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Fatigue Crack Growth and Propagation
In Zr-2.5 wt% Nb Alloy Pressure Tubing (a)

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Abstract

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Abstract

Zr-2.5 wt% Nb alloy tubes were fatigued in the tension-tension mode by cyclic internal pressures to cause axial crack growth and unstable fractures at room temperature. Pressure cycle rates were 400 and 3000 cycles per hour. Both the cold worked and heat treated conditions, before and after hydriding (200-300 ppm H_2) were investigated. Exploratory tests were done to determine the effect of: a) the axial length of the surface stress intensifying defect and b) multiple surface stress intensifying defects on fatigue crack initiation, growth and critical length at unstable fracture.

From short ($\leq$ tube wall thickness) length defects, fatigue crack initiation and growth will occur at nominal peak hoop stresses equal to or less than the estimated endurance limit ($\sim 25,000$ psi). For fatigue cracks initiated at the outside diameter surface, the shape of the crack front is semicircular. The number of stress cycles required to initiate fatigue cracking at the surface is inversely proportional to the square of the surface defect length. Crack growth rates, for non-hydrided tubing are proportional to ΔK to the fifth power, and to ΔK to the fourth power after hydriding. There was a tendency for the critical crack length at unstable fracture to decrease with an increase in the number of fatigue cycles required to initiate fatigue cracking. Multiple defects may act in concert to initiate unstable fracture.

The fracture toughness of the heat treated tubing before hydriding is less than for the cold worked condition either before or after hydriding, and after hydriding the fracture toughness is further reduced,

Introduction

Within the United States and Canada there are several power reactors that use pressure tubes in the reactor core section of the primary coolant system. Because of the low thermal neutron capture properties of aluminum and zirconium, their alloys are prime candidates for pressure tubing. For power reactors, only the zirconium alloys possess sufficient strength at intermediate temperatures (e.g. to 400°C) to be of engineering interest.

Creep deformation, corrosion, and crack propagating behavior of candidate materials are important in the design of pressure tubes. Creep and corrosion of the tube material are generally recognized as the factors limiting service life. They are generally inherently slow processes and most pressure tube design criteria specified in applicable codes allow for both. Even under adverse service conditions causing accelerated creep or corrosion or both there is usually some time available in which to correct operating conditions and replace the damaged component without excessive risk to the entire structure. "Brittle" fracture, however, may result in the destruction of a pressure tube and in the process, also cause significant damage to surrounding structural components. "Brittle" fracture may and often does occur without warning. Hence, conditions under which a flaw may be or grow to critical size resulting in unstable fracture is important in the design of pressure tubing. The fatigue crack growth and propagation investigations reported herein were intended to provide some of this needed information.

Discussion

Material and Test Procedures

The Zr-2.5 wt% Nb alloy used in these tests was obtained from prototypic reactor pressure tubing. The material conditions investigated were the, a) cold worked (30% to 60% reduction in area), b) heat treated (880° soak, water quench, 15% reduction in area and age 24 hours at 500°C), and c) both the cold worked and the heat treated material hydrided to concentration levels of 200-300 ppm.

All test specimens were short tubes cut from prototypic reactor pressure tubing. Test specimens were nominally 16 in. long, 2.1 in. inside diameter and wall thicknesses ranging from 0.140 to 0.180 in.

In these tests, a simulated surface flaw was made at the tube surface to produce a point of stress concentration during cyclic internal pressurization of the test specimen and to initiate a fatigue crack. The surface flaw was formed by cutting a small slot into the outer or inner surface using electrical discharge machining (EDM) methods. In all cases the EDM electrode was 5 mils thick and produced a slot nominally 7 to 8 mils wide. In one instance the EDM slot was about 15 mils wide. In machining a 0.025 in. radius EDM slot, the 0.005 in. thick by 0.025 in. wide electrode tended to vibrate causing the relatively large width of the slot. No such difficulties were encountered with the larger electrodes. In most cases the shape of the EDM slot was semicircular with the center of the semicircle at the outer surface of the tubular test piece. In one test, the EDM slot was rectangular in shape and in one test a semicircular EDM slot was made from the inside of the tube with the center of the semicircle at the inner surface. In all cases the EDM slot was parallel to the tube axis and located at the mid-length and the thinnest wall area. The radii of the semicircular EDM slots ranged from 15 per cent of the tube wall thickness to a maximum of about 80 per cent.

