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**ATOMIC POWER
LABORATORY**

*Notch Sensitivity of
Unirradiated Zircaloy
Subjected to
Bending Fatigue*

D.F. Mowbray
March 10, 1965

Operated for the
United States Atomic
Energy Commission by
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UC-25, Metals, Ceramics
and Materials

NOTCH SENSITIVITY OF UNIRRADIATED ZIRCALOY
SUBJECTED TO BENDING FATIGUE

D. F. Mowbray

March 10, 1965

E. E. Baldwin

Authorized Classifier

April 23, 1965

Date

General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York
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ABSTRACT

Fatigue-strength reduction factors (K_f) were determined for thick sections of wrought Zircaloy-4 and Zircaloy-4 weld metal. The experimental investigation was confined to determining K_f at 10^6 cycles and 600F. The specimen loading method used for all tests was pure bending. Specimens were tested which had net section depths of 0.60 and 1.00 in., and notch root radii of 0.0007, 0.004, 0.012, and 0.030 in.

The test results indicated that the weld metal was considerably more notch sensitive than the wrought metal. Maximum values of K_f found were ~ 3.0 for the wrought metal, and ~ 4.6 for the weld metal. These maximum values occurred at notch root radii greater than the smallest investigated. No increase in K_f was observed when the net section depth was increased from 0.60 to 1.00 in.

The data obtained are compared with existing thin section notched bending test data and notch sensitivity factor (q) curves are established for both wrought and weld materials. Also, the δ concept for estimating the applicable K_f for crack-like defects was applied to the test results. It was found that δ cannot be treated as a material property for Zircaloy-4.

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NOTCH SENSITIVITY OF UNIRRADIATED ZIRCALOY SUBJECTED TO BENDING FATIGUE

D. F. Mowbray

INTRODUCTION

An important factor in the design of Zircaloy components, as for any component subjected to cyclic loads, is a knowledge of correct values of the fatigue-notch factor (K_f) for use in the fatigue analyses of sections containing stress raisers. Values of K_f are ordinarily determined experimentally, but procedures have been proposed for estimating them in the absence of sufficient test data.¹

Fatigue tests conducted to date for the purpose of determining values of K_f for wrought and welded unirradiated Zircaloy have been performed on specimens having an effective section thickness of 0.140 in. or less.² However, thicker sections are being used, and there is a need for either thick-section test data or a reliable analytical procedure for utilizing available thin-section test data. It is well known that K_f for a given geometry is a function of the section thickness or stress gradient. In general, K_f increases with increasing test-section thickness and decreasing stress gradient.

This investigation was undertaken to obtain values of K_f for thick sections of Zircaloy. The data obtained supplement existing thin-section test data,^{2,3} enabling a better evaluation of available analytical techniques for estimating K_f . In this investigation, values of K_f were determined for wrought Zircaloy-4 and Zircaloy-4 weld metal, with specimens 0.60- and 1.00-in. thick. Evaluation of K_f was restricted to one cyclic life, 10^6 cycles, and to one temperature, 600F.

TEST DESCRIPTION

Material

The material used in this investigation was vacuum-melted, reactor-grade wrought Zircaloy-4 and Zircaloy-4 weld metal. The wrought material was obtained as fully annealed rolled plate, 3/4- and 1-1/4-in. thick. Weld material was obtained by depositing weld metal in a double vee-grooved piece of 3/4-in.-thick plate. Seven to eight weld passes on each side of the plate were required. The resulting granular structure in three mutually perpendicular directions is illustrated by the photographs in

Figure 1. The weld metal was observed to be free of porosity or other defects. The large columnar grains in the direction perpendicular to the applied stress simulate service conditions.

