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by Stanley J. Klima, Daniel J. Lesco, and John C. Freche
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ABSTRACT

An ultrasonic system was developed and used to observe the formation of fatigue cracks in center notched sheet specimens of unalloyed aluminum, two aluminum alloys, a mild steel, and a nickel-base alloy tested in axial tensile fatigue. S-N curves of life-to-initial detectable cracks as well as life-to-fracture were obtained. With the reflection technique, fatigue cracks that ranged in length from 0.0005 to 0.005 inch were detected while the test was in progress. Cracks were detected within approximately 1 to 3 percent of total specimen life for all of the materials considered over the range of stresses considered. The through-transmission technique was utilized to measure relatively long cracks.

INTRODUCTION

Fatigue involves the processes of crack initiation and crack propagation prior to fracture. Any method that can be used to detect small fatigue cracks nondestructively during the course of a fatigue test would be extremely useful as a research tool. If the method could also be successfully applied in the field, its usefulness would be even greater.

Methods are presently available that can be used to detect fatigue cracks, but generally speaking, each has associated difficulties, more or less severe, depending on its intended application. For example, commonly used inspection methods such as penetrating liquid, magnetic particle, and radiographic tech-

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niques, when applied to fatigue specimens, all require interruption of the fatigue test. Additional limitations exist because the penetrating-liquid and magnetic-particle techniques can only be used to detect cracks at or near the surface, and the use of X-ray techniques poses problems of safety and interpretation.

Optical microscopy is probably the most positive means of measuring the size of fatigue cracks, but this method requires highly polished surfaces and generally involves termination of the test and sectioning of the specimens prior to microscopic examination. Recent work (ref. 1) involved the production of replicas of the specimen surface suitable for use either in an electron microscope or in a light microscope. Plastic replicas were obtained while the specimens remained in the fatigue machine by simply stopping the test periodically. From these replicas it has been possible to detect cracks less than 0.0001 inch deep in flexure specimens after a relatively few load applications without destroying the specimen; however, detection of cracks by this method requires highly polished specimens and still involves lengthy procedures.

In an attempt to detect fatigue cracks more simply and without interruption of the test, electrical and ultrasonic techniques have recently been introduced. These are not as sensitive to extremely small cracks as the microscope, but they have practical advantages in that they generally can be more easily applied. An electric potential technique has been used to determine slow crack growth in tensile tests (refs. 2 and 3). The feasibility of crack detection by electrical impedance measurements has also been demonstrated (refs. 4 and 5). Changes in the electrical resistance of notched rotating-beam-type specimens (ref. 4) were correlated with depth of fatigue cracks. The smallest cracks that could be detected with certainty were on the order of 0.005 inch in depth.

Ultrasonic methods, which have been widely used for nondestructive inspection purposes, have recently been used to observe damage in fatigue specimens. Ultrasonic surface waves have been used (ref. 6) to detect surface flaws in bending-fatigue specimens, but crack sizes were not determined in this study. Very recently, ultrasonic inspection techniques have also been used (ref. 7) to detect cracks in thin (0.039 in.) center-notched steel-sheet specimens that were tested in axial fatigue. Cracks ranging from 0.003 to 0.004 inch in length were detected.

Of the methods described, the ultrasonic method was selected for further study in the present investigation. This method afforded certain advantages because it was not limited to detection of surface cracks, did not require interruption of the fatigue test, and could be used with many materials regardless of their electrical or magnetic properties. Also, this method does not require that specimens be insulated from the test apparatus as is necessary for the electrical methods. A program was therefore initiated at the NASA Lewis Research Center to further develop the ultrasonic method and to apply it to fatigue testing of various materials.

PRINCIPLES OF CRACK DETECTION BY ULTRASONICS

The principles of ultrasonic wave propagation are described in detail in texts dealing with the subject (refs. 8 to 10). A brief review of the theory involved is presented in the following sections.