Stress cycling was done by cyclic internal pressurization of the tubular test piece. The minimum and peak cyclic pressures were adjusted to produce the desired minimum and peak hoop stresses in a tension-tension mode. Except for end caps, which seal the tubular test piece, there were no external axial or circumferential restraints and a nominal 2 to 1 hoop to axial stress ratio was maintained throughout each pressure cycle of the entire test. All tests were done at room temperature.

The rate of pressure cycling ranged from about 400 cycles per hour to a high of 3000 per hour. In each test, however, the cycle rate was held constant throughout the entire test. In the majority of the tests pressure cycling was continued until the fatigue crack grew to critical size at which time the internal pressure was quickly and steadily increased until unstable fracture occurred. All fatigue crack lengths were measured at the outer surface of the tubular test piece. Crack lengths were measured to the nearest 0.005 in.

Discussion of Results

Effect of Defect Size on Fatigue Crack Initiation and Growth--One series of tests were done in which the nominal cyclic hoop stress range, minimum and peak stresses and the cycle rate were constant in each of the five tests. For these tests the stress range was 21,500 psi and the cycle rate was

about 400 cycles per hour, In each tubular test piece, one semicircular EDM slot was machined into the outer surface. For all tests the nominal peak cyclic hoop stress was 23,000 psi and which is believed to be slightly below the endurance limits for this alloy. For Zircaloy-2, O'Donnel and Langer (1) determined the endurance limit to be about 25,000 psi. This alloy is somewhat stronger than Zircaloy-2 and the endurance limit may be slightly greater. The radius of the EDM slot was varied from 0.025 in. to about 0.125 in.

The data from these tests are listed in Table 1 and shown graphically in Figure 1.

TABLE 1--EFFECT OF EDM SLOT SIZE ON FATIGUE AND GROWTH AND PROPAGATION

Test Identity	EDM Slot Radius (in.)	Cycles to Crack Initiation	Cycles to Leak	Leak Crack Length (in.)	Cycles to Failure	Critical Crack Length (in.)	Cycles from Leak to Failure
9	0.125	~ 5 300	9 695	0.43	18 628	1.37	8 933
11	0.100	~10 000	17 400	0.42	24 960	1.31	7 540
22	0.075	~15 000	28 400	0.41	35 554	1.08	7 154
22A	0.050	~22 000	40 550	0.41	47 199	0.95	6 649
26	0.027	~94 000	114 900	0.38	121 550	1.05	6 650

In Test 26, the EDM slot width was about twice that for all other EDM slots and was caused by vibration of the 0.005 in. thick by 0.025 in. wide electrode.

In Figure 1, the length of the crack initiating EDM slot is plotted on the ordinate at the number of cycles between the last surface inspection prior to and the first surface inspection subsequent to the occurrence of surface cracking. This number of cycles (determined within a few thousand cycles at most) is taken as the point at which fatigue cracking was initiated. Microscopic examination of the fractured surface of several of these test specimens suggests that, for the semicircular EDM slot with its center at the outer diameter surface, cracking originates at the outer diameter surface ends of the EDM slots. It is interesting to note that in tubing, the fatigue crack tends to assume a semicircular shape for stress concentrating defects.

Figure 1.

Fatigue Crack Extension as a Function of Pressure Cycles in
Zr-2-1/2 Nb Tubing at Room Temperature

located in the outer diameter surface. The photograph in Figure 2 shows this semicircular shape even though the EDM slot in the outside diameter surface was rectangular. This semicircular shape seems to be retained even as the crack grows toward critical size.

For this test series, it appears that the onset of fatigue cracking (visible through a microscope at 40 X) is signalled by the appearance of surface cracking. Using this criterion, it then appears that the number of stress cycles necessary to initiate fatigue cracking is inversely proportional to the square of the surface length of the EDM slot. From Figure 1, one can determine this proportionality as

$$N_i \propto \frac{1}{(2r)^2}$$

where

N_i = number of cycles required to initiate fatigue cracking

r = radius of the EDM slot with its center at the outer diameter surface

Further examination of the data in Table 1 shows that except for Test 26, the crack length at which leaking occurs is about 0.42 in. For Test 26 the tube wall thickness was nominally 0.15 in. while for the remainder of the tests, the tube wall thickness was nominally 0.17 in. Considering the ratio of crack length at the outer diameter surface to the nominal tube wall thickness, one finds this ratio to be very nearly constant. The crack length at which the tube leaks appears to be essentially a function of tube geometry. Once the fatigue crack penetrates the tube wall, the tube will leak (ooze) at about one-half ($\sim 9,000$ - $12,000$ psi) the nominal peak cyclic hoop stress.

