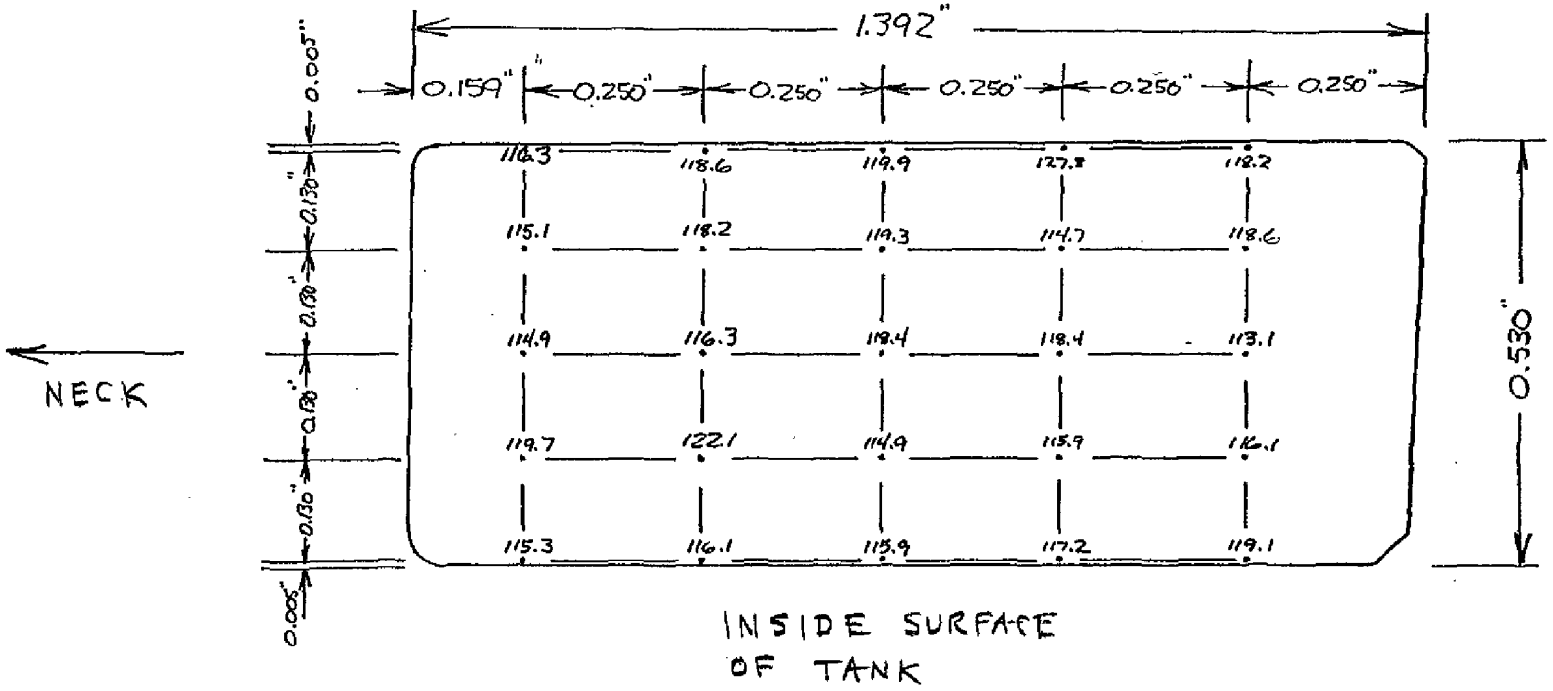


Fig. 9 Microhardness survey from Piece 2 (Fig. 2)

APPENDIX

FRACTURE TOUGHNESS TEST
DATA

ELASTIC-PLASTIC
FRACTURE TOUGHNESS ANALYSIS

Specimen Id.	11A82-6	Geometry	CT
Contract #	4661	Orientation	N/A
Material	Aluminum	Flow stress (ksi)	47.2
Temperature (F)	74	Modulus (ksi-1E6)	10.0
Environment	30% RH	Stroke rate (in/min)	0.020
		Loading rate (min)	0.335

Specimen Dimensions (in)

Thickness	0.496	Notch depth	0.430
Net thickness	0.496	Gage length	0.124
Width	1.002	Alpha ratio	1.000
Pin spacing	0.751		