Reflection Technique

Detection of fatigue cracks by the reflection of ultrasonic energy is similar to the use of radar in the detection of distant objects. Acoustic energy, in the form of pulsed envelopes of high-frequency waves, is transmitted from a transducer into the test specimen. After transmission of the pulse, the transducer acts as a receiver for energy reflected from any discontinuity in the specimen. The metal-air interface of a fatigue crack constitutes such a discontinuity. The low density of air and the relatively low velocity of ultrasonic waves in air result in an acoustic mismatch that causes the reflection of incident ultrasonic waves. The amount of energy reflected from a crack is directly related to the crack area, the intensity of the incident ultrasonic wave, and the orientation of the crack.

Through-Transmission Technique

A second technique for detection of discontinuities by means of ultrasonic energy does not depend upon the measurement of reflected energy. It employs two transducers; one acts as a transmitter, and the other as a receiver. The principle of operation is based upon the fact that a crack that forms and grows in the region of the specimen between the transducers will decrease the energy transmitted to the receiver. The amount of energy received is inversely related to the crack area.

SYSTEM DESIGN AND OPERATIONAL CHARACTERISTICS

A block diagram of the ultrasonic crack-detection system is shown in figure 1. A commercial ultrasonic flaw detector was used in this investigation. The commercial unit contained a pulse generator used to drive the piezoelectric crystal. It also contained the necessary amplifiers and a cathode-ray tube that amplified and displayed the reflected energy pattern, and time gating and integrator circuitry. A filter and an oscillograph were added. The oscillograph was used to obtain a permanent record of the signal reflected from the notch or crack in the specimen. The commercial transducer was modified so that it could be applied to the detection of fatigue cracks in notched-sheet specimens.

Transducer Design

Figure 2 shows a sketch of the transducer designs used with the crack-detection device. The transducer used with the reflection technique consisted of a lucite wedge on which were mounted two piezoelectric crystals (fig. 2(a)). A rectangular (1.0 by 0.5 in.) piezoelectric crystal was used to generate ultrasonic waves of fixed frequency and receive the reflected signals.

The shear-wave mode was used because it permitted ultrasonic energy to be transmitted through the specimen surface and subsequently propagate along the length of the specimen. Also, the velocity of shear waves is one-half that of longitudinal waves. This permitted detection of smaller flaws because of the decreased wavelength associated with the shear wave.

The wave mode and the angle of entry of the ultrasonic waves into the test specimen were controlled by the wedge angle and the refraction of the incident waves at the wedge-specimen interface. It was necessary that the wedge material have an acoustical propagation velocity less than the shear-wave velocity in the specimen materials. Lucite plastic possessed the required velocity characteristic. The optimum wedge angle θ was experimentally determined for each fatigue specimen material by the method of reference 11. These data are summarized in table I.

It was also necessary to provide a coupling medium between the wedge and the fatigue specimen to eliminate air from the interface and allow transmission of the ultrasonic waves into the specimen. The coupling material used in this investigation was a molybdenum disulphide lubricant normally used to prevent seizure of mating parts at high temperature. Although a rather high degree of coupling efficiency was attained with the molybdenum disulphide lubricant, not all of the ultrasonic energy generated in the wedge by the drive crystal was transmitted to the specimen because of the discontinuity at the wedge-specimen interface. The energy which did not enter the specimen was reflected back into the wedge as shown in figure 2(a). Changes in the intensity of these reflected waves during the course of a test were indicative of changes in coupling efficiency. An additional crystal (coupling monitor crystal) was mounted on the other end of the wedge to monitor these changes.

When the through-transmission technique was used, two transducers were needed; one to transmit ultrasonic waves, the other to receive them (fig. 2(b)). As may be seen from the figure, some of the ultrasonic waves introduced to the specimen pass through it and are detected by the receiving transducer. Some of the waves are reflected from the crack (dotted arrow) and are therefore not detected by the receiving transducer. Space limitations precluded the use of coupling monitor crystals when this technique was utilized. It was assumed that the coupling efficiency remained essentially constant.