The welding parameters employed are listed in Table 1; annealing times and temperatures, grain size, and chemical composition for each material in Table 2; and conventional tensile properties in directions transverse to rolling and welding in Table 3. Note that the weld material is of considerably higher strength and somewhat lower ductility (% reduction of area, RA) than are the wrought materials. Also note that the two heats of wrought material have nearly identical tensile strengths, but considerably different 0.2% yield strengths. When the static stress-strain curves for these two materials are compared, the only difference occurs at strains in the region of initial yielding. This difference is not considered significant with respect to fatigue properties, because this portion of the stress-strain curve is altered considerably upon cycling. O'Donnell and Langer⁴ show data for several heats of Zircaloy which indicate that the cyclic stress-strain properties are nearly independent of fabrication history.

TABLE 1. WELDING PARAMETERS

Condition	First Pass	Subsequent Passes
Arc voltage, dc, (straight polarity)	13.0	13.4 to 14.3
Current, amp	310	300
Travel speed, in./min	12	12
Electrode*	**	**
Arc start	High frequency	High frequency
Atmosphere	Argon	Argon
Purity, %	99.995	99.995
Pump vacuum down, † μ	0.03	0.03

*Pencil-point configuration.

**5/32-in. diam, 2% thoriated tungsten.

†Prior to backfill.

A. Orientation

B. Face Perpendicular to the (1) Direction.

C. Face Perpendicular to the (2) Direction.

D. Face Perpendicular to the (3) Direction.

Etchant: 45% HNO_3 ; 10% HF ; 45% H_2O . 10X.

FIGURE 1. Grain Structure of Weld Metal.
KS-56721
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TABLE 2. MATERIAL SPECIFICATIONS AND COMPOSITION

Material	Annealing Treatment	ASTM Grain Size	Chemical Composition								
			wt %					ppm			
			Sn	Fe	Cr	Ni	Zr	O	N	C	H
Wrought plate, 3/4-in. thick, Ingot No. OM-1006	1 hr at 1400F vacuum	7 to 8	1.43	0.21	0.10	<0.005	*	-	-	-	11
Wrought plate, 1-1/4-in. thick, Ingot No. M-47	1 hr at 1400F vacuum	7 to 8	1.37	0.22	0.09	<0.005	*	-	-	-	7
Weld metal, Ingot No. M-39	4 hr at 1200F vacuum after welding	See Figure 1	1.38	0.35	0.09	0.013	*	1050	100	310	14

*Balance.

TABLE 3. CONVENTIONAL TENSILE PROPERTIES OF
TEST MATERIALS*

Material	Ultimate Tensile Strength, psi	0.2% Yield Strength, psi	Elongation, %	Reduction of Area, %
Wrought, 3/4-in. plate	31,600	21,100	25.0**	64.9
Wrought, 3/4-in. plate	31,700	21,500	22.9**	65.1
Wrought, 1-1/4-in. plate	32,900	31,900	25.7**	70.7
Wrought, 1-1/4-in. plate	33,000	31,900	22.7**	71.1
Weld	39,400	29,200	25.1 [†]	61.7
Weld	42,500	29,200	26.7 [†]	63.4

*Test direction was transverse to direction of rolling
and transverse to direction of welding.

**Elongation in 1.5 in.

[†]Elongation in 0.373 in.

Specimens

The test specimen was a flat plate subjected to bending fatigue under constant-moment amplitude loading. The basic specimen design, notch condition, and specimen size are described in Figure 2. Test directions (direction of maximum applied stress) were transverse to the direction of rolling and transverse to the direction of welding.

The majority of the fatigue testing evaluated K_f over a range of r for specimens having an effective thickness of 0.60 in. Specific values of notch-root radius (r) included 0.030, 0.012, 0.004, and 0.0007 in. All the wrought metal specimens for these tests were removed from the 3/4-in.-thick plate.

An exception to the above tests was a group of wrought metal specimens removed from 1-1/4-in.-thick plate, having an effective thickness of 1.00 in. and tested with a notch-root radius of 0.0007 in. Results from the tests of these specimens helped to define the extent of the size effect for wrought Zircaloy.