Initial Ligament(s) (in)

0.525 0.501 0.481 0.458 0.445 0.436 0.439 0.449 0.479

Final Ligament(s) (in)

0.391 0.311 0.139 0.135 0.133 0.136 0.146 0.295 0.403

Precrack Parameters

Pmax (lbs)	300.0	Stress ratio (R)	0.10
Final a (in)	0.538	Kmax (ksi sqr[in])	6.57

Test Parameters

Initial ligament (in)	0.464	J15limit (in-lb/in^2)	1460
Final ligament ''	0.211	J20limit ''	1095
Delta a (actual) ''	0.252	J25limit ''	876
Delta a (EvB/P) ''	0.188	*JQ (813-81) ''	0.0
Delta a error ''	-0.065	*JQ (813-81)(NV) ''	67.0
Delta a error (%)	-25.6	*JQ (813-87) ''	0.0
Delta amax error (%)	-105.8	*JQ (813-87)(NV) ''	74.1
Compliance Adjustment	1.064		
CTODi (in)	0.0007	Tearing modulus	10.1

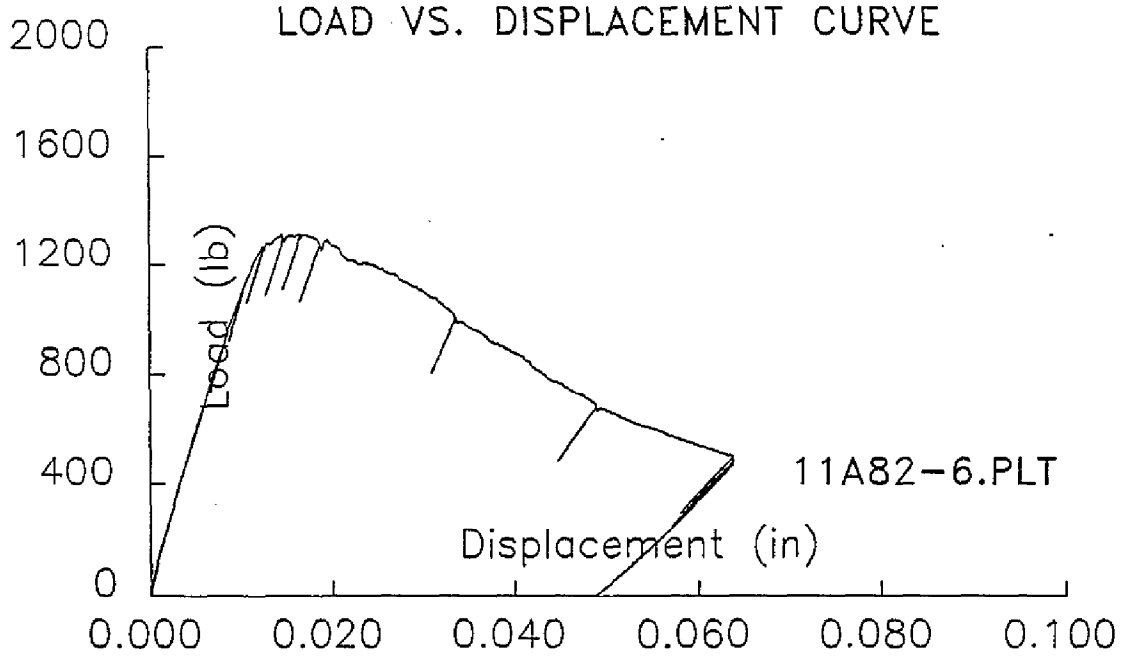
Comments

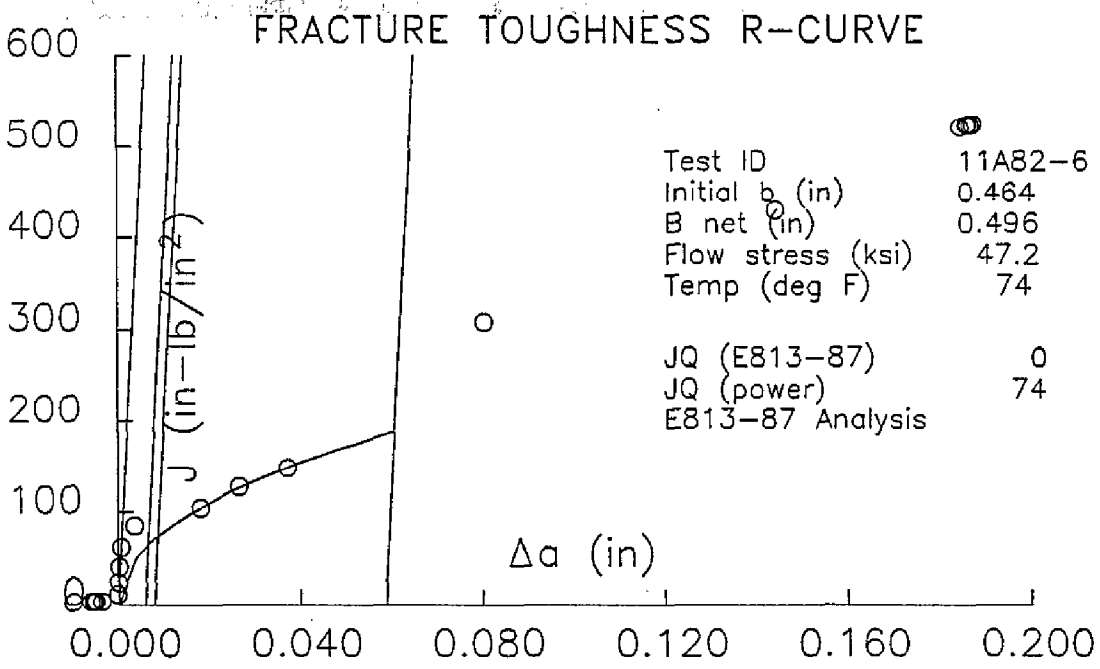
* Computed from E813-87 form for J

Date of test: 12-28-1994
Less than 4 data pts for JIc fit (Sec 9.3.2)
Crack front uneveness > 7% of a (Sec 9.4.1.5)
Final delta a error > 15% of DA (Sec 9.4.1.7)
Final delta a error > 15% of DAmax (Sec 9.4.1.7)

Specimen Id. 11A82-6

Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	K399 (ksi sqr[in])	K813	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0	0.0	0.0	0.0	0.0	0.0
1	258	0.0020	-.0100	-.0000	5.5	5.2	2.5	2.7	2.6	2.6
