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SPECIMEN SIZE CONSIDERATIONS IN FATIGUE-CRACK GROWTH RATE TESTING

Hanford Engineering Development Laboratory

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Hanford Engineering Development Laboratory

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L.A. James

December 1978

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Lee A. James

ABSTRACT

The effect of specimen size upon the fatigue-crack growth behavior of annealed AISI Type 304 stainless steel was studied at two stress ratios at an elevated temperature. The resulting data were examined in the light of the present ASTM size criterion (based upon monotonic yield strength) as well as a proposed criterion based upon the material flow strength. The flow stress criterion is considerably less restrictive than the present ASTM Criterion, and the results of this study indicate that the flow stress criterion is entirely appropriate for strain-hardening materials such as the austenitic stainless steels.

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SPECIMEN SIZE CONSIDERATIONS IN FATIGUE-CRACK GROWTH RATE TESTING (FF125/GRO)

I. INTRODUCTION

Linear-elastic fracture mechanics (LEFM) techniques presently offer the most generally applicable method for estimating the in-service extension of cracks and flaws in structural components. As the name implies, LEFM methods are valid only as long as there is a linear and elastic relationship between the loads applied to a cracked structure (or specimen), and the resulting displacements. There is, of course, a zone of plastically-deformed material in the immediate vicinity of the crack tip, but this is allowable as long as the plastic zone is relatively small compared to the other dimensions of the structure (or specimen). Hence, the small plastic zone is surrounded by a much larger region of elastically-loaded material, and the linear-elastic response is essentially preserved.

LEFM analyses of crack extension in structural components can only be as valid as the data that is input into them. Such crack growth rate data are usually obtained on specimens in the laboratory, and for reasons of economy (material, testing machine size, etc.) it is often desirable to have such specimens as small as possible. If, however, the specimens become too small, then there is the possibility that the crack tip plastic zone size will approach the other dimensions of the specimen, thereby invalidating the use of LEFM methods on that specimen.

In order to minimize the possibility of this occurring, as well as to standardize the other aspects of crack growth rate testing, the American Society for Testing and Materials (ASTM) has developed a tentative test method⁽¹⁾ for crack growth rate testing: E647-78T. Much of the background information and rationale leading to the development of

ASTM E647-78T may be found in Reference 2.

ASTM E647-78T limits the relative size of the plastic zone, and hence the specimen size, by limiting the minimum size of the remaining uncracked ligament ($W-a$), where W = the specimen width and a = the crack length (see Reference 1 for symbols and nomenclature pertaining to the ASTM Compact Specimen). It is essentially equivalent to restricting the plane stress monotonic plastic zone size ($2r_y$)

$$2r_y = \frac{1}{\pi} \left[\frac{K_{\max}}{\sigma_y} \right]^2 \quad [1]$$

to a fixed percentage of the remaining ligament ($K_{\max}$ = the maximum stress intensity factor, and σ_y = the monotonic yield strength). This is accomplished through the relationship:

$$(W-a) \geq \frac{4}{\pi} \left[\frac{K_{\max}}{\sigma_y} \right]^2 \quad [2]$$

Combining Equations [1] and [2] shows that the E647-78T size requirement limits the monotonic plastic zone to about 25 percent of the uncracked ligament.

While the size criterion of Equation [2] is probably appropriate for relatively high-strength materials which undergo little or no strain-hardening, there is evidence⁽²⁻⁴⁾ that it is unnecessarily restrictive (i.e., requires specimen sizes larger than necessary) for relatively low-strength materials that exhibit considerable strain-hardening (e.g., annealed austenitic stainless steels). It was suggested⁽³⁾ that a more appropriate size criterion for these strain hardening would be to replace the monotonic yield strength (σ_y) in Equation [2] with the flow stress (σ_f):

$$\sigma_f = \frac{\sigma_y + \sigma_u}{2} \quad [3]$$

where σ_u = the ultimate strength. References 2-4 present data which support the concept of a flow stress criterion for such materials.

It was, however, considered desirable to conduct additional tests to verify the validity of a remaining ligament criterion based upon the flow stress; particularly at elevated temperatures and at stress ratios ($R = K_{min}/K_{max}$) considerably higher than zero. The objective of the present study was, therefore, to conduct tests upon relatively large specimens of a strain-hardening material (which generally satisfied the criterion based upon monotonic yield strength) and compare the results with similar data from relatively small specimens of the same material (which generally violated the monotonic yield criterion).