Special Transducer Characteristics

The crystal used was chosen to have as high a frequency as possible without excessive ultrasonic wave attenuation in the wedge. It was experimentally determined that a frequency of 5 megacycles was the practical maximum with the available equipment.

Comparisons made of several 5-megacycle, 1.0- by 0.5-inch, crystals disclosed variations in their response to the presence of flaws. In order to obtain repeatability in experiments, the crystals were not interchanged.

Plots were also made of the variations in relative sensitivity to flaws across the long dimension of each crystal. This was accomplished by measuring the reflected energy from a 0.050-inch long slot in an aluminum alloy sheet as the transducer was moved laterally past the slot. Measurements were taken at intervals of 0.06 inch. A plot showing the variation in sensitivity for the 1.0 inch crystal used in this investigation, is shown in figure 3. The crystal was mounted on a 53.5^{o} wedge, and measurements were made at a distance of 0.25 inch from the flaw. The general shape of the curve is typical of all the crystals checked. After the region of maximum sensitivity of the transducer was determined, it was subsequently mounted on fatigue specimens so as to utilize this region to advantage.

Operation of System Electronics

Ultrasonic pulses were transmitted at the rate of 500 per second with a pulse time of about 1 microsecond. Since a typical velocity for ultrasonic shear waves in the specimens used in this investigation was about 0.1 inch per microsecond, sufficient time was provided between pulses for all reflected signals to return to the drive crystal when the reflection technique was employed. These reflected pulses were reconverted to electrical signals by the drive crystal, amplified, and displayed on the cathode-ray tube.

When the through-transmission technique was employed, only that portion of the ultrasonic pulse which was not reflected by specimen discontinuities was received by the receiving transducer. It was not necessary to allow time between pulses for the reflected signals to return to the crystal.

The commercial ultrasonic equipment included a time gate and integrator circuitry (fig. 1). The gate allowed only the reflected (or transmitted) signals, occurring within a preselected time interval after each transmitted pulse, to pass through to the integrator circuitry. Because the distance traveled by an ultrasonic pulse is proportional to time, the time gate may be interpreted as a "propagation-distance" gate. The output of the amplifier was gated for the specimen position at which fatigue cracking was expected to occur when the reflection technique was used. Extraneous reflections from the transducer-specimen interface and from the end of the specimen were blocked by this gate. With the through-transmission technique the amplifier was gated for the time at which the transmitted pulse reached the receiver.

The integrator circuitry provided a dc (direct current) voltage level proportional to the signal that passed through the time gate. After filtering to remove minor fluctuations in the integrator output, the resulting dc voltage was recorded on an oscillograph. Changes in the recorded dc voltages were proportional to changes in the amount of ultrasonic energy received.

Effect of Flaw Orientation on Output Voltages

An attempt was made to determine the effect of macroscopic crack orientation on the amplitude of ultrasonic waves received by the transducer when the reflection technique was employed.

Slots 0.05 inch in length were machined through a 0.060-inch-thickaluminum alloy plate to simulate crack surfaces at varous angles to the ultrasonic waves. These slot configurations and the corresponding normalized output voltages are shown in table II. The projected area of each configuration was maintained equal with respect to the direction of wave propagation. The angle between the slot and a plane normal to the plate is designated as φ for uniplaner slots and as φ' for biplanar slots. The angle between the slot and a plane normal to the edge of the plate is designated as α.

The output from each slot shown in the table is relative to the output from a slot lying normal to the direction of the ultrasonic waves. The transducer-to-slot distance was set at 0.25 inch for all tests (see fig. 2(a)). The arrows in the flaw orientation sketches indicate the propagation direction of the ultrasonic pulses. It was found that the amplitude of the reflected wave decreased as the orientation of the slot varied from a position normal to the ultrasonic wave (table II). The output for variations in φ and φ' can be approximated by the cosine function for the given angle. The decrease in output with increase in α is much more rapid than the decrease that occurs with an increase in φ. This might be expected because a value of α of 45° would reflect ultrasonic energy in a direction parallel to the transducer and would theoretically result in zero output.