2	267	0.0020	-.0062	-.0000	5.7	5.2	2.5	2.7	2.5	2.5
3	277	0.0021	-.0056	-.0000	6.0	5.5	2.8	3.0	2.8	2.8
4	283	0.0022	-.0050	-.0000	6.1	5.7	3.0	3.2	3.1	3.1
5	281	0.0022	-.0051	-.0000	6.1	5.7	3.0	3.2	3.1	3.1
6	292	0.0023	-.0038	-.0000	6.3	5.9	3.3	3.5	3.3	3.3
7	519	0.0043	-.0002	0.0001	11.4	10.8	11.1	11.6	11.4	11.4
8	737	0.0063	-.0000	0.0003	16.2	15.5	23.3	24.2	24.0	23.9
9	940	0.0083	0.0003	0.0005	20.6	20.2	39.6	40.9	40.7	40.7
10	1127	0.0103	0.0007	0.0008	24.7	24.8	59.7	61.4	61.3	61.3
11	1277	0.0124	0.0037	0.0013	28.3	29.2	83.7	85.3	85.7	85.8
12	1313	0.0144	0.0180	0.0018	30.6	32.3	105.2	104.6	106.5	107.4
13	1321	0.0165	0.0266	0.0024	31.7	35.7	130.1	127.5	130.9	132.7
14	1301	0.0185	0.0373	0.0030	32.5	38.5	152.4	148.2	152.5	156.0
15	1024	0.0336	0.0806	0.0076	30.2	55.6	303.6	308.6	302.0	332.7
16	697	0.0486	0.1442	0.0123	27.4	65.6	361.4	430.1	360.5	471.6
17	504	0.0636	0.1849	0.0169	24.6	72.2	412.5	521.8	411.3	589.1
18	456	0.0631	0.1866	0.0169	22.5	72.4	405.6	523.6	404.6	585.3
19	459	0.0631	0.1862	0.0169	22.6	72.3	406.3	523.4	405.4	585.4
20	457	0.0631	0.1865	0.0169	22.6	72.4	405.8	523.5	404.9	585.3
21	461	0.0633	0.1871	0.0169	22.9	72.4	406.1	523.8	405.1	586.5
22	467	0.0635	0.1877	0.0170	23.2	72.4	406.5	524.1	405.5	587.8


