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**ACOUSTIC EMISSION OF ZIRCALOY-2
DURING TENSILE
AND FATIGUE LOADING**

T. E. MICHAELS

AUGUST 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

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UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

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ERRATA

Page 14: In Figure 10, under "Percent of Fatigue Life at Which Test Was Stopped," delete "98%" and change "92%" (immediately underneath) to "98%".

Page 15: In Figure 11, under "Percent of Fatigue Life at Which Test Was Stopped," insert "98%" midway between the second "A" and the second "B" from the top.

Page 20: In second paragraph, first sentence should read:

Results of the acoustic emission monitoring of Zircaloy-2 tensile tests showed in both the signal voltage and the number of pulses per unit of engineering strain, a pronounced peak before the 0.2% off-set yield point.

Page 23: In the caption for Figure 15, substitute the word "Fatigue" for the word "Acoustic".

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BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
Richland, Washington

Printed in the United States of America
Available from
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National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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ABSTRACT

The acoustic emission of Zircaloy-2 has been studied during tensile and fatigue loading at room temperature. A considerable amount of signal was received during these loading tests and metallographic evidence relating acoustic emission to deformation processes was acquired.

ACOUSTIC EMISSION OF ZIRCALOY-2
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INTRODUCTION

This report, on the acoustic emission characteristics of Zircaloy-2 during tensile and fatigue loading, is part of a continuing effort in the utilization of acoustic emission as a laboratory tool to evaluate irradiated and unirradiated zirconium alloy pressure tubes.⁽¹⁾

Metals under applied stress release energy in the form of propagating vibrational waves, and this energy is defined as acoustic emission. This energy can be monitored by coupling a vibrational pickup device to the surface of the specimen and using the received acoustic emission as a means of measuring different metal properties or conditions associated with metal deformation. Examples of such acoustic emission application would be the measurement of localized or general yielding, stress intensification factors, crack generation, crack growth, and fatigue in metallic specimens.

SUMMARY AND CONCLUSIONS

Some of the acoustic emission characteristics of Zircaloy-2 during tensile and fatigue testing have been studied over frequencies ranging from 100 kHz to 1 MHz.

The Zircaloy-2 specimens tested in tension exhibited a pronounced acoustic emission signal peak just prior to the 0.2% offset yield point, after which the signal decreased as specimen failure was approached. The major portion of the signal is believed to be due to the initiation of dislocation movement, because the maximum in signal generation and the initiation of dislocation movement both occur before macro yielding of the specimen.

The acoustic emission response to tensile specimen load cycling was observed to decrease markedly after the first cycle and continue to decrease with each subsequent cycle. Reloading to above any previous stress maximum resulted in a sharp increase in the amount of acoustic emission response as the previous stress maximum level was passed. This increase was seen to be continuous with the acoustic emission response curve received during the first loading to that point.

Considerably more signal was received from the fatigue specimens loaded at a 30-cycle/sec rate than from the tensile test specimens because of the much higher strain rates involved. The monitoring instrumentation was operated at lower gain for the fatigue tests because of the increased amount of signal. The acoustic emission response received from the fatigue tests was initially high and then decreased to a stable value after approximately 10 to 25% of the fatigue life. The higher signal received during this first part of fatigue testing was believed to be related to yielding. The decay of signal with each load cycle corresponded to observations on the load cycling of the tensile specimens. Photomicrographs of specimens fatigued from 10 to 25% of fatigue life gave no evidence of gross crack movement or twinning events. The acoustic emission response appeared to remain constant over the middle range of the specimen fatigue life until immediately prior to failure. Metallographic examination indicated that a fatigue crack was initiated during this middle range of fatigue life and that the twin density gradually increased. A build-up occurred in acoustic emission response just prior to failure and was observed to be reproducible from test to test. This build-up was approximately 10 sec in length for all cases observed. Oscilloscope traces showed the majority of these signals to be nonperiodic at a 30 cycle/sec loading frequency.

Metallographic examination showed this portion of the fatigue life to correspond to a period of crack propagation, with much twinning evident in grains adjacent to the crack tip. The majority of signals received during the build-up prior to failure was believed to be due to the observed twinning events, the initiation of dislocation movement in the plastic zone ahead of the crack tip, and possibly some mechanical noise produced by slapping together of the crack walls with each load cycle.

DISCUSSION

MONITORING SYSTEM

The monitoring system consisted of a lead zirconate titanate peizoelectric transducer used as the pickup device, a 26 dB gain preamplifier, a variable gain amplifier stretcher, and a strip chart recorder. This system is shown schematically in Figure 1. The peizoelectric crystal was fluid coupled to the surface of the specimen within a few inches of the maximum stress region. The total circuit gain was set at 80 dB for the tensile test monitoring, and at 67 dB for fatigue test monitoring. The information, pulse in appearance, was received over a frequency range from 100 kHz to 1 MHz and was conditioned by stretching before recording to place it in the frequency response range of a strip chart recorder.

