MASTER

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MASTER

Report GDCA -DBG-71-002

SHARP NOTCH TENSION FRACTURE
TOUGHNESS EVALUATION OF WELDED
6061-T6 ALUMINUM ALLOY SHEET
AT -423°F

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INTRODUCTION

A test program was initiated by General Dynamics Corporation, Convair Aerospace Division, to determine the sharp notch tension fracture toughness of welded 6061-T6 aluminum alloy sheet at -423° F. This program was funded by a contract from Aerojet Nuclear Systems Company (ANSC).

MATERIALS

A group of sixteen (16) welded 6061-T6 aluminum alloy sheet test specimens were submitted by ANSC for the program. The thickness at the weld bead was approximately 0.167-inch, while the base metal thickness was 0.0160-inch. These specimens were of the center notch type and conform to ANSC P/N 1138226-27-07, which is similar to the test specimen recommended in ASTM E338-68. The center notch was located in a weld bead which was transverse to the specimen length.

EXPERIMENTAL PROCEDURE

The test specimens were submitted with through-the-thickness notches in the center of the test section. It is recommended in ASTM E338 that the center notches have a high notch acuity and that this condition can easily be achieved by producing fatigue cracks at the tips of the center notches. Therefore, two Sonntag fatigue testing machines (SF-1U and SF-10U) were used to cyclically load the specimens in tension to produce the desired fatigue cracks. These machines operate at 1800 cycles per minute and a load ratio, R , of +0.1 was used. Precracking of a test specimen is shown in Figure 1.

Fatigue precracking was performed at room temperature and the loads used are based upon the yield strength (σ_{ys}) of the test material at room temperature. Since the yield strength of the welded 6061-T6 material was not available, the yield strength reported in the NERVA Data Book was used. A yield strength of 49 KSI and an allowable of 35 KSI is given in this reference. Cyclic loading was then started at a maximum tension load of 25% of the room temperature yield strength and continued for 50,000 to 100,000 cycles. If cracking did not initiate, then the maximum tension load was increased by increments of 5% for 50,000 to 100,000 cycles. When crack initiation occurred, the load was reduced to the previous value, but to not less than 25% of the room temperature yield strength. Crack growth was continued until a total crack length, as measured on the specimen surface, of 0.91 to 1.10-inch was obtained (see data presented in Table 1).

Difficulty was encountered with the precracking of most of the center notches. This difficulty was attributed to the: a) large radii at the notch tips, and b) short notch lengths. Three test specimens (Nos. 1, 2 and 11) failed in the grip ends at the spot welds which join the reinforcing plates to the specimen ends. The failures may have been premature and caused by the close proximity of the spot welds to the loading pin hole, and also the extremely deep electrode indentation at the spot welds.

Specimen No. 1 was subjected to more than one million cycles at different loads with insufficient crack growth. This specimen was then placed in a three-point bending fixture and cyclically loaded at various levels of maximum bending stresses. This mode of loading was used to avoid failure in the grip ends. At increments of 100,000 cycles, the specimen was turned since this bending fixture can be used only in a tension-tension manner of loading. The bending fatigue was continued for more than two million cycles with no crack growth. The specimen was again loaded in the tension-tension fixture, but failure occurred in the grip end.

The center notches of the remaining test specimens were increased in length and the notch tip radii were reduced by sawing with a fine jeweler's saw blade. An error in planning resulted in testing specimen No. 19 without fatigue cracks at the notch tips.

After precracking, the specimens were installed in a viewing cryostat (Figure 2) which is attached to a Tinius Olsen 60,000-pound Universal tensile machine. A double cantilever clip-in displacement gage, as shown in ASTM E399-70, was inserted in the center notch. The output of this gage is used to obtain a load versus displacement record on a Tinius Olsen strain gage converter unit. Since the standard integral or attachable knife edges as described in ASTM E399-70 were not available for the specimens supplied, the clip-in gage did not always remain in the notch during the entire test.

A machinist's six-inch scale was also attached with clips to the test specimens in a manner which allowed the observation of both the scale and the crack tips with two transits (see Figure 2). The cryostat was closed and the vent lines attached. Gaseous helium was used for purging the cryostat. The liquid hydrogen fill lines were then attached, and the cryostat was filled with liquid hydrogen. The level of liquid hydrogen is visible through the viewing port of the cryostat shown in Figure 2. The liquid hydrogen was allowed to boil off until the liquid level dropped to the vicinity of the center notch in the specimen.