LOAD VS. DISPLACEMENT CURVE
2000
1600
1200
800
400
0
Load (lb)
11A82-6.PLT
Displacement (in)
0.000
0.020
0.040
0.060
0.080
0.100


FRACTURE TOUGHNESS R-CURVE
600
500
400
300
200
100
J (in-lb/in²)
Δa (in)
0.000
0.040
0.080
0.120
0.160
0.200
Test ID 11A82-6
Initial b (in) 0.464
B net (in) 0.496
Flow stress (ksi) 47.2
Temp (deg F) 74
JQ (E813-87) 0
JQ (power) 74
E813-87 Analysis

ELASTIC-PLASTIC
FRACTURE TOUGHNESS ANALYSIS

Specimen Id.	11A82-1	Geometry	CT
Contract #	4661	Orientation	UNK
Material	Aluminum	Flow stress (ksi)	47.2
Temperature (F)	74	Modulus (ksi-1E6)	10.0
Environment	30% RH	Stroke rate (in/min)	0.020
		Loading rate (min)	0.336

Specimen Dimensions (in)

Thickness	0.503	Notch depth	0.430
Net thickness	0.503	Gage length	0.124
Width	1.001	Alpha ratio	1.000
Pin spacing	0.750		

Initial Ligament(s) (in)

0.534 0.515 0.499 0.494 0.480 0.476 0.478 0.483 0.496

Final Ligament(s) (in)

0.534 0.482 0.227 0.234 0.220 0.245 0.344 0.445 0.534

Precrack Parameters

Pmax (lbs)	410.0	Stress ratio (R)	0.10
Final a (in)	0.510	Kmax (ksi sqr[in])	8.07

Test Parameters

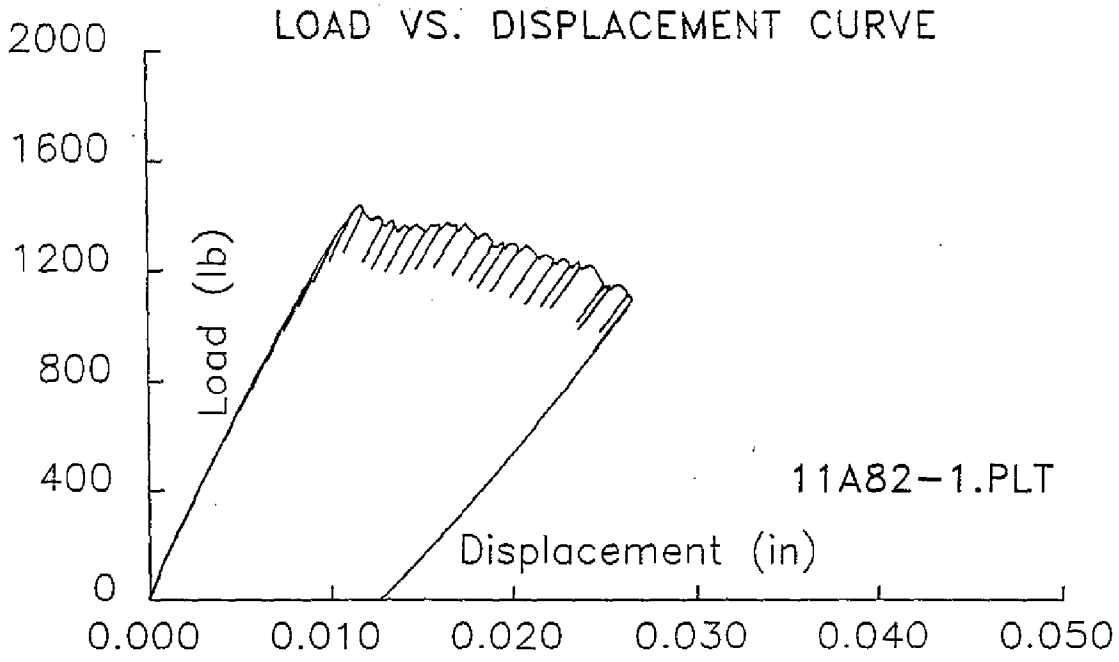
Initial ligament (in)	0.493	J15limit (in-lb/in^2)	1550
Final ligament ''	0.341	J20limit ''	1162
Delta a (actual) ''	0.151	J25limit ''	930
Delta a (EvB/P) ''	0.085	*JQ (813-81) ''	64.2
Delta a error ''	-0.066	*JQ (813-81)(NV) ''	64.2
Delta a error (%)	-43.7	*JQ (813-87) ''	76.8
Delta amax error (%)	-108.8	*JQ (813-87)(NV) ''	76.8
Compliance Adjustment	1.045		
CTODi (in)	0.0006	Tearing modulus	7.2