TENSILE TESTING ARRANGEMENT

The tensile specimens were machined from 0.130 in. annealed sheet of Zircaloy-2 (Figure 2). A pinned type fixture coupled the load to the tensile specimen to exclude possible generation of vibrational noise due to slippage of the specimen in a grip arrangement. All tensile tests were conducted at room temperature.

FIGURE 1. Acoustic Emission Monitoring System

FIGURE 2. Zircaloy-2 Tensile Specimen
Showing Transducer Location

FATIGUE TESTING ARRANGEMENT

The cantilever beam flexure fatigue specimens were machined from 0.130 in. annealed sheet of Zircaloy-2 (Figure 3). The fatigue fixture consisted of an electromagnetic shaker coupled to the specimen to produce the required displacement. The signal from a variable frequency sine wave generator was amplified sufficiently to drive the electromagnetic shaker (Figure 4). All fatigue tests were conducted at room temperature.

ACOUSTIC EMISSION RESULTS OF TENSILE TESTS

Several tensile tests were conducted with the acoustic emission monitoring system in place. A few representative tests are discussed in this report. The number of pulses of information per unit of engineering strain $\frac{dn}{d\epsilon}$, has been superimposed on an engineering stress-strain curve as determined for each of three tests conducted (Figure 5). A peak on this curve was observed for all specimens immediately prior to the 0.2% offset yield point. Also shown in Figure 5 is the total signal voltage per unit engineering strain $\frac{dv}{d\epsilon}$, as superimposed on the engineering stress-strain curve determined for each specimen. A peak in the signal voltage curve is also observed immediately prior to the 0.2% offset yield point. The total acoustic emission response, i.e. both $\frac{dn}{d\epsilon}$, and $\frac{dv}{d\epsilon}$, is seen to decrease as the ultimate strength is approached. The curves plotted in Figure 5 represent strains to one half of the strain at failure. Although not shown, the signal in all cases continued to decrease as failure was approached.

The acoustic emission response has been superimposed on the engineering stress-strain curve for a specimen load cycled several times to different stress levels (Figure 6). In observing the acoustic emission response, two trends are apparent. First, upon load cycling from zero stress to a particular maximum

FIGURE 3. Zircaloy-2 Fatigue Specimen Showing Transducer Location

FIGURE 4. Fatigue Fixture and Electrical System

FIGURE 5. Acoustic Emission of Zircaloy-2 During Tensile Loading

FIGURE 6. Acoustic Emission Behavior of Zircaloy-2 During Load Cycling of a Tensile Specimen

stress, the amount of acoustic emission response decreases with each cycle. This is observable in the acoustic emission response received from the first four load cycles. Second, an increase in acoustic emission response as the previous maximum stress level is passed during recycling is observable between cycles 4 and 5, 5 and 6, 6 and 7, and 7 and 8. Figure 7 is generated if the data from Figure 6 is plotted as a single stress-strain curve (omitting data obtained during recycling up to previous maximum stress levels). Again, both $\frac{dn}{d\epsilon}$, and $\frac{dv}{d\epsilon}$, have a pronounced maximum near the 0.2% yield point.

ACOUSTIC EMISSION RESULTS OF FATIGUE TESTS

A summary of two groups of fatigue tests is superimposed on a stress versus load cycles to failure curve in Figure 8. The general shape of the curve was first established and data from these initial groups of tests were plotted in assuming an endurance limit of approximately 23,000 psi to calibrate the stress axis.⁽²⁾

The acoustic emission data from these initial tests showed two general trends. First, the pulse rate and pulse amplitude, initially high at the start of the fatigue test, decayed to a stable value after approximately 10% of the fatigue life. Second, a build-up in the acoustic emission response was observed immediately prior to failure in all cases (Figure 9). The length of this burst of information before failure was approximately 10 sec in all cases under these test conditions.

The second series of fatigue tests was conducted to investigate in more detail both of these trends. A stress of 26,000 psi was chosen for this series of tests. First, a specimen was fatigue cycled until an estimated 75% of the acoustic emission build-up immediately prior to failure was received that the test was then stopped. This point corresponded to approximately 99.5% of

FIGURE 7. Composite Acoustic Emission Response from Load Cycled Specimen of Zircaloy-2

* Stress estimation based upon an assumed endurance limit of 23,000 psi.(2)

FIGURE 8. Flexure Fatigue Characteristics of Zircaloy-2

FIGURE 9. Increase in Acoustic Emission Response of Zircaloy-2 Immediately Prior to Fatigue Failure

the fatigue life of the specimen. Another specimen was fatigued to the point at which the build-up of acoustic emission was first detected and the test was then stopped. This corresponds to approximately 98% of the fatigue life of the specimen. Still other specimens were fatigued at 26,000 psi to an estimated 50 and 10% of their fatigue lives.

