MASTER

AN EVALUATION OF THE ROUND COMPACT SPECIMEN
FOR FATIGUE-CRACK GROWTH RATE TESTING

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AN EVALUATION OF THE ROUND COMPACT SPECIMEN
FOR FATIGUE-CRACK GROWTH RATE TESTING

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ABSTRACT

A proposed round compact specimen was evaluated for its suitability for fatigue-crack growth rate testing. The results were compared to results from standard compact specimens (per ASTM E647-78T), and the two specimens were found to yield equivalent results. A number of K-solutions have also been proposed for the round compact specimens, and these are reviewed. The agreement between the various solutions was quite good, and the Newman Equation was used to evaluate the present results.

AN EVALUATION OF THE ROUND COMPACT SPECIMEN FOR FATIGUE-CRACK GROWTH RATE TESTING

INTRODUCTION

Fatigue-crack growth tests commonly utilize the ASTM Compact Specimen which has been standardized in ASTM E647-78T. This specimen offers many desirable features: it has a well-characterized K-solution, offers a wide range of K-levels within a single specimen at a given load, is conservative of material, has a relatively high compliance, and requires relatively low loads to achieve a given K-level. However, perhaps the biggest disadvantage of the standard Compact Specimen (CS) is its relatively high cost. Since fracture mechanics tests are sometimes required on materials with a circular cross-section (e.g., round bar stock, sintered products, etc.), a round version of the Compact Specimen would have attractive cost-saving features, and indeed several such specimens have been proposed and utilized.⁽¹⁻⁶⁾ ASTM Committee E-24 (Fracture Testing of Metals) is currently considering round Compact Specimens for standardization. Because most of the previous studies have been aimed at fracture toughness testing applications, the present study was undertaken to evaluate the Round Compact Specimen (RCS) design for fatigue-crack growth rate testing.

STRESS INTENSITY FACTOR SOLUTIONS

A requirement for any specimen design to be considered as a laboratory standard is an accurate K-solution over a wide range of crack lengths. A number of K-solutions for RCS designs have been proposed^(1,2,6,7,9,10), and they will be briefly reviewed and compared herein.

Feddern and Macherauch,⁽¹⁾ conducted compliance tests on Round Compact Specimens (see Figure 1 and the appendix for definitions) and derived the relationship given in Equation [1]. This relationship was proposed for the range $0.3 < \alpha < 0.7$.

$$K = \frac{P\sqrt{a}}{BW} [29.6 - 162\alpha + 492.6\alpha^2 - 663.4\alpha^3 + 405.6\alpha^4]^* \quad [1]$$

Mowbray and Andrews⁽²⁾ conducted compliance tests as well as two analytical procedures (finite element and J-integral) to derive K-solutions. The

expressions from the three methods all gave similar results, but they considered the finite element results to be the most accurate. Their relationships for K and load-line displacement are given in Equations [2] and [3], respectively, for the range $0.475 < \alpha < 0.825$.

$$K = \frac{P}{B\sqrt{W}} \exp [-8.51 + 56.67\alpha - 112.01\alpha^2 + 98.18\alpha^3 - 28.47\alpha^4] \quad [2]$$

$$\delta = \frac{P}{EB} \exp [11.77 - 65.63\alpha + 175.61\alpha^2 - 194.99\alpha^3 + 82.94\alpha^4] \quad [3]$$

Gross,⁽⁶⁾ using a boundary collocation technique, derived the relationship of Equation [4], where

$$K = \Gamma (\sigma_p + \sigma_m) \sqrt{A_t(1 - A_t/R_o)} \quad [4]$$

Γ , σ_p , σ_m , A_t , and R_o are defined in Ref. 6. Equation [4] is valid over the range $0.533 < \alpha < 0.80$. In a later paper,⁽⁷⁾ Gross extended his collocation solution for K to cover the range $0.133 < \alpha < 1.0$. Crack surface displacements have also been determined by Gross⁽⁸⁾ over the range $0.2 < \alpha < 0.933$.

Cull and Starrett⁽⁴⁾ conducted compliance experiments on an RCS and, although they did not derive values of K from these compliances, their plots of 2BEC versus a/W can be used to derive K using the expressions of Equation [5] for the range $0.3 < \alpha < 0.6$.

$$\left. \begin{aligned} \frac{d(2BEC)}{d(a/W)} &= 2BEW \left[\frac{dC}{da} \right] \\ G &= \frac{p^2}{2B} \frac{\partial C}{\partial a} \\ K &= \sqrt{GE} \end{aligned} \right\} \quad [5]$$

Underwood and Kendall⁽⁹⁾ have developed a C-shaped specimen for fracture mechanics testing. Although it differs from the RCS shown in Figure 1, in the limit the C-Specimen approaches the RCS as the inner radius shrinks to zero. Therefore, the equation for the C-Specimen can be used to estimate K in the RCS over the relatively narrow range $0.633 < \alpha < 0.7$, if the inner radius is taken to be zero.