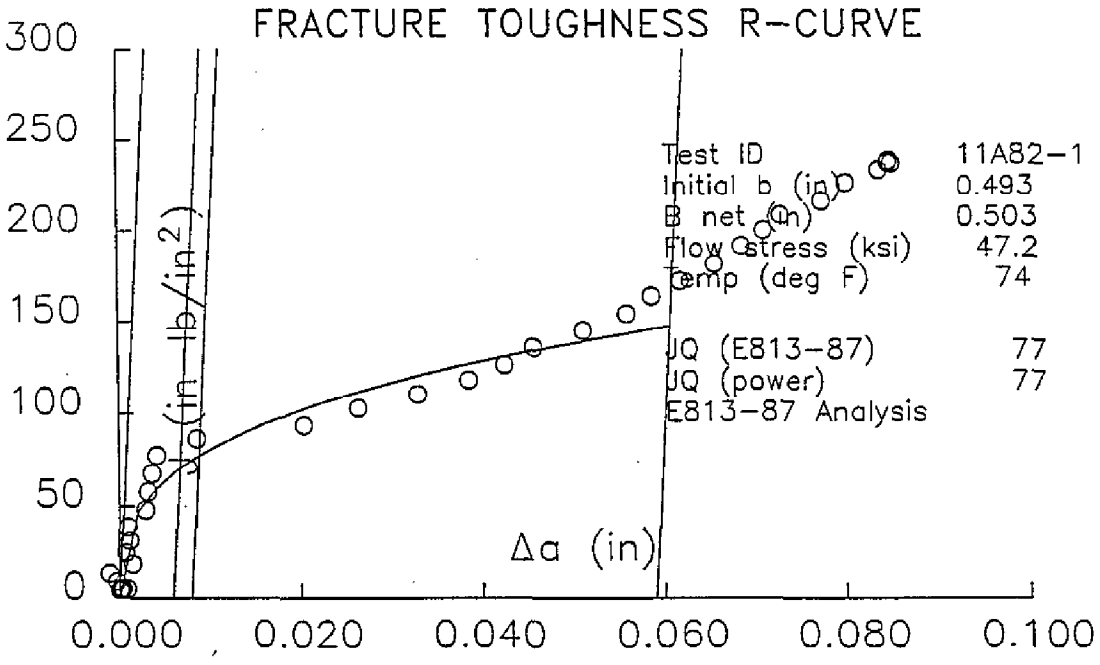
Comments * Computed from E813-87 form for J