Effective Thickness	T	a	t	r	L	K_t
0.60	0.600	-	-	-	6.00	-
0.60	0.720	0.600	0.120	0.030	6.00	3.34
0.60	0.720	0.600	0.120	0.012	6.00	4.89
0.60	0.720	0.600	0.120	0.004	6.00	7.99
0.60	0.720	0.600	0.120	0.0007	6.00	18.23
1.00	1.200	1.000	0.200	0.0007	10.00	23.36

FIGURE 2. Plate-Bending Fatigue Specimens.
KS-56722

Unclassified

All specimens were machined from the fully annealed plates and weldments, and tested without additional heat treatment. The machining was done carefully to prevent residual stresses on the specimen surface. After machining, the test-section surfaces of the unnotched specimens were polished with 600-grit paper. The resulting surface scratches were all parallel to the test direction. The grooves in the notched specimens were finish-machined by a grinding operation that produced very fine machining scratches transverse to the test direction. Although this fabrication procedure may tend to accentuate the resulting values of K_f , it is the procedure normally used for evaluating the fatigue strength of grooved bars.

Fatigue Testing Machine and Procedure

All fatigue tests were conducted on a Sonntag Model SF-1-U fatigue testing machine. The specimens were subjected to completely reversed flexure in pure bending, with moment amplitude held constant throughout each test. The cyclic frequency was 1800 cpm.

The test temperature was 600F, controlled automatically to within $\pm 5F$; also, the temperature throughout the test section varied no more than $\pm 5F$.

The purpose of the tests was to evaluate K_f only at 10^6 cycles. To this end, six specimens of each material and notch condition (notched and unnotched) were tested. Attempts were made in testing each group of six specimens to have two specimens fail below 10^6 cycles, two fail above 10^6 cycles, and two fail as near 10^6 cycles as possible. Values of K_f were then evaluated by plotting the six data points on σ_n vs cycles-to-failure coordinates, fairing a mean line through the points, determining the value of σ_n corresponding to the mean line at 10^6 cycles, and dividing the pertinent unnotched value of σ_n by the notched value. Specimen failure was considered as a crack extending through approximately one-half the net section thickness.

Applicability of Data

Some discussion concerning the general applicability of the data obtained is considered pertinent. First, one should keep in mind that K_f is being measured at 10^6 cycles under constant-moment (or constant-load) amplitude loading. The values of K_f , so determined, should not differ appreciably from values predicted by the results of constant-strain amplitude tests, because 10^6 cycles is in the high-cycle-life region where stresses are nominally elastic.

Second, let one remember also that values of K_f are being measured at only one cyclic life. For constant-load amplitude loading, K_f ordinarily decreases as the cyclic life decreases.⁵ Thus, K_f values determined from

constant-load amplitude loading in the high-cycle-life region will be conservative at the shorter cyclic lives. For constant-strain amplitude loading, it is sometimes assumed^{1,4} that the same value of K_f applies regardless of the cyclic life. If this is in fact true, then values of K_f determined from these tests would be applicable to constant-strain amplitude loading at all cyclic lives.

Finally, it should be emphasized that values of K_f measured from specimens in plane bending (as are the specimens tested in this investigation) are not directly applicable to cases where different states of stress exist.⁶ In such cases, the data obtained should be applied only after an appropriate analysis has been performed.⁷

TEST RESULTS

The results of the fatigue tests on both wrought and weld metal are listed in Table 4, and plotted in Figures 3 and 4 in terms of σ_n and cycles to failure. Figure 3 includes the data for wrought metal, and Figure 4 the corresponding data for weld metal. Best-fit curves have been faired (by eye) through the data points for each test condition.