For these tests (Table 1), it was found that the critical crack length for unstable fracture under cyclic stress tends to decrease in those tests where a greater number of cycles are required to initiate fatigue cracking. Here again Test 26 seems to be somewhat of an exception. Crack growth rates, however, do not seem to be significantly affected (see Figure 3). While one is inclined to conclude that prior fatigue may adversely affect the critical crack size for unstable fracture, the observed variations may be due in part to material scatter. Perhaps the most significant observation

EDM Slot at Which the Fatigue Crack Started

Figure 2.

Photograph of the Fatigue Crack Surface. Note the Circular Shape of the Advancing Fatigue Crack Front and the Grainy Appearance of the Fatigued Surface

one can make from these tests is that a pressure tube is likely to leak sometime before it fails catastrophically.

Effect of Cyclic Stress Range on Fatigue Crack Growth-- In addition to the above series of five tests, several tests were done at various cyclic stress ranges. Here again the cycle rate was about 400 cycles per hour. The purpose of these tests was primarily to provide test specimens for unstable crack propagation tests. One test, however, is of special interest in that the fatigue crack initiating defect was cut into the inner diameter surface from inside the tubular test specimen. In this specimen the EDM slot radius was nominally 0.125 in. and the nominal cyclic hoop stress range was 18,500 psi. An accelerometer was attached to the tube in an attempt to detect the onset of fatigue cracking. While the accelerometer was not sensitive enough to detect the onset of the fatigue cracking it readily signalled leakage as the crack grew through the tube wall. When leakage occurred the fatigue crack at the outer diameter surface measured approximately 0.12 in. Under cyclic conditions the crack grew to a critical length (outer diameter measurement) of about 2.05 in. This critical size appears to be somewhat greater than for tests wherein fatigue cracking initiated from an EDM slot at the outer diameter surface.

For all of the aforementioned tests, the crack growth rates were determined. These data were plotted as a function of ΔK (see Figure 3). For these data ΔK was calculated from:

$$\Delta K = \Delta \sigma_0 \sqrt{a}$$

where:

$\Delta \sigma_0$ = nominal hoop stress range - ksi

a = the one-half crack length measured at the outer diameter surface

This is the standard equation for a center notched infinitely large plate subjected to uniform normal body stresses (2). In tubing, body stresses are normally are biaxial and in these tests the nominal hoop-to-axial stress ratio was 2 to 1. In thick wall tubing, there is a small stress gradient across the tube wall; at the inner diameter surface the fiber stress is

greatest. In spite of these differences, this equation seems to fit the data as well as any that are analytically tractable (3,4).

For the aforementioned tests, the curve of crack growth rates versus ΔK is shown in Figure 3. For all but one test, all data appears to fit a straight line with a slope of about one-fifth on a log-log plot. For the test wherein the fatigue crack started at an EDM slot in the inner surface, the slope of the growth rate versus ΔK curves appears to be about one-fourth or less. Part of this difference may be due to the shape of the fatigue crack and the way crack length measurements are obtained. As was seen in Figure 2, the fatigue crack front is semicircular. Crack length measurements are made at the outer diameter surface. Hence, when the fatigue crack starts at an EDM slot in the outer diameter surface, the measured crack length, for a given growth rate is larger than it is when the fatigue crack starts at an EDM slot in the inner diameter surface. The effect of crack origin diminishes as the crack radius becomes large. Some of the difference may also be due to the fact that the fiber stress is greatest at the inner diameter surface.

According to Paris (5) the crack growth rate is a function of ΔK to the fourth-power. If an average crack length is used instead of the outer diameter surface length, the slope of the curve in Figure 3 would tend toward a value of one-fourth. This suggests that in these tests, the axial stress had little effect on fatigue crack growth.

Effect of Hydriding on Fatigue Crack Growth-- Six tests were done on hydrided tubing. Tubing in the cold worked and the heat treated conditions was hydrided at about 425°C to saturation levels (200-300 ppm H_2). A semicircular EDM slot with a radius of about 0.125 in. was cut into the outer diameter surface of each of the test specimens. For these tests the cycle rate was about 3000 cycles per hour.