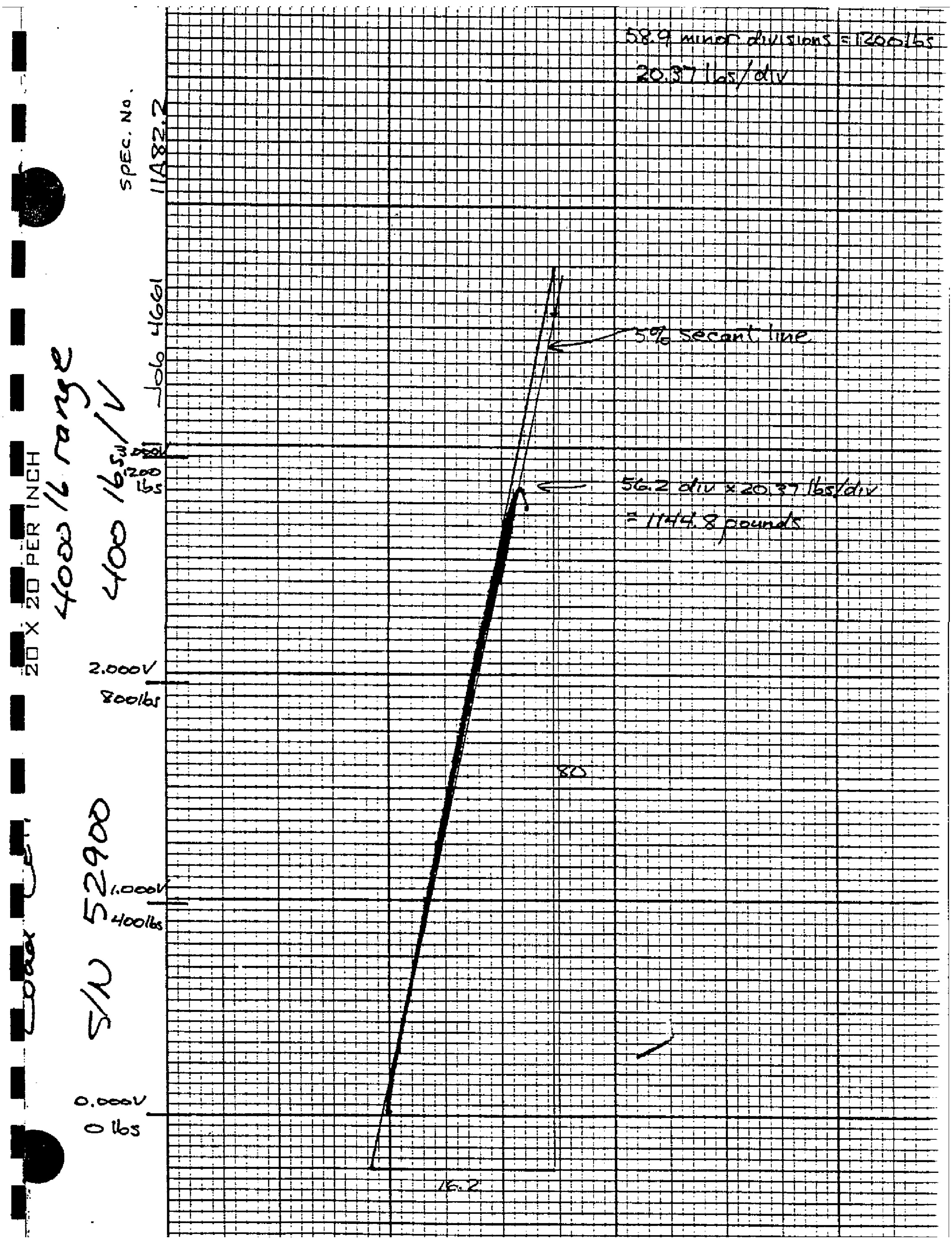
Date of test: 12-28-1994
Crack front uneveness > 7% of a (Sec 9.4.1.5)
Final delta a error > 15% of DA (Sec 9.4.1.7)
Final delta a error > 15% of DAmax (Sec 9.4.1.7)