TABLE 4. FATIGUE TEST RESULTS

Specimen Number	Material	Notch-Root Radius, in.	Effective Thickness, in.	Stress Amplitude, psi	Cycles to Failure	Failure
1	Wrought, 3/4-in. plate	Unnotched	0.600	24,000	2,400,000	None
2				25,000	2,500,000	None
3				26,500	1,980,000	None
4				27,000	2,440,000	None
5				27,500	2,800,000	None
6		↓ 0.030	↓	27,500	355,000	
7				9,500	868,000	
8				10,000	1,721,000	
9				10,500	992,000	
10				10,500	715,000	
11				11,000	868,000	
12		↓ 0.012	↓	15,000	128,000	
13				8,000	1,840,000	None
14				9,000	1,500,000	
15				9,500	2,644,000	
16				9,500	2,400,000	None
17				12,000	189,000	
18				15,000	112,000	

TABLE 4 (continued)

Specimen Number	Material	Notch-Root Radius, in.	Effective Thickness, in.	Stress Amplitude, psi	Cycles to Failure	Failure
19	Wrought,	0.0007	0.600	6,000	2,000,000	None
20	3/4-in.	↓	↓	9,000	5,500,000	
21	plate	↓	↓	9,500	1,699,000	
22	↓	↓	↓	10,000	1,500,000	
23	↓	↓	↓	10,000	868,000	
24	↓	↓	↓	10,000	272,000	
25	Wrought,	↓	1.000	10,000	2,695,000	
26	1-1/4-in.	↓	↓	10,000	1,467,000	
27	plate	↓	↓	11,000	1,430,000	
28	↓	↓	↓	11,000	844,000	
29	↓	↓	↓	11,000	301,000	
30	↓	↓	↓	12,000	556,000	
31	Weld	Unnotched	0.600	27,000	3,087,000	None
32	↓	↓	↓	27,500	7,067,000	None
33	↓	↓	↓	27,500	375,000	
34	↓	↓	↓	30,000	1,784,000	
35	↓	↓	↓	31,000	805,000	
36	↓	↓	↓	31,500	10,000,000	None
37	↓	0.030	↓	8,500	891,000	
38	↓	↓	↓	9,500	722,000	
39	↓	↓	↓	10,000	2,460,000	None
40	↓	↓	↓	10,000	961,000	
41	↓	↓	↓	10,000	455,000	
42	↓	↓	↓	11,000	560,000	
43	↓	0.012	↓	7,000	10,000,000	None
44	↓	↓	↓	7,000	1,800,000	None
45	↓	↓	↓	8,000	758,000	
46	↓	↓	↓	8,000	650,000	
47	↓	↓	↓	10,000	634,000	
48	↓	↓	↓	11,000	508,000	
49	↓	0.004	↓	6,000	1,769,000	None
50	↓	↓	↓	6,000	2,529,000	
51	↓	↓	↓	6,000	974,000	
52	↓	↓	↓	6,000	772,000	
53	↓	↓	↓	7,000	441,000	
54	↓	↓	↓	7,000	401,000	
55	↓	0.0007	↓	8,000	7,245,000	None
56	↓	0.0007	↓	8,000	4,996,000	None

(Table continued)

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TABLE 4 (continued)

Specimen Number	Material	Notch-Root Radius, in.	Effective Thickness, in.	Stress Amplitude, psi	Cycles to Failure	Failure
57	Weld	0.0007	0.600	9,000	1,296,000	
58	↓	↓	↓	9,000	756,000	
59	↓	↓	↓	10,000	1,280,000	
60	↓	↓	↓	10,000	274,000	

The values of K_f derived from the curves of Figures 3 and 4 at 10^6 cycles are listed in Table 5. The one value of K_f reported for specimens having an effective thickness of 1.00 in. (from 1-1/4-in. plate) was calculated employing the unnotched fatigue strength of the 3/4-in. plate, in lieu of unnotched properties for the 1-1/4-in. plate. It is not felt that this results in a significant error, as the fatigue strength of Zircaloy plate does not vary appreciably from heat to heat.