II. EXPERIMENTAL PROCEDURE

The specimens used in this study were of the ASTM Compact Specimen design⁽¹⁾, and were constructed of annealed AISI Type 304 stainless steel. The material was furnished by the Westinghouse R&D Center, and was the same heat of Type 304 utilized in Reference 4.

Tensile tests were not conducted on this material at 550°F (288°C). They were, however, conducted at room temperature and reported in Reference 4:

$$\left. \begin{array}{l} \sigma_y = 39.0 \text{ ksi (269 MPa)} \\ \sigma_u = 84.0 \text{ ksi (579 MPa)} \\ \sigma_f = 61.5 \text{ ksi (424 MPa)} \end{array} \right\} \text{ monotonic}$$

$$\sigma_y = 61.0 \text{ ksi (421 MPa)} - \text{cyclic}$$

The present crack growth tests were conducted at 550°F (288°C), and the percentage reductions in room temperature properties at this temperature⁽⁶⁾ give:

$$\begin{aligned} \sigma_y &= (0.617) (39.0) = 24.0 \text{ ksi (165 MPa)} \\ \sigma_u &= (0.767) (84.0) = 64.4 \text{ ksi (444 MPa)} \end{aligned}$$

Therefore, using Equation [3], a flow stress of 44.2 ksi (305 MPa) is calculated for 550°F (288°C).

Two specimen sizes were employed in the testing: "1T" specimens with width $W = 2.0$ inch (50.8 mm) and thickness $B = 0.25$ inch (6.35 mm), and "4T" specimens with $W = 8.0$ inch (203 mm) and $B = 1.0$ inch (25.4 mm). The "4T" specimens were tested in such a way as to maximize the amount of data taken under conditions satisfying the monotonic yield strength criterion. The "1T" specimens, on the other hand, were tested in such a way that they essentially violated the monotonic criterion from the start of the test, while the data overlap with the "4T" specimens was maximized. Two stress ratios were studied: $R = 0.05$ and $R = 0.5$.

The specimens were tested on MTS feedback-controlled testing machines using load as the control parameter. A sinusoidal waveform at a cyclic frequency of 150 cpm (2.5 Hz) was used for all tests. Testing was conducted in air-circulating furnaces at 550°F (288°C). Temperatures were controlled to within 2°F (1.1°C) for "1T" specimens, and to within 4°F (2.2°C) for "4T" specimens. Crack lengths were determined periodically throughout each test on both sides of each specimen using a travelling microscope. (See the Appendix for crack length vs. cycles data for each specimen.) In general, all of the testing and data analysis procedures for ASTM E647-78T were adhered to.

The crack growth rates (da/dN) were calculated using the "secant method"⁽⁵⁾, and the stress intensity factor was obtained using the relationship of Equation [4].

$$K = \frac{P}{B\sqrt{W}} \left[\frac{2 + \alpha}{(1-\alpha)^{1.5}} \right] [0.886 + 4.64(\alpha) - 13.32(\alpha)^2 + 14.72(\alpha)^3 - 5.6(\alpha)^4] \quad [4]$$

where P = the applied load and α = the relative crack length ($\alpha = a/W$).

Although the stress intensity factor range (ΔK) is usually employed as the crack-driving parameter, it is felt⁽²⁾ that the maximum stress intensity factor ($K_{\max}$) is of greater importance in establishing size criteria than is ΔK . Therefore, the results of this study were displayed as logarithmic plots of da/dN as a function of $K_{\max}$.

III. RESULTS AND DISCUSSION

Tests were conducted at stress ratios of 0.05 and 0.5, and these results are plotted in Figures 1 and 2, respectively. Also plotted in these figures are the K -levels where each specimen size (either "1T" or "4T") fails either the criterion based upon the monotonic yield strength (Eq. [2]) or the criterion based upon the flow stress.