Actual data traces from a strip chart recorder, as received from this last series of fatigue tests conducted at 26,000 psi and 30 cps, are shown in Figure 10. The top pair of traces is from a specimen fatigued completely to failure. The next pair is from a sample fatigued to 99.5% of its life and so on down for 98, 50, and 10% fatigue life values. There is some variation in the signal gain for the tests.

These specimens were then examined metallographically to follow the progress of fatigue damage as displayed in Figures 11 and 12.

Two illuminations were used at a magnification of 250X. Bright field illumination was used to emphasize the appearance of the crack, and polarized light illumination was used to emphasize the microstructural effects. The crack is shown to be clearly visible starting at 50% of the fatigue life. The crack growth rate appeared low up to 98% of the fatigue life and appeared high between 98 and 99.5% of the fatigue life. The extent of twinning is demonstrated best by the polarized light photomicrographs of Figure 12. In going from 10 to 98% of the fatigue life, the twin density increases very substantially. The twin density is greatest in the grains adjacent to the crack front in the specimen stopped at 98% of its fatigue life. Very little twinning, except for deformation twins in the grains adjacent to the machined notch, was seen in the untested specimen.

The acoustic emission characteristics are summarized in Figures 13 and 14 for the fatigue tests conducted. Figure 13

FIGURE 10. Acoustic Emission Characteristics
of Zircaloy-2 During Fatigue Loading
(fatigue frequency--30 cps)

Percent of Fatigue Life
at Which Test was Stopped

A--Polarized Light
B--Bright Field

250X

FIGURE 11. Metallography of Zircaloy-2 from Notched Section
of Fatigue Specimens After Fatigue Loading

Percent of Fatigue Life
at Which Test was Stopped

99.5%

98%

50%

10%

0%

FIGURE 12. *Metallography of Zircaloy-2 After Fatigue Loading
Showing the Extent of Deformation Twinning*

250X
Polarized Light

FIGURE 13. *Acoustic Emission Pulse Rate Variation with Fatigue Life for Zircaloy-2 (fatigue frequency--30 cps)*

represents the number of pulses per second $\frac{dn}{dt}$. Figure 14 represents the total signal voltage per unit time $\frac{dv}{dt}$. The pulse rate and the signal voltage received per unit time were obtained manually by counting pulses over 0.1 volts on the strip chart records. During periods of high signal density, many pulses become obscured due to overlap on the recorder chart. The net result was that the counted values of $\frac{dn}{dt}$ and $\frac{dv}{dt}$ were much lower than their exact values during periods of high signal density. In Figures 13 and 14, the manually counted values become questionable in the last 2% of the fatigue life due to high signal density during the final build up before failure. For this reason, a test was conducted with a pulse rate counter applied to the acoustic emission output in order to estimate the amount of error involved in the manual pulse rate count during the signal build-up before failure. All pulses over 0.1 V and displaced in time by more than 100 μ sec were registered distinctly. The pulse rate received indicated the error to be in excess of an order of magnitude during this period of high signal density. The pulse rate leading to this build-up did, however, compare favorably to the manually counted values. The pulse rate and total voltage rate curves in Figures 13 and 14 thus are solidly filled in for the first 98% of the fatigue life. The constancy of this final build-up has been demonstrated (Figure 9) and, in light of this constancy, a probable pulse rate curve has been dashed in on Figure 13. The graphs are intended to show qualitatively the pulse rate variation with specimen fatigue life for the flexure fatigue of Zircaloy-2.

The mean amplitude of signals received from test to test was hard to control. The signal amplitude is a function of specimen loading, specimen characteristics, transducer coupling, and electronic instrumentation gain. Many of the tests, therefore, appeared to show different overall gains. A good example

FIGURE 14. Acoustic Emission Total Signal Voltage Rate Variation with Fatigue Life for Zircaloy-2 (fatigue frequency--30 cps)

of this difference is the 50% test shown in Figure 10 for which the gain appears less than the gain in any of the other tests.

TENSILE TEST ANALYSIS

The acoustic emission response for these tensile tests has been represented in this report as a function of unit engineering strain rather than as function of unit time. The number of pulses per unit of strain has more significance for these tests than the number of pulses per unit time because the tests were conducted in a loading situation for which the strain rate was not constant.