Tensile loads not exceeding 100 KSI/min. were applied. During this time the crack tips were observed with the transits to detect any crack growth. Crack growth was not detected. In all tests, the crack opened until a typical Y-shaped plastic zone appeared at the crack tip prior to fracture.

After specimen fracture, the hydrogen was boiled off and the specimen was removed from the cryostat. The critical crack length ($2a$) was then measured on the fracture surface. The fracture surfaces were also examined to determine the fracture obliquity as required in ASTM E388. In some instances, the crack lengths determined with the transits were compared with the crack lengths measured on the fracture surfaces. Due to the curved crack fronts, the crack lengths measured on the fracture surfaces were slightly greater. Photographs of the fracture surfaces are shown in Figures 3 to 6.

RESULTS AND DISCUSSION

The plane stress critical stress intensity factor (K_C) was determined by using the procedure presented in Reference 1. The approach was necessary since the procedures given in ASTM E388 do not include recommendations for determining K_C .

The first step involved the calculation of the uncorrected plane stress critical intensity factor (K'_C) as follows:

$$K'_C = \sigma_G \sqrt{W \tan \frac{\pi a}{W}} \quad (1)$$

where σ_G = the maximum gross stress

W = specimen width

a = half the critical crack length measured on the fracture surface.

A plastic zone corrected critical crack length ($2a_c$) was determined as follows:

$$a_c = a + \frac{1}{2\pi} \left(\frac{K'_C}{\sigma_{ys}} \right)^2 \quad (2)$$

where σ_{ys} = yield strength of the material at -423°F .

Since tensile tests were not performed with the material tested, the σ_{ys} at -423°F was determined as follows:

$$\sigma_{ys}(-423) = F_{ty}(-423) \times \frac{\sigma_{ys}(\text{RT})}{F_{ty}(\text{RT})} \quad (3)$$

where F_{ty} = allowable or minimum yield strength at temperature
($F_{ty} = 35 \text{ KSI @ RT}$ and $46 \text{ KSI @ } -423^\circ\text{F}$, $\sigma_{ys} = 40 \text{ KSI @ RT}$; Reference NERVA Data Book)

The calculated value of $\sigma_{ys}(-423)$ is 52.6 KSI.

The value of K_C was calculated with the following equation:

$$K_C = \sigma_G \sqrt{W \tan \frac{\pi a_c}{W}} \quad (4)$$

The sharp notch strength (σ_N) was obtained by dividing the maximum load by the net section stress. The measured and calculated results of the fracture tests are presented in Table 2. The comments relating to fracture appearance conform to the recommendations in ASTM E338.

Values of K_C for 6061-T6 at -423°F could not be found in the literature, therefore, the values obtained in this program could not be compared with previous data.

REFERENCES

Witzell, W. E., "Fracture Data for Materials at Cryogenic Temperatures," AFML-TR-67-257, Nov. 1967.

Table 1

Fatigue Precracking of 6061-T6 Welded Specimens
(Room Temperature, R = +0.1)

Specimen No.	Area, Net Section, in. ²	Maximum Net Section Stress, KSI	Cycles	Remarks
1	0.360	10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	75,000	fractured at spot welds
2	0.360	10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	137,000	initial crack
3	0.360	12.0	33,000	fractured at spotwelds
		10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	14,000	initial crack
		12.0	198,000	0.92" crack length
		10.0	50,000	crack growth
4	0.360	10.0	464,000	no crack
		12.0	50,000	no crack
		14.0	297,000	no crack
5	0.347*	10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	704,000	1.05" crack length
6	0.341	10.0	194,000	1.00" crack length
7	0.341	10.0	58,000	no crack
		12.0	50,000	no crack
		14.0	35,000	initial crack
8	0.336	12.0	437,000	1.02" crack length
		10.0	308,000	crack growth
		10.0	50,000	no crack
10	0.346	12.0	70,000	initial crack
		10.0	1,104,000	crack growth
		10.0	50,000	no crack
11	0.338	12.0	41,000	initial crack
		10.0	1,233,000	no growth
		4.7**	168,000	no growth
		10.0**	1,283,000	no growth
		12.0**	384,000	no growth
		14.0**	315,000	no growth
		14.0	651,000	fractured at spot welds
		10.0	410,000	1.04" crack growth
		10.0	252,000	crack growth
12	0.336	10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	128,000	initial crack
13	0.360	12.0	262,000	1.02" crack length
15	0.336	10.0		
		12.0		
		14.0		