The variation of K_f with r for 0.60-in.-thick specimens is shown in Figure 5 by the data points and solid lines. A greater fatigue notch sensitivity is indicated for the weld metal. Also, the weld metal shows considerable variation in K_f over the range of r investigated, whereas the wrought metal shows only a negligibly small variation. Maximum K_f values determined are ~ 4.6 for weld metal and ~ 3.0 for the wrought plate stock. Note that the maximum values do not occur at the smallest notch-root radii.

An index commonly used for judging notch sensitivity of materials in fatigue is the notch-sensitivity factor, $q^{6,7}$, defined as:

$$q = \frac{K_f - 1}{K_t - 1} \quad (1)$$

which provides a scale of notch sensitivity that varies from $q = 0$, or no notch effect, to $q = 1$, or full theoretical effect. Plots of q vs r for wrought and weld Zircaloy materials are shown in Figure 6. These plots include the Zircaloy data* obtained in this investigation with thick-section specimens, as well as those obtained previously from thin-section specimens of similar geometry, and subjected to identical loading. These supplementary data are also listed in Table 5. When plotted in this form, the thin- and thick-section test data are in quite good agreement, and again, the higher notch sensitivity of the weld metal is evident.

*All the data shown are for failure at 10^6 cycles.

FIGURE 3. Notched and Unnotched Wrought Zircaloy-4 Fatigue Data at 600F.
KS-56723   Unclassified

FIGURE 4. Notched and Unnotched Zircaloy-4 Weld-Material Fatigue Data at 600F.
KS-56724   Unclassified

FIGURE 5. Experimental and Predicted Variations of K_f with Notch-Root Radius (r) for Wrought and Weld Zircaloy-4 Materials at 600F.
KS-56725 Unclassified

FIGURE 6. Variation of Notch-Sensitivity Factor (q) with Notch-Root Radius (r) for Wrought and Weld Zircaloy Materials at 600F.
KS-56726 Unclassified

TABLE 5. COMPILATION OF NOTCHED BENDING FATIGUE
TEST RESULTS FOR ZIRCALOY

<u>Material</u>	<u>Effective Thickness, in.</u>	<u>Root Radius, in.</u>	<u>K_t</u>	<u>K_f</u>	<u>q</u>	<u>Reference</u>
Wrought	0.60	0.0007	18.23	2.75	0.10	-
↓	0.60	0.012	4.89	2.90	0.49	-
↓	0.60	0.030	3.34	2.75	0.75	-
↓	1.00	0.0007	23.36	2.62	0.07	-
Weld	0.60	0.0007	18.23	3.16	0.12	-
↓	0.60	0.004	7.99	4.61	0.52	-
↓	0.60	0.012	4.89	4.00	0.77	-
↓	0.60	0.030	3.34	3.16	0.92	-
Wrought	0.044	0.0015	5.00	1.19	0.05	3
↓	0.044	0.005	3.00	1.61	0.30	3
↓	0.062	0.030	1.60	1.18	0.30	2
↓	0.14	0.001	9.00	2.02	0.13	2
↓	0.14	0.012	3.00	1.93	0.47	2
Weld	0.0275	0.001	5.08	2.11	0.27	3
Weld	0.0275	0.001	5.08	2.00	0.25	3

An indication of how section thickness affects the notched fatigue strength (size-effect) of Zircaloy is given by Figure 7, where K_f has been plotted as a function of effective thickness for wrought Zircaloy test results. Included in this figure are data for the sharpest machined notches (specimens having notch-root radii in the range from 0.0007 to 0.0015 in.) and effective thicknesses up to 1.00 in. Although K_f increases fairly rapidly with thickness for sections <0.20 in., there is a leveling off with no apparent increase between thicknesses of 0.60 and 1.00 in.

DISCUSSION

Notch Sensitivity

The relative notch sensitivity of metals of identical chemical composition, but of different fabrication histories, can generally be rationalized in terms of differences in the resulting strength, ductility, and grain size. For instance, with ferritic steels^{7,8} K_f increases as the strength increases, ductility decreases, and grain size decreases. In the case of Zircaloy, it follows that there should be a difference in

FIGURE 7. Effect of Section Thickness on K_f for Sharply Notched Bend Specimens of Wrought Zircaloy.