A number of observations may be made regarding the data shown in Figures 1 and 2. First, it is apparent that there is excellent agreement at both stress ratios between the data for the "1T" and "4T" specimens, regardless of whether the monotonic yield strength criterion is satisfied or not. In general, the data scatter is within the factor of two considered "normal" for intralaboratory tests on the same heat of material⁽⁵⁾. Data at both stress ratios are easily fitted by linear relationships between $\log (da/dN)$ and $\log (K_{\max})$. Linear regression analyses (units: inch/cycle and $\text{ksi}\sqrt{\text{in.}}$) of all data shown in Figures 1 and 2 give:

$$\left. \begin{array}{l} \frac{da}{dN} = 2.567 \times 10^{-12} (K_{\max})^{4.416} \\ \text{correlation coefficient} = 0.9865 \end{array} \right\} \begin{array}{l} \text{Spec. 1795 and 1797} \\ R = 0.05 \end{array}$$

$$\left. \begin{array}{l} \frac{da}{dN} = 1.494 \times 10^{-11} (K_{\max})^{3.354} \\ \text{correlation coefficient} = 0.9813 \end{array} \right\} \begin{array}{l} \text{Spec. 1796 and 1798} \\ R = 0.5 \end{array}$$

The relatively high correlation coefficients (unity indicates a "perfect" linear fit) give additional evidence of the similar response

Figure 1. Fatigue-crack growth behavior of "1T" and "4T" specimens of annealed Type 304 tested in air at 550°F (288°C) at a stress ratio $R = 0.05$. (Negative 7810910-4)

Figure 2. Fatigue-crack growth behavior of "1T" and "4T" specimens of annealed Type 304 tested in air at 550°F (288°C) at a stress ratio of $R = 0.5$. (Negative 7812994-1)

of the two specimen sizes. Similar observations regarding the equivalence of results between specimens of different sizes (the smaller of which do not meet the monotonic yield criterion) may be found in References 2-4.

One of the questions raised in Reference 2 was that a criterion such as the proposed flow stress criterion (which implicitly depends upon strain-hardening) might be appropriate for stress ratios close to zero (where stress reversals are large) and yet not be appropriate at higher stress ratios (where stress reversals are much smaller). This is because there are actually two plastic zones at the tip of a fatigue crack: a relatively large "monotonic yield zone" created during the tensile loading portion of each fatigue cycle, and a smaller "cyclic yield zone" created during the stress reversals occurring on the unloading portion of each cycle. As discussed in Reference 2, the cyclic zone can be considerably smaller than the monotonic zone in strain-hardening materials tested at relatively high stress ratios. Reference 2 pointed out the lack of data for different specimen sizes in strain-hardening materials tested at high stress ratios that could help resolve the question of the validity of the flow stress criterion under these conditions. The results shown in Figure 2 certainly lend support to the validity of the flow stress criterion, at least for annealed Type 304 stainless steel at stress ratios up to $R = 0.5$.

The "4T" specimens were instrumented with a clip gage that allowed measurement of the load-line displacements at the test temperature. The original intention was to measure the total load-line displacements in the manner suggested in Appendix B of E647-78T, thereby determining the crack length at which the total actual displacement (elastic plus plastic) exceeded some given percentage of the theoretical elastic displacement. However, it was found that the vibration during testing of the heavy braided metal clip gage leads (necessary for elevated temperature testing) caused the clip gage to constantly shift and reseal on the load-line knife edges. However, although it was not possible to obtain

total deflection versus crack length information as suggested in E647-78T, it was possible to obtain load versus load-line displacement information (at elevated temperature) at the completion of a given block of cycles. This was done for Specimen 1795 (tested at $R = 0.05$) at crack lengths of $\alpha = 0.6061$, 0.6961 , and 0.7228 , and for Specimen 1796 (tested at $R = 0.5$) at $\alpha = 0.6830$ and $\alpha = 0.7228$. These data are plotted in Figures 3-7, respectively.

Theoretical load-line displacements were calculated using the relationship⁽⁷⁾:

$$\frac{BEV}{P} = \left(\frac{1+\alpha}{1-\alpha}\right)^2 [2.16299 + 12.219(\alpha) - 20.065(\alpha)^2 - 0.9925(\alpha)^3 + 20.609(\alpha)^4 - 9.9314(\alpha)^5] \quad [5]$$

where B = thickness, E = Young's Modulus, V = Load-line displacement, P = load, and $\alpha = a/W$. A value of $E = 25.75 \times 10^6$ psi (177.5 GPa) for Type 304 at 550°F (288°C) was obtained from the Nuclear Systems Materials Handbook.