The results obtained with slots of predetermined orientation can be applied to explain differences in ultrasonic reflection from fatigue cracks whose surfaces lie at different angles with respect to the direction of ultrasonic waves. Thus, a crack which lies on the macroscopic shear plane of a specimen would not appear to be as large as one lying normal to the specimen surface when the direction of the ultrasonic waves is parallel to the specimen axis.

Because the use of the through-transmission technique depends primarily on a blocking of the transmitted waves by the projected area of a crack, the technique is relatively independent of crack orientation per se. Consequently, the effect of crack orientation on output voltage was not investigated for this technique.

MATERIALS AND FATIGUE TEST PROCEDURE

Specimen Materials

Five materials, unalloyed aluminum, two aluminum alloys (6061-T6 and 2014-T6), mild steel (approx. 0.035 percent carbon), and Inconel were tested in axial tensile fatigue. Sheet specimens were employed which had thicknesses ranging from 0.046 inch for Inconel to 0.064 inch for unalloyed aluminum. A sketch of the test specimens is shown in figure 4. Center-notched specimens were used so that eccentric loading would be reduced after cracks were formed and, also, so that the cracks would appear in a region of the specimen positioned in line with that part of the piezoelectric crystal having the most sensitive characteristics.

Fatigue Tests

The specimens of all alloys were subjected to axial tensile loads that were alternately increased and decreased in a sinusoidal pattern. The frequency was either 16 or 1970 cpm depending on the expected specimen cyclic life. The ratio of the minimum stress to maximum stress was maintained at 0.14 for all of the alloys investigated. All tests were conducted at ambient temperatures in air.

Application of Ultrasonic Detection System

The ultrasonic reflection technique was utilized to detect cracks less than

0.005 inch in length in all the materials tested. When this technique was used, the transducer was positioned on the specimen 0.25 inch from the specimen notch. The transducer was attached to the specimen with C-type clamps arranged so as not to interfere with the passage of ultrasonic waves through the specimen. The reflections from the center of the notch were damped in part by the application of adhesive tape to the reflecting surface of the notch. The amplifier suppression (dc bias) was then adjusted to reduce the remaining notch signal to a low output level, which was used as the zero level for crack detection. Changes in the recorded output indicated fatigue cracking at the notches.

The through-transmission technique required the positioning of a receiving transducer on the side of the notch opposite the transmitting transducer. In this case, amplifier gain and suppression were adjusted to provide a full-scale signal of the received energy prior to stressing. A decrease in the signal was indicative of the presence of a crack.

Crack Length Measurement

On first detection of a crack, some specimens were removed from the fatigue machine and sectioned for microscopic examination. After sectioning, the specimen surface was ground (usually until one-half the specimen thickness remained), polished, and etched to better define the crack. The image of the area containing the crack was projected on a metallograph screen at a magnification of 500, and the length of the crack image was measured to the nearest 0.010 inch (crack length variation of 0.00002 in.). Specimens with longer cracks (approx. 0.07 in.) were first broken in tension and the fatigue-cracked portion of the fracture surface was then measured directly with a ruler at a magnification of 10.

As described previously, the amplitude of the received signal is dependent on the intensity of the ultrasonic waves as well as on the crack area. The intensity of the ultrasonic waves passing through a unit area of the specimen cross section is, in turn, inversely proportional to the specimen thickness. Since the crack area for a given crack length is proportional to specimen thickness, the received signal for shear waves is therefore a function of the crack length, independent of specimen thickness. Consequently, description of fatigue cracks was made in terms of length and provided a standarized comparison for all the materials investigated.

FATIGUE DATA

The S-N curves showing cyclic life-to-initial detectable fatigue cracks and cyclic life-to-fracture are shown in figure 5.