Specimen Id. 11A82-1

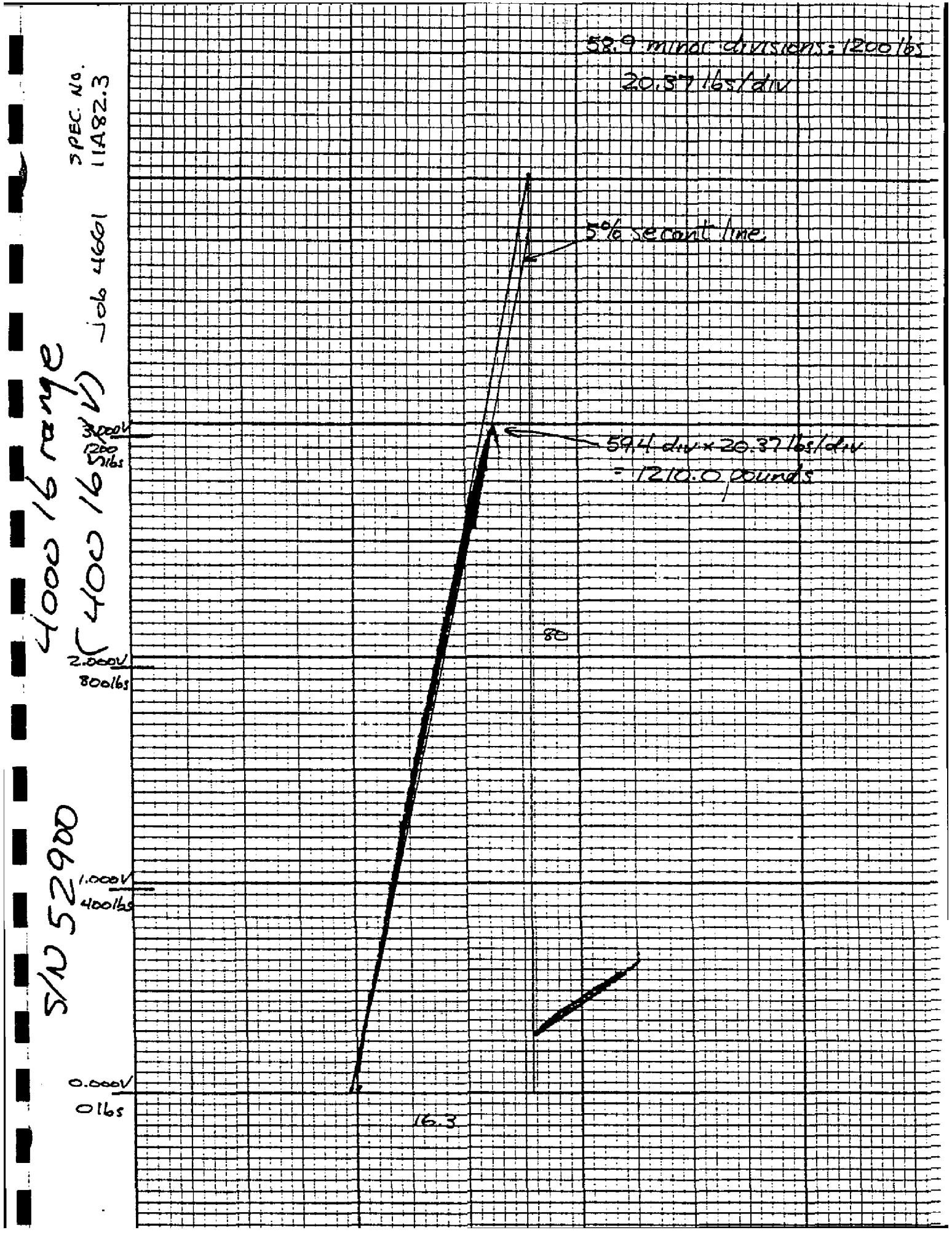
Index	Load (lbs)	Disp. (in)	Delta a (in)	CTOD (in)	K399 (ksi sqr[in])	K813	J813-81	J813-87 (in-lb/in^2)	J1152	Jmod
0	0	0.0000		0.0000	0.0	0.0	0.0	0.0	0.0	0.0
1	378	0.0025	0.0000	-.0000	7.4	6.8	4.3	4.6	4.6	4.6
2	400	0.0027	0.0004	-.0000	7.9	7.3	5.0	5.3	5.3	5.3
3	398	0.0027	0.0002	-.0000	7.8	7.3	5.0	5.3	5.3	5.3
4	400	0.0027	0.0002	-.0000	7.9	7.3	5.0	5.3	5.3	5.3
5	413	0.0027	0.0009	-.0000	8.2	7.3	5.0	5.3	5.3	5.3
6	523	0.0036	-.0003	0.0000	10.3	9.7	8.9	9.4	9.4	9.4
7	627	0.0044	-.0010	0.0001	12.3	11.8	13.1	13.9	13.8	13.8
8	734	0.0052	0.0015	0.0002	14.5	13.7	17.9	18.9	18.9	18.9
9	838	0.0060	0.0007	0.0002	16.5	15.8	23.7	25.0	25.0	25.0
10	934	0.0068	0.0012	0.0003	18.4	17.8	30.1	31.7	31.8	31.8
11	1030	0.0076	0.0010	0.0004	20.3	19.8	37.3	39.2	39.4	39.4
12	1129	0.0085	0.0029	0.0006	22.4	21.9	46.0	48.0	48.4	48.4
13	1224	0.0094	0.0032	0.0007	24.3	24.1	55.6	57.9	58.4	58.4
14	1313	0.0102	0.0036	0.0009	26.1	25.9	64.9	67.3	68.1	68.1
15	1387	0.0110	0.0042	0.0010	27.7	27.8	74.7	77.2	78.2	78.3
16	1436	0.0118	0.0085	0.0012	29.0	29.4	84.1	86.1	87.7	87.9
17	1403	0.0127	0.0203	0.0015	29.5	30.6	92.9	93.4	95.9	96.6
18	1383	0.0136	0.0264	0.0018	29.6	32.0	103.0	102.7	105.7	106.8
19	1365	0.0144	0.0329	0.0021	29.9	33.2	111.5	110.4	113.8	115.5
20	1354	0.0152	0.0385	0.0024	30.2	34.4	120.1	118.2	122.2	124.5
21	1363	0.0160	0.0424	0.0026	30.8	35.6	129.3	126.4	131.2	134.0
22	1373	0.0169	0.0456	0.0029	31.4	36.9	140.2	136.1	142.0	145.3
23	1355	0.0178	0.0510	0.0032	31.6	38.1	150.0	145.3	151.5	155.8
24	1344	0.0187	0.0558	0.0035	31.8	39.3	160.0	154.6	161.2	166.4
25	1303	0.0195	0.0585	0.0038	31.2	40.5	169.4	164.1	170.3	176.2
26	1299	0.0203	0.0617	0.0040	31.4	41.5	178.3	172.3	179.1	185.8
27	1286	0.0212	0.0655	0.0043	31.5	42.6	188.1	181.7	188.7	196.6
28	1260	0.0221	0.0685	0.0046	31.3	43.8	198.1	191.6	198.5	207.4
29	1240	0.0229	0.0710	0.0049	31.1	44.8	207.0	200.3	207.2	217.0
30	1232	0.0237	0.0729	0.0052	31.1	45.7	216.1	208.8	216.2	226.7
31	1215	0.0245	0.0775	0.0054	31.2	46.5	223.2	216.4	223.1	235.6
32	1147	0.0253	0.0801	0.0058	29.7	47.6	231.4	226.5	231.0	244.6
33	1147	0.0261	0.0836	0.0060	30.1	48.3	238.5	233.4	238.0	253.4
34	1062	0.0262	0.0851	0.0062	28.0	48.7	238.6	237.1	237.8	254.0
35	1063	0.0262	0.0846	0.0062	28.0	48.7	238.9	237.2	238.2	254.1
36	1074	0.0263	0.0847	0.0062	28.3	48.8	240.0	237.8	239.3	255.3
37	1073	0.0264	0.0848	0.0062	28.3	48.9	241.1	238.8	240.4	256.4
38	1073	0.0264	0.0847	0.0062	28.3	48.9	241.2	238.8	240.5	256.4