KS-56727

Unclassified

notch sensitivity between welded and wrought Zircaloy because of a difference in strength and ductility. However, the trends indicated for ferritic steels (BCC structure), with respect to grain size, are apparently not applicable for Zircaloy (HCP structure), because the grain size of the weld metal is considerably larger than that of the wrought metal.

The high notch sensitivity of the weld metal suggests a grain orientation effect. X-ray diffraction techniques were used to study the crystallographic orientation of the weld metal with respect to the welding and testing directions. The basal planes of the HCP structure were found to be predominantly perpendicular to the welding direction and parallel to the testing direction. This in itself renders the primary slip systems favorable for easy slip. (The primary slip systems in zirconium at 600F are the $(10\bar{1}0)$ planes and $\langle 11\bar{2}0 \rangle$ directions). The highest intensity of $(10\bar{1}0)$ planes was observed at 30 deg to the testing direction. This means that some of the $\langle 11\bar{2}0 \rangle$ directions are also at 30 deg to the test direction. For these angles the resolved shear stress is 87% of the maximum possible.

Of considerable interest are the results of some notched Zircaloy weld-metal fatigue tests in which the principal stress was applied parallel to the welding direction (least favorable direction for easy slip). Beitscher⁹ performed such tests employing notched, round, axial specimens having a net section thickness of 0.104 in. and a notch-root radius of 0.0005 in. In the cyclic life region from 10^3 to 10^5 cycles, he found no observable reduction in fatigue strength due to the presence of the notch, indicating that Zircaloy weld metal is not very notch-sensitive when loaded in this direction.

The high notch sensitivity indicated by the results of this investigation for the Zircaloy weld metal (in comparison with the wrought metal), is due in part to the lower notched fatigue strength of the weld metal, and in part to a higher unnotched fatigue strength. There is ~2500 psi difference in the unnotched fatigue strengths of the weld and wrought materials at 10^6 cycles. This is expected solely on the basis of the higher tensile strength of the weld metal. In general, unnotched fatigue strength is not a function of grain size, as is notched fatigue strength.

Design Factors

For design purposes, the relation defining q is expressed in the following form:⁷

$$K_{tf} = q(K_t - 1) + 1, \quad (2)$$

where K_{tf} is an estimated fatigue-notch factor, calculated for a particular notch geometry using an average q value from curves such as those in Figure 6. Thus, in the absence of notched-Zircaloy fatigue data for a

particular section thickness, and provided that a crack-like defect is not involved, the q -curves in Figure 6 can be used directly for estimating K_f in design problems involving members in plane bending. For members containing crack-like defects ($r \rightarrow 0$, $K_f \rightarrow \infty$), other methods are required. A recent publication⁴ describing a fatigue design basis for Zircaloy components, recommends use of the δ -concept of R. E. Peterson.⁶

The δ -concept is based on the premise that the stress at some finite distance, δ , below the surface is the stress which limits fatigue life. The concept considers that because metals are granular structures and because fatigue cracks initiate on slip planes in the grains, it should be necessary to increase the elastic stress amplitude so that the fatigue limit below the root of the notch is exceeded to some finite depth, which is denoted δ .

In its broadest possible application, δ is assumed to be a material property¹⁰ independent of section size. If this concept is indeed true, then only a single value of K_f is necessary for determining the applicable value of δ . This value of δ , so determined, could then be used for predicting K_f values for all section sizes, provided that elastic stress distributions in the vicinity of the notch tips were known.

Application of δ as a material property to results of tests in this investigation is illustrated in Figure 5. Using the recommended values of δ^* for wrought and weld metal from Reference 4 ($\delta = 0.002$ in. for wrought metal and 0.0008 in. for weld metal), values of K_f as a function of r were determined for the geometries tested. The elastic stress distributions were determined by the procedures described in Reference 10, employing a digital computer for the computations. The results are indicated by the dotted lines in Figure 5.