Data Obtained With Reflection Technique

The reflection technique was found to be most sensitive to the initial detection of fatigue cracks, and all the initial crack-detection data were obtained in this manner. Crack lengths as shown in the figures represent the sum of the length of cracks emanating from both ends of the specimen center notch. The length of first detectable cracks in 1100 aluminum, mild steel, and Inconel, ranged from 0.0005 to 0.005 inch (figs. 5(a), (d), and (e)). In 6061-T6 and 2014-T6 aluminum alloys, the length of first detectable cracks was somewhat less, ranging from 0.0005 to 0.0025 inch (figs. 5(b) and (c)). The maximum variation of crack length with thickness was found to be approximately 0.001 inch.

It has long been known that fatigue cracks can exist in materials without failure occurring within a span of cyclic life that can, for all practical purposes, be considered infinite. It is interesting to note that evidence of such cracks was obtained with the ultrasonic crack-detection device for 2014-T6 aluminum in this investigation. This is shown in figure 5(c) where cracks were detected in three specimens tested at a maximum cyclic stress of 7650 pounds per square inch; two were removed from test at the time of crack detection, and the third was run to 10^7 cycles before the test was terminated. Crack lengths in all three specimens were virtually the same at the time of test termination.

Data Obtained With Through-Transmission Technique

The through-transmission technique was utilized with the ultrasonic crack-detection device to indicate the presence of cracks having a length greater than 0.010 inch in 2014-T6 aluminum. The S-N curve representing the number of cycles until cracks of approximately 0.062 to 0.082 inch in length were formed is shown in figure 5(c). These data were taken to obtain an indication of the reproducibility of the instrument output for cracks much larger than those which were detected with the reflection technique.

A full-scale signal change on the oscillograph was indicative of crack lengths ranging between 0.062 to 0.082 inch with the exception of one specimen in which the length of the crack was found to be 0.104 inch. In this instance, coupling changes may have affected the results. Except for this single case the results were fairly reproducible; this latter point is not plotted in figure 5(c). Reported crack lengths represent the average of a series of measurements made at five positions through the thickness of each specimen. There was a considerably greater variation in crack length with specimen thickness for these longer cracks than for the much shorter cracks detected by the reflection technique. Crack length in any given specimen varied as much as 0.035

inch with the longest portion usually located about midway between the surfaces. It appears from these data that the through-transmission technique is suitable for measuring relatively long fatigue cracks that can occur relatively late in specimen life.

DISCUSSION

Considerations Pertinent to Initial Crack Detection

Detection of cracks by ultrasonic techniques is normally limited to those cracks that present a reflecting area with dimensions greater than one-half the ultrasonic wavelength. The wavelength of the ultrasonic waves generated in this system was approximately 0.013 inch; however, cracks as small as 0.0005 inch were detected because of the manner in which the crack detection system was applied.

By employing notched specimens a high amplitude signal was obtained from the notch. This signal was much larger than those arising from other sources such as grain boundaries, which could otherwise confuse signal interpretation. Since the crack propagates from the notch roots, the clearly distinguishable notch signal will increase further; thus it becomes possible to detect minute cracks by monitoring the large signal. If no reference indication (e.g., reflection from the notch) were available, the shortest detectable crack probably would have been 0.013 inch or greater.

Relation Between Output Voltage and Crack-Length-Reflection Technique

The relation betwen output voltage and crack length was investigated for two of the materials: 6061-T6 and 2014-T6 aluminum. Table III shows crack-detection data for 6061-T6 aluminum alloy specimens examined after instrument outputs of 5.5 and 11 percent of full scale had been obtained. The average crack length for the lower output voltage was 0.0012 inch while for the higher output it was 0.0029 inch. Thus, it is evident that the output voltage was directly related to crack length. The spread in crack length, relative to the average crack length, however, is greater for the lower voltage output than for the higher voltage output.

The relationship between instrument output and crack length was further explored with 2014-T6 aluminum. Figure 6 shows a plot of crack length against output voltage for this material. The crack lengths were measured on the specimen surface with a microscope at a magnification of 100 while the test specimen was under load in the fatigue machine. The data points were taken from five specimens fatigued at different stress levels. The output was linear with respect to crack length over the full scale of the oscillograph. The deviation from the curve, referenced to full scale (0.008 in.), is about ±25 percent.