Unstable fracture under cyclic conditions occurred only in the heat treated and hydrided tubes. In several of the heat treated and hydrided tubes unstable fracture occurred within about 2000 pressure cycles and crack growth data could not be obtained. The results of these tests are shown in Figure 4 as a curve of crack growth rate versus ΔK . After hydriding, the slope of

Figure 3.

Crack Growth Rates Versus ΔK for Heat Treated Zr-2 1/2 Nb Tubing

Figure 4.
Crack Growth Rate Versus ΔK for Hydrided Zr-2-1/2 Nb Tubing

the ΔK -growth rate curve is about one-fourth. Compared to the non-hydrided material, hydriding appears to have the effect of diminishing crack growth rates. There were rather large differences in cycle rates which may have some effect on crack growth rates.

Effect of Multiple Defects on Fatigue Crack Growth-- Four tests were done on tubes with two parallel EDM slots cut into the outer diameter surface. The purpose was to determine whether or not there was a serious adverse effect of clustered defects on the critical crack length at unstable fracture. In all four tests the two EDM slots were parallel to the tube axis, separated circumferentially by $3/8$ in. and had radii of about 0.15 in. Axial center to center spacing of the EDM slots was varied from zero to 0.9 in. Pressure cycle rates for these tests was about 3000 cycles per hour.

Curves of crack extension versus pressure cycles for each of the tests are shown in Figure 5. For the test (Test 30) where the axial spacing was zero, crack growth occurred mostly from one EDM slot only. While crack growth did occur from the second EDM slot throughout the test its total growth was limited to about 0.40 in. Hence, the crack growth behavior was essentially that of a single fatigue crack. Leaking occurred very early in the test and before surface fatigue cracking was observed. Subsequent examination revealed that the EDM slot was cut nearly through the tube wall.

As the axial spacing is increased to about 0.6 in., the number of cycles to unstable fracture and the critical crack length tend to decrease. When the axial spacing was increased to 0.9 in. there was no apparent reduction in cycles to failure but the critical crack length appears to have been reduced. In each of the three tests, crack growth from each of the two EDM slots was comparable.

This test series suggests that when the tips of two or more fatigue cracks are near, some interaction may occur. More experiments, however, are needed to verify and quantify such effects.

Critical Crack Size-- One of the main purposes of these fatigue tests was to obtain critical crack size data. These data are listed in Table 2 and are shown graphically in Figure 6.

Figure 5.

Fatigue Crack Extension as a Function of Pressure Cycles in Zr-2-1/2 Nb Tubing with Two Parallel Fatigue Cracks

Figure 6,
Hoop Stress Versus Critical Crack Length for Zr-2-1/2 Nb
Tubing

Of all material conditions investigated, the heat treated condition after hydriding (200-300 ppm H_2) possesses the lowest fracture toughness (see Figure 6). In all specimens, fracture occurs essentially in the plane strain mode. A typical fracture is shown in the upper photograph of Figure 7.

The heat treated condition in the absence of hydriding fails in essentially the same manner as it does after hydriding. Fracture toughness is, however, roughly 50% greater than after hydriding. There is, however, appreciable scatter in these data. Some of these test specimens experience a rather large number of fatigue cycles prior to unstable fracture. As seen in Table 1 and Figure 1, the critical crack length tends to decrease with increasing amounts of prior fatigue damage.

Tubing in the cold worked condition either before or after hydriding possesses good fracture toughness. The curve of hoop stress versus crack length is not included in Figure 6 because there was no unstable crack propagation from the ends of the fatigue cracks. In all but one test, ductile tearing was limited to that needed to relieve the pressure in the tube. A typical fracture of cold worked tubing before or after hydriding is shown in the lower photograph of Figure 7.

An unusual fracture occurred in one cold worked test specimen after hydriding. This unusual fracture is shown in the center photograph of Figure 7, and in Figure 8. This test specimen had previously been used in a fracture test using a one-eighth in. wide milled slot as the fracture initiator. After welding in a dry box, the specimen was pressure cycled until a fatigue crack, 3 in. long was produced. The tube was then steadily pressurized until failure occurred. Some limited ductile tearing from the ends of the fatigue crack occurred. (See Figure 7). Unstable fracture, however, initiated in the heat affected zone of the weld. (See Figure 8). This crack propagated axially for a short distance in the heat affected zone and then turned out of the heat affected zone. The crack then again turned and ran parallel to the axis. This crack propagated nearly the full length of the tube.