Load-displacement readings were made on a point-to-point basis, and the series of readings fitted with a linear regression analysis; the inverse of the slope being the measured compliance at that value of α . It will be noted in Figures 3-7 that, in general, the linearity between loads and displacements is excellent, as indicated by the values of the correlation coefficients very close to unity. Comparisons are made to the theoretical compliances calculated using Equation [5]. In general, the agreement between theoretical and measured compliances is good, although there is a tendency for the errors to increase with decreasing values of α . This may be due, in part, to one or more of the following reasons:

- a) Since the original intent was to measure total load-line displacements, the clip gage was calibrated for much larger displacements than shown in Figures 3-7. Hence, accuracy might be slightly reduced at lower values of α .
- b) The assumed value of E could be incorrect, which would affect

Figure 3. Load-displacement behavior of Specimen 1795 at $\alpha = 0.6061$. (Negative 7810910-1)

Figure 4. Load-displacement behavior of Specimen 1795 at $\alpha = 0.6961$. (Negative 7810910-3)

Figure 5. Load-displacement behavior of Specimen 1795 at $\alpha = 0.7228$. (Negative 7810910-2)

Figure 6. Load-line displacement behavior of Specimen 1796 at $\alpha = 0.6830$. (Negative P05152-3)

Figure 7. Load-line displacement behavior of Specimen 1796 at $\alpha = 0.7228$. (Negative P05152-2)

compliance calculations at all values of α . c) Theoretical compliances were based on crack lengths measured on the surfaces of the specimens, and crack "tunnelling" (which would increase with increasing α) is therefore not accounted for in the theoretical calculations. Nevertheless, the agreement between measured and theoretical compliances is reasonable, and linear relationships between load and displacement are observed throughout each test.

"Before and after" photographs of the "1T" and "4T" specimens tested at $R = 0.05$ are shown in Figures 8 and 9. Although not shown, the specimens tested at $R = 0.5$ are quite similar in appearance. The most striking features of these photographs are the extensive crack-tip plasticity and the permanent opening displacement along the crack line. These photographs were taken at the completion of testing, and it must be remembered that by this time both specimens had failed to satisfy the flow stress criterion.

A person viewing specimens in such a condition would justifiably suggest that they could not be analyzed with LEFM methods. Yet at crack lengths only slightly less than those pictured (see the Appendix for tabular data), these specimens still satisfied the flow stress criterion and (in the case of the "1T" specimens) were producing results in excellent agreement with "valid" data satisfying the monotonic yield criterion. In addition, the crack-tip plasticity and permanent opening displacements were not visibly different from those pictured in Figures 8 and 9.

Hence, we are faced with a paradox: LEFM methods apparently continue to describe cracking behavior (witness the excellent agreement in da/dN vs. K_{max} curves and the agreement between theoretical and measured compliances) on specimens where visual observation (and some analytical treatments) indicates they should not. The basic concepts of LEFM can be rigorously derived from the theory of elasticity, but it should be remembered that no rigorous derivation exists for the relationship

Figure 8. "Before" and "After" photographs of "1T" Specimens (Specimen 1797 at $\alpha = 0.5658$)
(Negative 7810630-1)

Figure 9. "Before" and "After" photographs of "4T" Specimens (Specimen 1795 at $\alpha = 0.7228$).
(Negative 7810630-2)

between da/dN and K : it remains an empirical observation. The results of this study suggest that this empirical observation perhaps has a wider range of applicability than suggested by rigid adherence to linear-elastic requirements.

Finally, it will be noted in Figures 1 and 2 that some of the data points at the lower values of K_{max} are closed, rather than open symbols. These represent data that were taken prior to the attainment of the minimum precrack specified by ASTM E647-78T. This requirement states that the minimum precrack length from the machined notch shall be one-tenth the specimen thickness (B) or the height (h) of the notch, whichever is the greater. For the "1T" specimens used in this study $0.1B = 0.025$ inch and $h = 0.093$ inch, and for the "4T" specimens $0.1B = 0.10$ inch and $h = 0.375$ inch. Hence, the " h " dimension governs in both cases. The closed data points in Figures 1 and 2 suggest that this requirement on minimum precrack length might be somewhat restrictive. Little or no difference in behavior is noted between open and closed data points in the same general vicinity. Similar observations were made⁽⁸⁾ concerning the minimum precrack requirements during the testing of standard ASTM Compact Specimens and the proposed Round Compact Specimens at room and elevated temperatures in precipitation heat-treated Alloy 718.