Gregory,⁽¹⁰⁾ using an asymptotic analysis, developed the expression of Equation [6], valid over the range $0.5 < \alpha < 0.8$, where $b = W-a$.

$$K = \frac{P}{B\sqrt{W}} \left[\frac{2}{\left(\frac{D}{W}\right)\left(\frac{D}{W} - \frac{b}{W}\right)} \right]^{1/2} \left[\frac{\frac{D}{W} - \frac{b}{W}}{0.3557 \left(\frac{b}{W}\right)^{1.5}} + \frac{2 - \frac{D}{W}}{0.9665 \left(\frac{b}{W}\right)^{0.5}} \right] \quad [6]$$

Finally, Dr. James C. Newman, Jr. of the NASA Langley Research Center has used boundary collocation methods to derive an expression for the stress intensity factor of the RCS that is valid over a wide range of α : $0.25 \leq \alpha < 1.0$. This relationship, given in Equation [7], is considered the most accurate over this wide range of α , and is the equation used to calculate the present results. Equation [7] is likely the one to be adopted by ASTM Committee E-24.

$$K = \frac{P}{B\sqrt{W}} \left[\frac{2+\alpha}{(1-\alpha)^{1.5}} \right] [0.76 + 4.8\alpha - 11.58\alpha^2 + .11.43\alpha^3 - 4.08\alpha^4] \quad [7]$$

It is interesting to compare the various relationships for K, but in order to do so they must be expressed in a common manner.* A convenient way of comparing the results is through the use of a non-dimensional geometry factor, Y, defined in Equation [8]. Values of Y for the various

$$K = \frac{P}{B\sqrt{W}} Y \quad [8]$$

K-solutions are plotted in Figure 2 as a function of α , and it is seen that in general the agreement is quite good. Also plotted is the solution⁽¹⁶⁾ for the standard Compact Specimen as given by Equation [9]. It will be noted in Figure 2 that Equations [7] and [9] give reasonably similar results, and the higher values of Y associated with the RCS at large values of α are undoubtedly related to the removal of the material in the corners of the specimen. Figure 2 also shows that a larger range of Y (and hence K) is possible for an RCS than for a standard CS with the same width W. Hence, at least in theory, it may be possible to get slightly more fatigue-crack growth rate data from an RCS.

$$K = \frac{P}{B\sqrt{W}} \left[\frac{2+\alpha}{(1-\alpha)^{1.5}} \right] [0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4] \quad [9]$$

EXPERIMENTAL PROCEDURE

The material used to evaluate the RCS in this study was Alloy 718, a precipitation-hardenable nickel-base alloy. The chemical composition of this material is given in Table II. All specimens (with the exception of Specimen

*The geometries utilized by the various investigators are summarized in Table I.

1907) were obtained from a piece of 76.2 mm (3 in.) diameter bar stock. Specimen 1907 was machined from a 50.8 mm (2 in.) diameter bar from a different heat of material. Following machining, the specimens were given a precipitation heat treatment consisting of:

Solution anneal 1 hour at 1093°C (2000°F), cool to 718°C (1325°F) at 56°C/hour (100°F/hour), age 4 hours at 718°C (1325°F), cool to 621°C (1150°F) at 56°C/hour (100°F/hour), age 16 hours at 721°C (1150°F), air cool.

Tensile tests were not performed on this material, but the average room temperature hardness in the heat-treated condition was $R_C = 41.7$. The results of tensile tests on another heat of Alloy 718 given the same heat-treatment (resulting in $R_C = 41.4$) may be found in Ref. 11.

Two types of specimens were employed in this study: standard Compact Specimens (per ASTM E647-78T) with nominal width and thickness dimensions of 38.1 mm (1.50 in.) and 8.89 mm (0.35 in.), respectively, and round Compact Specimens with nominal width, diameter and thickness dimensions of 51.2 mm (2.25 in.), 76.2 mm (3.00 in.) and 8.89 mm (0.35 in.), respectively. Specimen 1907 had W and B dimensions of 37.6 mm (1.48 in.) and 7.62 mm (0.30 in.), respectively. All specimens were in the C-R orientation per ASTM E399-78.