For crack lengths greater than 0.010 inch the relation between output voltage and crack length was no longer linear and scatter increased markedly. Therefore calibration of the instrument for longer crack lengths with the reflection technique was not possible; however, the data of figure 6 indicate that the instrument has at least a limited capability for specifying crack length as well as detecting the presence of small fatigue cracks.

Effect of Cyclic Stress on Sensitivity

Responses from a load cell mounted in series with the specimen were recorded simultaneously with ultrasonic output voltage. It was observed that the presence of a crack could be noted earlier in cyclic life if measurements were taken while the specimen was subjected to the maximum cyclic stress than while it was subjected to the minimum cyclic stress. This may be explained by the fact that the adjacent metal surfaces created by a small crack are pulled apart to a greater degree at maximum load than at any other tensile load. As a consequence, ultrasonic waves would tend to be reflected at high loads; whereas, they would tend to be transmitted across the crack interface at low loads. In view of this, it appears that output voltage readings should always coincide with the maximum applied cyclic stress in order for this instrument to be operated in the most efficient manner possible for the detection of small cracks.

GENERAL OBSERVATIONS

The fatigue data show that, in the sharply notched specimens utilized, cracks were detected within 1 to 3 percent of the total life to fracture for all materials tested over the range of stresses considered. It is interesting to note that although the materials varied widely in mechanical properties, it was nevertheless possible to detect cracks with this device at a very small fraction of the total life to fracture. It should be noted that, although approximately the same fraction of total life to fracture was used in forming the first detectable cracks in all the materials investigated, the actual number of cycles required to form such cracks varied considerably from material to material.

Although the ultrasonic system for detecting fatigue cracks developed in this investigation is intended primarily for use as a research tool, the results indicate that it may also have applications for fatigue crack detection in the field. For example, the notched specimen employed in this study may be considered analogous to critically stressed airplane components containing stress risers. By detecting small flaws in such components while a prototype airplane is being subjected to anticipated fatigue loads on the ground, substantial savings in time might be achieved over cumbersome visual inspection techniques. Similarly, application of the device to known critically stressed sections of an aircraft after specified periods of flight time might indicate the presence of minute cracks early enough to allow time for remedial measures to be taken. Further research is of course needed to make this ultrasonic crack detection system suitable for such practical applications.

SUMMARY OF RESULTS

1. With the reflection technique, fatigue cracks that ranged from 0.0005 to 0.005 inch in length were detected during fatigue testing of the more ductile materials (i.e., pure aluminum, mild steel, and Inconel), and cracks ranging from 0.0005 to 0.0025 inch in length were detected in the less ductile materials (6061-T6 and 2014-T6 aluminum alloys).

2. In the sharply notched specimens utilized in this investigation, cracks were detected within approximately 1 to 3 percent of total specimen life for all of the materials considered over the range of stresses considered.

3. The reflection technique was more sensitive to the detection of minute fatigue cracks than was the through-transmission technique. Thus, it was possible to detect much smaller cracks with the reflection technique.

4. The through-transmission technique gave consistently reproducible output voltages for cracks on the order of 0.062 to 0.082 inch in 2014-T6 aluminum. This reproducibility was better than that obtained with the reflection technique for similarly long cracks. The through-transmission technique thus appears to be better suited for measuring the length of cracks greater than about 0.010 inch.

5. The effects of crack orientation on output voltage with the reflection technique was studied by means of slots machined into flat plates. Slot surfaces normal to the direction of the ultrasonic waves produced the greatest output voltage. The further the slot surface deviated from a position normal to the wave propagation direction, the smaller the output, even though the slot surface area, whcn projected on a plane normal to the wave, was constant.