The minimum precrack length requirement is, of course, intended to minimize the possibility of an influence of the machined notch, since the effect of the notch is not accounted for in Equation [4]. Some guidance regarding the effect of notches on the K -solutions for cracks may be found in Reference 9. Cracks emanating from rectangular notches (probably more severe in their interaction with the crack than the vee-shaped notches used in Compact Specimens) in an infinite sheet were studied. Although the infinite sheet represents a different geometry than the Compact Specimen, Reference 9 should nevertheless allow an upper-bound estimate of the interaction. These results show that when the precrack length is greater than about $h/2$, the interaction factor is approximately

1.01, while at a length of h (corresponding to the present E647-78T requirement) the interaction factor is approximately 1.005. Since both of these factors are smaller than many of the other uncertainties involved in fatigue-crack growth testing, and since the rectangular notch of Reference 9 is probably more severe than notches allowed on Compact Specimens, and because of the results shown in Figures 1 and 2 and also in Reference 8, it does not seem unreasonable to relax the minimum precrack length requirements of E647-78T.

IV. SUMMARY AND CONCLUSIONS

The effect of specimen size upon the fatigue-crack growth behavior of annealed AISI Type 304 stainless steel (a material exhibiting considerable strain-hardening behavior) was studied at two stress ratios at an elevated temperature. The results may be summarized as follows:

- "1T" and "4T" Compact Specimens have been tested at 550°F (288°C) at stress ratios of 0.05 and 0.5. The results show essentially equivalent behavior over the entire range of data overlap, regardless of whether the remaining ligament criterion of ASTM E647-78T is satisfied or not. The results also support a remaining ligament criterion based upon flow stress for strain-hardening materials such as austenitic stainless steels; the flow stress criterion is considerably less restrictive than that of E647-78T.
- Load-line displacement measurements were made on the two "4T" specimens at the test temperature of 550°F (288°C). Linear relationships between loads and displacements, plus excellent agreement between theoretical and measured compliances were obtained, even at very long crack lengths where the flow stress criterion was violated.
- Limited results suggest that the E647-78T criterion for minimum precrack length from the machined notch could be relaxed somewhat, thereby permitting slightly more data to be taken at shorter crack lengths.

V. REFERENCES

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APPENDIX

TABULAR CRACK GROWTH DATA

TABLE A1
CRACK GROWTH DATA FOR SPECIMEN 1797

SPECIMEN NO.: 1797
 MATERIAL: ANNEALED TYPE 304 S.S (T-L ORIENTATION)
 TEST TEMPERATURE: 550°F (288°C)
 CYCLIC FREQUENCY: 150 cpm (2.5 Hz)
 MAXIMUM LOAD: 1200 lb (5.34 kN)
 STRESS RATIO: R = 0.05
 SPECIMEN WIDTH: W = 1.9989 in. (50.77 mm)
 SPECIMEN THICKNESS: B = 0.2516 in. (6.39 mm)
 SPECIMEN DESIGN: ASTM COMPACT SPECIMEN