An unusual fracture was also found to occur in one tube in which

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Figure 7.

Tube at Top Shows Characteristic Crack Propagation in Heat Treated and Hydrided Zr-2-1/2 Nb Tubing. Center Tube Shows an Unusual Failure in a Cold Worked and Hydrided Zr-2-1/2 Nb Tubing. Bottom Tube Shows Characteristic Ductile Crack Extension in Cold Worked and Hydrided Zr-2-1/2 Nb Tubing

Figure 7.

Crack Propagation Behaviour in a 30% Cold Worked and Hydrided Zr-2-1/2 Nb Tube.
Failure was Initiated at an Area of Very Large Grains in the Heat Affected Zone
of the Weld

two parallel fatigue cracks were grown. (See Figure 9). In this tube it appears that unstable fracture began at the ends of the lower left hand fatigue crack. As the hoop stress on the crack propagating from the right end was relieved by the upper right fatigue crack and was arrested, unstable fracture began at the right end of the upper right fatigue crack. The length of either fatigue crack was slightly less than the minimum critical size for any of the tests in which a single fatigue crack initiated unstable fracture.

Summary and Conclusions

In tubing, fatigue cracks parallel to the tube axis can be readily and easily produced by cyclic internal pressurization. From appropriate stress intensifiers at the inner diameter or outer diameter surface, fatigue crack initiation and growth will occur at nominal peak hoop stresses (hoop to axial stress ratio equal to 2 to 1) equal to or less than the estimated endurance limit ($\sim 25,000$ psi). Data are not yet available to determine whether or not the axial stress (parallel to the fatigue crack) has any significant effect on fatigue crack growth rates or critical crack sizes.

For short (equal to or less than the tube wall thickness) defects in the outer diameter surface, which initiate fatigue cracking, the crack front is semicircular with its center approximately at the outer diameter surface. The number of fatigue cycles required to initiate fatigue cracking is inversely related to the square of the surface length of the EDM slot at which cracking initiates. Crack growth rates, for non-hydrided tubing are proportional to ΔK to the fifth power and to ΔK to the fourth power after hydriding. Critical crack size, may diminish with an increase in numbers of fatigue cycles required to initiate fatigue cracking.

The fracture toughness of cold worked Zr-2.5 wt% Nb tubing either before or after hydriding (200-300 ppm H_2) is greater than for heat treated tubing. For heat treated tubing the fracture toughness after hydriding is reduced by about one-third.

The results of a few tests suggest that two or more defects may act in concert to initiate unstable fracture. More data are needed to verify and quantify the influence of multiple defects on crack growth and propagation.

Figure 9,
Crack Propagation Behaviour in Zr-2-1/2 Nb Tube with Two Parallel Slots

TABLE 2--CRITICAL CRACK LENGTH FOR FRACTURE

Test Identity	Material Condition	Nominal Hoop stress, ksi	Critical Crack Length (in.)	Test Conditions	Fracture Comments
9	Heat treated	23	1.37	Cyclic	Plane strain- full propagation
11	" "	23	1.31	"	" "
22	" "	23	1.08	"	" "
22A	" "	23	0.95	"	" "
26	" "	23	1.05	"	" "
27	" "	20	2.05	"	" "
21	" "	26.5	0.95	"	" "
26A	" "	21	1.5	"	" "
30*	" "	28	1.25	"	" "
11A*	" "	27	1.21	"	" "
99*	" "	25	1.05	"	" "
7*	" "	25.5	0.92	"	" "
28	" "	34	0.85	Static	" "
30-11SR	30% CW	58	0.68/0.43	"	Ductile tearing - no propagation
30-8	30% CW & hydrided	21		"	See Figure 8 Plane strain
30-11	30% CW & hydrided	21		Cyclic	Ductile tearing - no propagation
60-11	60% CW & hydrided	67		Static	Ductile tearing - no propagation
10A	Heat treated & hydrided	17.5	1.2	Cyclic	Plane strain - no propagation
17A	Heat treated & hydrided	20	0.76	Cyclic	" "
23	Heat treated & hydrided	26	0.46	Cyclic	" "

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