It can be observed in Figure 5 that qualitatively the δ -concept does the correct things when δ is treated as a material property. That is, the concept predicts that K_f increases as the section thickness increases, and that K_f is a maximum for some value of $r > 0$. Recommended procedure for conservative design is to select, as the applicable K_f for cracks, the peak value¹⁰, or the extrapolated point on the K_f ordinate.¹¹ In this case, such predictions would give estimates of the maximum K_f that are conservative; but from the designers standpoint, they can probably be considered grossly conservative.

It would appear from the thick-section test results in Figure 5 that δ is not unique for Zircaloy-4 over the major portion of the range of r investigated. In this respect, Peterson has stated in a recent publica-

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*These values were established on the basis of thin-section specimen test results, selected so as to always produce conservative results.

tion¹¹ that, although δ may be taken as constant over a considerable practical range, it is not necessary that δ remain constant down to the steepest gradients corresponding to zero-notch radius.

In light of the characteristic shape of the experimental K_f -vs- r curves and the observed limitations of the δ -concept, it is suggested that when confronted with determining an applicable value of K_f for a crack-like defect in a Zircaloy member, a more realistic but conservative estimate can be obtained by selecting the maximum experimental value of K_f achieved at values of $r > 0$. The q -vs- r curves established for each material can be used for approximating K_f -vs- r curves for varying section thicknesses < 0.60 in.

CONCLUSIONS

The experimental results obtained in this investigation support the following conclusions on the notched bending-fatigue strength of unirradiated Zircaloy-4.

1. Weld metal is more notch-sensitive than wrought metal when crack propagation in the weld metal is parallel to the long axis of the columnar grains.
2. The maximum value of K_f for weld-metal specimens having an effective section thickness of 0.60 in. is ~ 4.6 . This maximum occurs at a notch-root radius near 0.004 in., and not at the smallest notch-root radii which correspond to crack-like defects.
3. The maximum value of K_f for wrought-metal specimens having an effective thickness of 0.60 in. is ~ 3.0 ; also K_f is relatively insensitive to notch-root radius in wrought metal.
4. Increasing the section thickness of wrought specimens to 1.00 in. did not increase the value of K_f for a notch-root radius of 0.0007 in.

When the fatigue data generated in this investigation are examined together with existing notched bending fatigue data for unirradiated Zircaloy, the following two observations about design factors are noted:

1. There are sufficient data available to establish notch-sensitivity factor, q , curves for wrought and weld materials.
2. When δ is treated as a material property, and is established on the basis of thin-section test-specimen results, it may lead to grossly conservative predictions of K_f for thick sections.

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NOMENCLATURE

- a = Effective section thickness (defined as the net section depth for bend specimens notched on one side only, and 1/2 the net section depth for bend specimens notched on both sides), in.
- c = Distance from neutral axis to extreme fiber, in.
- δ = Distance from surface of notch (see Reference 10), in.
- I = Moment of inertia of cross section, in⁴
- K_f = Fatigue-notch factor for bending load* (defined as the ratio of fatigue strength of unnotched material to fatigue strength of notched material at a given number of cycles to failure).
- K_t = Stress concentration factor for normal stress, $\sigma_{\max}/\sigma_n$.
- K_{tf} = Estimated fatigue-notch factor, $q (K_t - 1) + 1$.
- M = Applied bending moment, in.-lb.
- q = Fatigue-notch-sensitivity factor, $\frac{K_f - 1}{K_t - 1}$.
- r = Notch-root radius, in.
- σ = Local normal tensile stress, psi.
- σ_{max} = Maximum normal tensile stress, psi.
- σ_n = Nominal net section bending stress amplitude, Mc/I, psi.

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*Used in this report for bending load only.