LOAD VS. DISPLACEMENT CURVE
2000
1600
1200
800
400
0
Load (lb)
11A82-1.PLT
Displacement (in)
0.000
0.010
0.020
0.030
0.040
0.050


FRACTURE TOUGHNESS R-CURVE
300
250
200
150
100
50
0
0.000
0.020
0.040
0.060
0.080
0.100
Jo (in-lb/in^2)
Δa (in)
Test ID 11A82-1
Initial b (in) 0.493
B net (in) 0.503
Flow stress (ksi) 47.2
Temp (deg F) 74
JQ (E813-87) 77
JQ (power) 77
E813-87 Analysis



20 X 20 PER INCH
SPEC. NO. 11A82.2
Load Cell
400 lb range
400 lbs/V
S/N 52900
Job 4661
58.9 minor divisions = 1200 lbs
20.37 lbs/div
5% secant line
3.000V
1200 lbs
56.2 div × 20.37 lbs/div
= 1144.8 pounds
2.000V
800 lbs
80
1.000V
400 lbs
0.000V
0 lbs
16.2


SPEC. NO. 11A82.3
Job 46001
4000 16 range
(400 16 V)
S/N 52900
3.000V
1200 lbs
2.000V
800 lbs
1.000V
400 lbs
0.000V
0 lbs
58.9 minor divisions: 1200 lbs
20.37 lbs/div
5% secant line
59.4 div x 20.37 lbs/div
= 1210.0 pounds
80
16.3