The specimens were fatigue cycled on a feedback-controlled electrohydraulic testing machine using load as the control parameter. Tests were conducted in an air environment at room temperature and at 538°C (1000°F). Sinusoidal waveforms were employed at frequencies of 600 cpm and 40 cpm for the tests at room temperature and 538°C, respectively. The stress ratio ($R = K_{min}/K_{max}$) was 0.05 for all tests. The test parameters are summarized in Table III.

Crack lengths were determined periodically throughout each test using a traveling microscope. Fatigue-crack growth rates (da/dN) were calculated using the "secant method",⁽¹²⁾ and the corresponding stress intensity factors (K) were calculated using Equations [7] or [9], as appropriate. The results were displayed as plots of $\log(da/dN)$ versus $\log(\Delta K)$, where ΔK is the stress intensity factor range ($K_{max} - K_{min}$).

A few of the data points were "not valid" according to the recently adopted ASTM method for fatigue-crack growth rate testing, E647-78T. These data were plotted as closed symbols. At low values of ΔK , a few data points were obtained for crack extensions less than 2.5 mm (0.10 in.) from the

machined notch. At high values of ΔK , a few data points violated the criterion for remaining uncracked ligament size:

$$(W - a) \geq \frac{4}{\pi} \left(\frac{K_{\max}}{\sigma_y} \right)^2 \quad [9]$$

where σ_y is the 0.2% offset monotonic yield strength.* Although these data easily satisfied a less restrictive criterion based on flow strength rather than yield strength,⁽¹³⁾ they are nevertheless displayed herein as "invalid".

RESULTS AND DISCUSSION

The results of the crack growth tests conducted at room temperature and 538°C (1000°F) are shown in Figures 3 and 4, respectively. At both test temperatures the two specimen designs appear to give equivalent results. The two Round Compact Specimens tested at each temperature had test loads differing by 50%, thereby producing the same value of K with different combinations of load and crack length. Again, agreement between the two specimens is excellent. Ref. 12 established that a scatter factor of 2 is considered normal for intralaboratory tests on a single heat, and the present results fall within that general guideline. The slightly greater scatter at 538°C (1000°F) is attributed to the greater difficulty in measuring the crack lengths at elevated temperatures.

To further evaluate the equivalency of the results, least-squares regression analyses were performed on the data for each specimen design at both temperatures. The results (expressed in American Customary Units) are given below (individual regression lines are not plotted in Figures 3 and 4):

Standard C.S. at 24°C (Specimens 1516 & 1517)
 $\log(da/dN) = -20.441 + 3.3159 \cdot \log(\Delta K)$
Correlation Coefficient** = 0.9895

Round C.S. at 24°C (Specimens 1519 & 1520)
 $\log(da/dN) = -20.246 + 3.2674 \cdot \log(\Delta K)$
Correlation Coefficient = 0.9913

Standard C.S. at 538°C (Specimen 1518)
 $\log(da/dN) = -17.181 + 2.6829 \cdot \log(\Delta K)$
Correlation Coefficient = 0.9626

*Values of $\sigma_y = 1011$ MPa (146.7 ksi) and 866 MPa (125.6 ksi) at 24 and 538°C, respectively, were obtained from Ref. 11.

**A correlation coefficient of unity indicates a perfect fit.

Round C.S. at 538°C (Specimens 1521 & 1522)
 $\log(da/dN) = -17.023 + 2.6505 \cdot \log(\Delta K)$
Correlation Coefficient = 0.9750

Only those data considered valid by ASTM E647-78T (i.e., the open symbols in Figures 3 and 4) were included in the regression analyses. It is seen that the regression equations for the two specimen designs are very similar. In fact, comparison of these equations at the extreme growth rates where data for the two designs overlap indicates a maximum difference in da/dN between the two equations at room temperature of 9.9%, and at 538°C (1000°F) a maximum difference of 4.6%. Again, this is considered well within normal scatter and indicates the equivalency of the results.

It is interesting to note that, even though the "invalid" data were not included in the regression analyses, examination of Figures 3 and 4 suggests that they continued to exhibit behavior comparable to that of the valid data.

Although there are minor differences in the quantities L/W , D/W , d/W , and r/W between the specimen analyzed by Newman and those used in the present work and previous studies (see Table I), the excellent agreement between the various K-solutions (see Figure 2) as well as the good agreement in the present study between standard and round specimens suggests that these minor dimensional variations are relatively unimportant.