CYCLES	CRACK LENGTH (inch)		da/dN (inch/cycle)	K _{max} (ksi√in)	
	SIDE "A"	SIDE "B"			
0	0.7244	0.7467			
			2.650 x 10 ⁻⁶	22.78	
5,000	0.7370	0.7606	2.425 x 10 ⁻⁶	23.34	Notes 1&2
15,000	0.7635	0.7826	2.830 x 10 ⁻⁶	23.93	
20,000	0.7791	0.7953	3.714 x 10 ⁻⁶	24.57	
27,000	0.8068	0.8196	2.771 x 10 ⁻⁶	25.33	
34,000	0.8212	0.8440	5.121 x 10 ⁻⁶	26.29	
41,000	0.8666	0.8703	5.563 x 10 ⁻⁶	27.36	
45,000	0.8874	0.8940	7.141 x 10 ⁻⁶	28.23	
48,200	0.9078	0.9193	5.442 x 10 ⁻⁶	28.99	
50,800	0.9271	0.9283	1.065 x 10 ⁻⁵	29.87	
53,400	0.9611	0.9497	1.239 x 10 ⁻⁵	30.99	
55,200	0.9850	0.9704	1.811 x 10 ⁻⁵	32.53	
57,500	1.0251	1.0136	2.089 x 10 ⁻⁵	34.11	
58,400	1.0433	1.0330	1.986 x 10 ⁻⁵	35.01	
59,100	1.0597	1.0444	2.686 x 10 ⁻⁵	35.96	Note 3
59,800	1.0755	1.0662	3.367 x 10 ⁻⁵	37.15	
60,400	1.1031	1.0790	3.060 x 10 ⁻⁵	38.29	
60,900	1.1107	1.1020	4.940 x 10 ⁻⁵	39.65	
61,400	1.1384	1.1237			

Note 1 - Data taken prior to the attainment of the minimum precrack length allowed by E647-78T: 0.093 inch for Specimen 1797. All precracking done at the normal maximum test load: 1200 lb.

Note 2 - All data below K_{max} = 24.10 ksi√in satisfies remaining ligament criterion based on the monotonic yield strength.

Note 3 - All data below K_{max} = 37.68 ksi√in satisfies remaining ligament criterion based on the flow stress.

TABLE A2
CRACK GROWTH DATA FOR SPECIMEN 1795

SPECIMEN NO.: 1795
 MATERIAL: ANNEALED TYPE 304 S.S. (T-L ORIENTATION)
 TEST TEMPERATURE: 550°F (288°C)
 CYCLIC FREQUENCY: 150 cpm (2.5 Hz)
 MAXIMUM LOAD: 6900 lb (30.69 kN)
 STRESS RATIO: R = 0.05
 SPECIMEN WIDTH: W = 8.0007 in. (203.2 mm)
 SPECIMEN THICKNESS: B = 0.9992 in. (25.38 mm)
 SPECIMEN DESIGN: ASTM COMPACT SPECIMEN

CYCLES	CRACK LENGTH (inch)		da/dN (inch/cycle)	K _{max} (ksi√in)	
	SIDE "A"	SIDE "B"			
0	3.1384	3.1085			
95,000	3.2244	3.2071	9.716 x 10 ⁻⁷	17.59	
155,000	3.2910	3.2733	1.098 x 10 ⁻⁶	18.06	
209,800	3.3459	3.3422	1.138 x 10 ⁻⁶	18.45	Note 1 ↑
295,000	3.4529	3.4384	1.193 x 10 ⁻⁶	18.96	
380,000	3.5760	3.5684	1.489 x 10 ⁻⁶	19.72	
435,000	3.6603	3.6481	1.519 x 10 ⁻⁶	20.45	
491,500	3.7509	3.7558	1.755 x 10 ⁻⁶	21.12	
577,000	3.9126	3.9214	1.914 x 10 ⁻⁶	22.16	
620,000	4.0197	4.0327	2.540 x 10 ⁻⁶	23.32	
660,000	4.1233	4.1428	2.671 x 10 ⁻⁶	24.32	
704,660	4.2532	4.2091	2.197 x 10 ⁻⁶	25.35	
758,400	4.5395	4.5313	5.662 x 10 ⁻⁶	27.54	
783,400	4.8255	4.8144	1.138 x 10 ⁻⁵	31.42	
789,400	4.8781	4.8634	8.467 x 10 ⁻⁶	34.08	
796,400	4.9352	4.9631	1.120 x 10 ⁻⁵	35.21	
801,400	4.9851	4.9700	See Note 2		Note 3 ↑
806,400	5.0803	5.0694	1.946 x 10 ⁻⁵	37.39	
809,900	5.1876	5.1731	3.014 x 10 ⁻⁵	39.51	
811,400	5.2382	5.2259	3.447 x 10 ⁻⁵	41.28	
812,800	5.3012	5.2847	4.350 x 10 ⁻⁵	42.65	
814,100	5.3550	5.3429	4.308 x 10 ⁻⁵	44.14	
815,300	5.4283	5.4149	6.054 x 10 ⁻⁵	45.87	
816,300	5.5223	5.4932	8.615 x 10 ⁻⁵	48.17	
			1.023 x 10 ⁻⁴	50.49	