Results of the acoustic emission monitoring of Zircaloy-2 tensile tests showed in both the number of pulses per unit of engineering strain, a pronounced peak before the 0.2% off-set yield point. Events associated with initial dislocation movement appear the most probable cause for the sharp drop in curves representing total pulse and voltage as macro yield begins. The hypothesis is that the majority of the information received in a tensile test of Zircaloy-2 is due to these events. Before the macro yield point, some dislocations lightly pinned in preferentially oriented grains are able to break away from their barriers and thus give rise to acoustic emission upon the application of very low stresses. The number of such dislocations breaking away will increase as the applied stress increases up to the macro yield point. Events occurring after macro yield can be attributed to dislocations breaking away from stronger pinning points in less favorably oriented grains within the plastic zone and to extension of the plastic zone out of the gage section of the specimen. The later two effects after macro yield should decrease with increasing stress. The acoustic emission response of the specimen thus should decrease as the ultimate strength is approached. The acoustic emission behavior during load recycling can be explained by the decrease

in the number of dislocations freed with increasing cycles to the same stress amplitude. Thus, the acoustic emission response should decrease with each stress cycle upon recycling to a prior stress level. Upon reloading to a stress above a previously high stress level, the amount of plastic strain increases dramatically. Therefore, the number of dislocation depinning events should increase with a corresponding increase in the acoustic emission response. Experimental evidence supports this conclusion (Figure 6).

FATIGUE TEST ANALYSIS

In the fatigue tests, a loading frequency of 30 cycles/sec was used to provide much more acoustic emission information per second than could be obtained from tensile tests. To prevent signal saturation, the monitoring system gain had to be decreased 13 dB from the setting used in monitoring the tensile tests.

In analyzing the fatigue test results, it is useful to recall the effect of load cycling on the tensile test results. Cyclic tensile loading results suggest acoustic emission response to be maximum at the start of the test and to decrease with an increase in the number of load cycles. This expectation has been confirmed and, within the first 10 to 25% of the fatigue life, the acoustic emission response decreases to and remains near a stable value until failure is approached. The work of Gough has shown that a metal deforms under cyclic strains by slip on the same atomic planes and in the same crystallographic directions as in the unidirectional strain case of a tensile test.⁽³⁾ The difference is that slip is widespread in the unidirectional strain case whereas, in fatigue, slip lines are not apparent in all the grains. This finding indicates that the major slip processes are confined to the more favorably oriented grains during fatigue. Slip lines produced during fatigue are usually visible after a few thousand load

cycles. Their density usually approaches a constant value after 10% of the fatigue life in most cases.^(4,5) The fact that the acoustic emission response and the slip band density both approach a constant value after approximately 10% of the fatigue life further supports the hypothesis that much of the signal is caused by the initiation of dislocation movements.

As the fatigue process continues, slip line forms intrusions and extrusions on a microscopic scale and usually define the start of the fatigue crack which is generally transgranular. A detailed view of the notch on several specimens in Figure 11 shows the progress of the fatigue crack. Note that the crack is first visible between 10 and 50% of the fatigue life as observed here. The crack growth appears to be very gradual up until the last 2% of the fatigue life.

The twinning processes are expected to produce a very substantial report when they occur. Twinning events are audible to the ear in some metallurgical systems as "tin crying," twinning in zinc single crystals, etc. The formation rate of twin bands was observed to be uniform up to 98% of the fatigue life. In the last 2% of the fatigue life, a great deal of twinning was seen to occur, particularly in grain adjacent to the crack tip (Figure 12). The last 2% of the fatigue life was also characterized by a dramatic build-up in the acoustic emission response (Figure 15). Figure 9 shows the constancy from test to test that lasted approximately 10 sec prior to failure. Because of the change in twin band density observed during the 10 sec prior to the failure portion of the fatigue test, some of the signal in this final build-up can most certainly be attributed to twinning. A great deal of this signal might also be due to opening and closing of the crack tip and to propagation of the crack. A fluctuating plastic zone will move through the specimen ahead of the crack tip as the crack transverses the

sample. Dislocation movement initiated in this plastic zone should also contribute to the signal observed in the final build-up before failure. An oscilloscope trace made during the build-up prior to failure shows no periodic relationship between the majority of the information and the loading frequency (Figure 16). This observation indicates sources other than crack tip noise as responsible for the build-up and is relatable to deformation processes occurring with crack propagation.

FIGURE 16. *Oscilloscope Trace of Signal Build-up Prior to Fatigue Failure*

ACKNOWLEDGEMENTS

The experimental assistance of R. E. Page and R. M. Ferdinand in conducting this study is gratefully acknowledged. The assistance of G. M. Everett and T. R. Rouse in data reduction was also appreciated.

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