Finally, the regression lines for other heats of similarly heat-treated Alloy 718 tested under identical conditions of temperature, frequency, waveform, and stress ratio (using Standard Compact Specimens) are shown in Figures 3 and 4 for comparison purposes. It will be seen that the agreement between the present results and those of the previous studies is quite good, again suggesting the equivalency of the RCS.

SUMMARY AND CONCLUSIONS

The various K-solutions suggested for the RCS were reviewed, and found to be in good agreement with one another. The Newman Equation (Equation [1]) is considered the most accurate over the widest range of values of α , and hence is the expression with which the present results are evaluated.

Although a large number of specimens were not tested, the results of this study suggest that the standard Compact Specimens and the Round Compact Specimens yield equivalent results for room temperature and elevated temperature

fatigue-crack growth rate testing. Hence, considering the economic advantage of the RCS for some product forms, it appears to be a satisfactory alternative to the standard CS in these instances.

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APPENDIX - NOMENCLATURE

- a, crack length
- B, specimen thickness
- C, specimen compliance
- d, see Figure 1
- da/dN, fatigue-crack growth rate
- D, specimen diameter
- E, Young's Modulus
- f, cyclic frequency
- G, strain energy release rate
- K, stress intensity factor
- L, see Figure 1
- P, applied load
- r, radius of loading holes
- R, stress ratio, $K_{\min}/K_{\max}$
- W, specimen width
- Y, dimensionless geometry factor, see Equation [8]
- α , relative crack length, a/W
- δ , load-line displacement
- ΔK , stress intensity factor range, $K_{\max} - K_{\min}$

TABLE I
COMPARISON OF SPECIMEN GEOMETRIES
FOR ROUND COMPACT SPECIMENS

Specimen	$\frac{L}{W}$	$\frac{D}{W}$	Hole Location	
			$\frac{d}{W}$	$\frac{r}{W}$
Feddern & Macherauch (Ref. 1)	0.333	1.333	0.266	0.133
Mowbray & Andrews (Ref. 2)	0.333	1.333	0.333	0.083
Cull & Starrett (Ref. 4)	0.333	1.333	0.250	0.083
Gross (Ref. 6-8)	0.333	1.333	—	—
Underwood & Kendall (Ref. 9)	0.333	1.333	0.266	0.133
Gregory (Ref. 10)	0.325	1.350	—	—
Newman	0.325	1.350	0.275 ^(a)	0.125 ^(a)
Present Work ^(b)	0.333	1.333	0.311	0.083
Present Work ^(c)	0.325	1.350	0.275 ^(a)	0.125 ^(a)

(a) Same as standard ASTM E647-78T Compact Specimen.

(b) Specimens 1519-1522.

(c) Specimen 1907.

TABLE II
CHEMICAL COMPOSITION OF ALLOY*
718 USED IN THIS STUDY

<u>Element</u>	<u>Percent by Weight</u>
C	0.04
Mn	0.15
Fe	17.97
S	0.005
Si	0.15
Cu	0.10
Ni	53.06
Cr	18.50
Al	0.62
Ti	0.95
Co	0.09
Mo	3.06
Cb & Ta	5.29

*Except Specimen 1907.

TABLE III
SUMMARY OF TEST PARAMETERS

<u>Specimen Number</u>	<u>Specimen Type</u>	<u>Test Temp.</u>	<u>Maximum Load</u>	<u>Range of α Tested</u>	<u>Cyclic Frequency</u>
1516	Std. CS	75°F	900 lb.	$0.400 < \alpha < 0.806$	600 cpm
1517	Std. CS	75°F	1350 lb.	$0.405 < \alpha < 0.727$	600 cpm
1518	Std. CS	1000°F	1000 lb.	$0.415 < \alpha < 0.719$	40 cpm
1519	RCS	75°F	800 lb.	$0.502 < \alpha < 0.847$	600 cpm
1520	RCS	75°F	1200 lb.	$0.508 < \alpha < 0.807$	600 cpm
1521	RCS	1000°F	800 lb.	$0.493 < \alpha < 0.781$	40 cpm
1522	RCS	1000°F	1200 lb.	$0.497 < \alpha < 0.719$	40 cpm
1907	RCS	75°F	950 lb.	$0.300 < \alpha < 0.782$	600 cpm

All specimens tested at a stress ratio, $R = 0.05$.

Figure 1: Standard Compact Specimen and proposed Round Compact Specimens.

Figure 2. Comparison of results for various expressions for the Round Compact Specimen.

Figure 3. Comparison of results for Standard and Round Compact Specimens tested at room temperature.

Figure 4. Comparison of results for Standard and Round Compact Specimens tested at 538°C (1000°F).