TABLE A2 (Continued)

CYCLES	CRACK LENGTH (inch)		da/dN (inch/cycle)	K _{max} (ksi√in)	
	SIDE "A"	SIDE "B"			
816,900	5.5802	5.5581	8.275 x 10 ⁻⁵	52.11	
817,300	5.6133	5.5912	7.438 x 10 ⁻⁵	53.20	
817,700	5.6464	5.6176	1.289 x 10 ⁻⁴	54.69	
818,100	5.6980	5.6691	1.250 x 10 ⁻⁴	56.63	Note 4
818,500	5.7438	5.7233	1.238 x 10 ⁻⁴	58.65
818,900	5.7926	5.7735			

Note 1 - Data taken prior to the attainment of the minimum precrack length allowed by E647-78T: 0.375 inch for specimen 1795. All precracking done at the normal maximum test load: 6900 lb.

Note 2 - Load amplitude dropped off during this increment. Therefore data for this increment not considered valid.

Note 3 - All data below K_{max} = 37.68 ksi√in satisfies remaining ligament criterion based upon the monotonic yield strength.

Note 4 - All data below K_{max} = 59.09 ksi√in satisfies remaining ligament criterion based on the flow stress.

TABLE A3
CRACK GROWTH DATA FOR SPECIMEN 1798

SPECIMEN NO.: 1798
MATERIAL: ANNEALED TYPE 304 S.S. (T-L ORIENTATION)
TEST TEMPERATURE: 550°F (288°C)
CYCLIC FREQUENCY: 150 cpm (2.5 Hz)
MAXIMUM LOAD: 1170 lb (5.20 kN)
STRESS RATIO: $R = 0.5$
SPECIMEN WIDTH: $W = 1.9989$ in. (50.77 mm)
SPECIMEN THICKNESS: $B = 0.2522$ in. (6.41 mm)
SPECIMEN DESIGN: ASTM COMPACT SPECIMEN

CYCLES	CRACK LENGTH (inch) SIDE "A"	CRACK LENGTH (inch) SIDE "B"	da/dN (inch/cycle)	K_{max} (ksi $\sqrt{in}$)	
0	0.7178	0.7362			
			5.763×10^{-7}	22.05	Note 1
40,000	0.7421	0.7580	4.600×10^{-7}	22.65	▲
80,000	0.7584	0.7785	5.663×10^{-7}	23.27	Note 2
120,000	0.7824	0.7998			▲
			7.613×10^{-7}	24.10	
160,000	0.8058	0.8373	5.050×10^{-7}	24.82	
190,000	0.8277	0.8457	7.417×10^{-7}	25.47	
220,000	0.8531	0.8648	8.233×10^{-7}	26.31	
250,000	0.8846	0.8827	9.317×10^{-7}	27.29	
280,000	0.9032	0.9200	1.188×10^{-6}	28.43	
305,000	0.9327	0.9499	1.568×10^{-6}	29.73	
325,000	0.9679	0.9774	9.818×10^{-7}	30.68	
336,000	0.9800	0.9869	1.091×10^{-6}	31.21	
347,000	0.9899	1.0010	9.636×10^{-7}	31.76	
358,000	0.9976	1.0145	2.682×10^{-6}	32.77	
369,000	1.0367	1.0344	1.528×10^{-6}	33.91	
378,000	1.0484	1.0502	2.483×10^{-6}	34.92	
387,000	1.0705	1.0728	3.038×10^{-6}	36.31	Note 3
395,000	1.0949	1.0970			▲
			2.793×10^{-6}	37.70	
402,000	1.1127	1.1183			

Note 1 - Data taken prior to the attainment of the minimum precrack length allowed by E647-78T: 0.093 inch for Specimen 1798. All precracking done at the normal maximum test load: 1170 lb.

Note 2 - All data below $K_{max} = 23.45$ ksi $\sqrt{in}$ satisfies remaining ligament criterion based upon the monotonic yield strength.

Note 3 - All data below $K_{max} = 37.16$ ksi $\sqrt{in}$ satisfies remaining ligament criterion based upon the flow stress.