Table 1
(Continued)

<u>Specimen No.</u>	<u>Area, Net Section, in.²</u>	<u>Maximum Net Section Stress, KSI</u>	<u>Cycles</u>	<u>Remarks</u>
16	0.336	10.0	50,000	no crack
		12.0	13,000	initial crack
		10.0	510,000	crack growth
18	0.339	10.0	50,000	no crack
		12.0	50,000	no crack
		14.0	28,000	initial crack
		12.0	405,000	crack growth

* Net area changed because center notch was enlarged with a jeweler's saw blade.

** Cyclically loaded in three-point bend fixture with span equal to 2.5-inch. Load was based upon maximum bending stress.

Table 2

Fracture Toughness of Welded 6061-T6 Aluminum Alloy at -423°F

Specimen No.	Weld Metal Thickness, inch	2a, inch	Max. Tension Load, P, lbs.	σ_G , KSI	σ_N , KSI	K'_c , KSI $\sqrt{\text{in}}$	2a _c *, inch	K_c KSI $\sqrt{\text{in}}$	Fracture Appearance
1	Fractured in grip end during fatigue precracking								
2	Fractured in grip end during fatigue precracking								
3	0.1675	0.94	15,500	30.8	44.9	39.1	1.12	43.6	34% oblique
4	0.1675	0.88	14,250	28.4	40.2	34.7	1.02	37.8	predominantly oblique
5	0.1655	1.08	11,500	25.3	41.6	36.9	1.24	40.6	predominantly oblique
6	0.1692	1.00	15,200	29.9	44.8	39.3	1.18	43.7	flat
7	0.1665	1.02	15,000	30.0	45.5	40.0	1.20	44.3	flat
8	0.1664	0.99	15,500	31.1	46.4	40.6	1.18	45.4	40% oblique
10	0.1650	1.03	14,400	29.1	44.3	38.9	1.20	43.0	predominantly oblique
11.	Fractured in grip end during fatigue precracking								
12	0.1672	1.05	15,750	31.4	48.3	39.0	1.24	47.4	predominantly oblique
13	0.1696	0.93	16,600	32.7	47.3	41.3	1.13	46.3	flat
15	0.1672	1.03	13,650	27.2	41.4	36.4	1.18	39.9	predominantly oblique
16	0.1666	0.96	16,050	32.1	47.2	41.3	1.16	46.2	flat

Table 2

(Continued)

<u>Specimen No.</u>	<u>Weld Metal Thickness, inch</u>	<u>2a, inch</u>	<u>Max. Tension Load, P. lbs.</u>	<u>σ_G, KSI</u>	<u>σ_N, KSI</u>	<u>K'_c, KSI $\sqrt{\text{in}}$</u>	<u>$2a_c^*$, inch</u>	<u>K_c, KSI $\sqrt{\text{in}}$</u>	<u>Fracture Appearance</u>
18	0.1666	0.89	18,800	37.7	53.5	46.3	1.14	53.8	47% oblique
19	0.1683	0.88	18,200	36.0	51.0	43.9	1.10	50.3	predominantly oblique

∞ * $a_c = a + r_y$ ($\sigma_{ys} = 52.6 \text{ KSI @ } -423^\circ\text{F}$).

Figure 1. Fatigue Precracking of a Center Notch Test Specimen
(114632B)

Figure 2. Equipment Used to Test Fracture Toughness Specimens in Liquid Hydrogen (114631B)

Figure 3. Fracture Surfaces of Welded 6061-T6 Aluminum (Specimen Nos. 7, 13, and 12; Photo No. 115090B)

Figure 4. Fracture Surfaces of Welded 6061-T6 Aluminum (Specimen Nos. 10, 8, and 5; Photo No. 1150898B).

Figure 5. Fracture Surfaces of Welded 6061-T6 Aluminum (Specimen Nos. 19, 16, 15, and 18; Photo No. 115088B).

Figure 6. Fracture Surfaces of Welded 6061-T6 Aluminum (Specimen Nos. 4, 3, and 6; Photo No. 115087B).