TABLE A4
CRACK GROWTH DATA FOR SPECIMEN 1796

SPECIMEN NO.: 1796
 MATERIAL: ANNEALED TYPE 304 S.S. (T-L ORIENTATION)
 TEST TEMPERATURE: 550°F (288°C)
 CYCLIC FREQUENCY: 150 cpm (2.5 Hz)
 MAXIMUM LOAD: 7500 lb. (33.26 kN)
 STRESS RATIO: R = 0.5
 SPECIMEN WIDTH: W = 7.9993 in. (203.2 mm)
 SPECIMEN THICKNESS: B = 0.9997 in. (25.39 mm)
 SPECIMEN DESIGN: ASTM COMPACT SPECIMEN

CYCLES	CRACK LENGTH (inch) SIDE "A"	CRACK LENGTH (inch) SIDE "B"	da/dN (inch/cycle)	K _{max} (ksi√in)	
0	3.1701	3.1555			
213,000	3.2749	3.2539	4.770 x 10 ⁻⁷	19.40	Note 1 ↑
430,610	3.3764	3.3336	4.163 x 10 ⁻⁷	20.03	
650,000	3.4959	3.4630	5.673 x 10 ⁻⁷	20.77	
870,000	3.6251	3.5735	5.448 x 10 ⁻⁷	21.67	
1,120,030	3.7746	3.7029	5.577 x 10 ⁻⁷	22.68	
1,320,060	3.9106	3.8446	6.941 x 10 ⁻⁷	23.85	
1,490,060	4.0297	3.9710	7.221 x 10 ⁻⁷	25.04	
1,546,000	4.0825	4.0012	7.419 x 10 ⁻⁷	25.84	
1,692,000	4.2091	4.1417	9.147 x 10 ⁻⁷	26.74	
1,755,000	4.2753	4.1970	9.643 x 10 ⁻⁷	27.81	
1,805,000	4.3119	4.2394	7.900 x 10 ⁻⁷	28.38	
1,930,000	4.4569	4.3858	1.166 x 10 ⁻⁶	29.50	
2,040,000	4.6116	4.5589	1.490 x 10 ⁻⁶	31.55	
2,100,000	4.7095	4.6380	1.475 x 10 ⁻⁶	33.40	Note 2 ↑
2,162,000	4.8366	4.7793	2.165 x 10 ⁻⁶	35.21	
2,222,000	4.9853	4.9303	2.498 x 10 ⁻⁶	37.75	
2,252,000	5.1041	5.0435	3.867 x 10 ⁻⁶	40.44	
2,267,000	5.1758	5.1191	4.910 x 10 ⁻⁶	42.56	
2,280,000	5.2316	5.1583	3.654 x 10 ⁻⁶	44.02	
			4.854 x 10 ⁻⁶	45.36	

TABLE A4 (Continued)

CYCLES	CRACK LENGTH (inch)		da/dN (inch/cycle)	K_{max} (ksi $\sqrt{in}$)	
	SIDE "A"	SIDE "B"			
2,292,000	5.2831	5.2233	6.640 x 10 ⁻⁶	47.03	
2,302,000	5.3473	5.2919	8.570 x 10 ⁻⁶	49.20	
2,312,000	5.4234	5.3872	8.350 x 10 ⁻⁶	51.42	
2,319,000	5.4847	5.4428	1.156 x 10 ⁻⁵	53.54	
2,325,000	5.5467	5.5195	1.118 x 10 ⁻⁵	55.74	Note 3
2,330,000	5.6033	5.5747	1.281 x 10 ⁻⁵	58.01	
2,335,000	5.6595	5.6466	1.579 x 10 ⁻⁵	60.56	
2,339,000	5.7239	5.7085	2.200 x 10 ⁻⁵	63.38	
2,342,000	5.7880	5.7764			

Note 1 - Data taken prior to the attainment of the minimum precrack length allowed by E647-78T: 0.375 inch for Specimen 1796. All precracking done at the normal maximum test load: 7500 lb.

Note 2 - All data below $K_{max} = 37.08 \text{ ksi}\sqrt{in}$ satisfies remaining ligament criterion based upon the monotonic yield strength.

Note 3 - All data below $K_{max} = 59.70 \text{ ksi}\sqrt{in}$ satisfies remaining ligament criterion based upon the flow stress.

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