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TABLE I. - WEDGE ANGLE FOR MAXIMUM ULTRASONIC SHEAR WAVE AMPLITUDE IN SPECIMEN MATERIALS

Material	Specimen thickness, in.	Wedge angle, deg
2014-T6 Aluminum	0.060	53.5
6061-T6 Aluminum	.064	53.5
1100 Aluminum	.064	53.5
Mild steel	.053	46.0
Inconel	.046	46.0

TABLE II. - OUTPUT VOLTAGE AS FUNCTION OF FLAW ORIENTATION

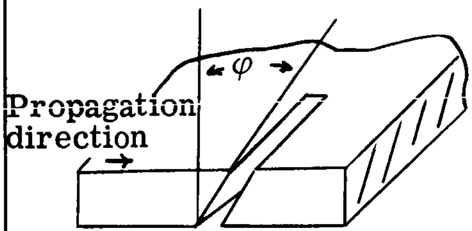
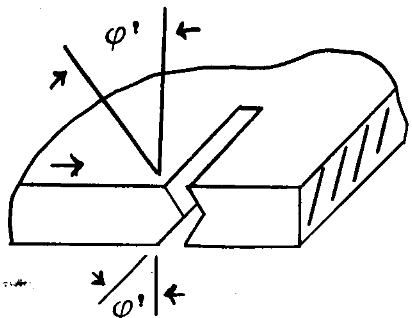
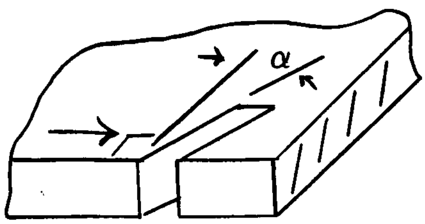
Flaw	Orientation angle, deg	Normalized output voltage
$\alpha = 0^{\circ}$	φ	
	0	1.00
	10	.96
	30	.96
	45	.74
$\alpha = 0^{\circ}$	φ'	
	0	1.00
	30	.81
	45	.75
$\varphi = 0^{\circ}$	α	
	0	1.00
	10	.92
	30	.30
	45	.00

TABLE III. - CRACK MEASUREMENT DATA FOR 6061-T6 ALUMINUM FOR VOLTAGE OUTPUTS OF 5.5 AND 11 PERCENT OF FULL SCALE

Specimen	Crack length, in.
5.5-Percent output	
1	0.0005
2	.0005
3	.0008
4	.0009
5	.0010
6	.0010
7	.0012
8	.0012
9	.0014
10	.0014
11	.0017
12	.0019
13	.0025
Average	0.0012
11-Percent output	
14	.0016
15	.0017
16	.0025
17	.0026
18	.0029
19	.0029
20	.0042
21	.0044
Average	0.0029

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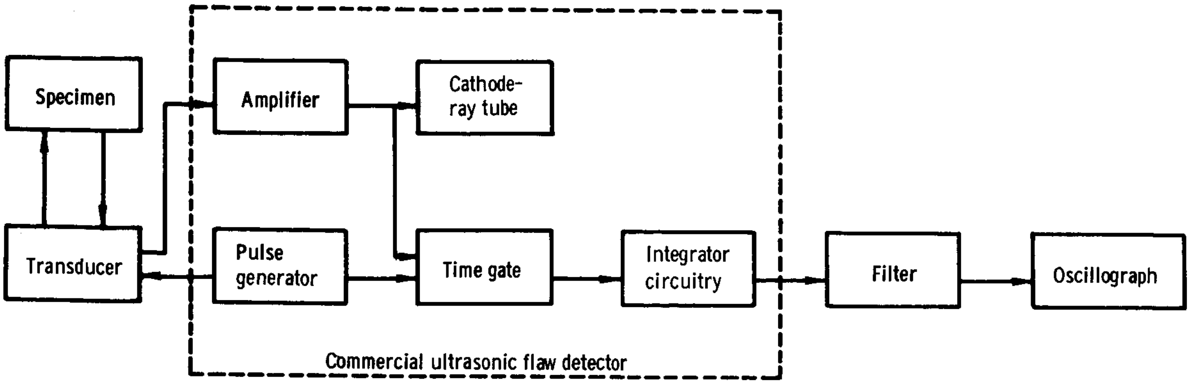
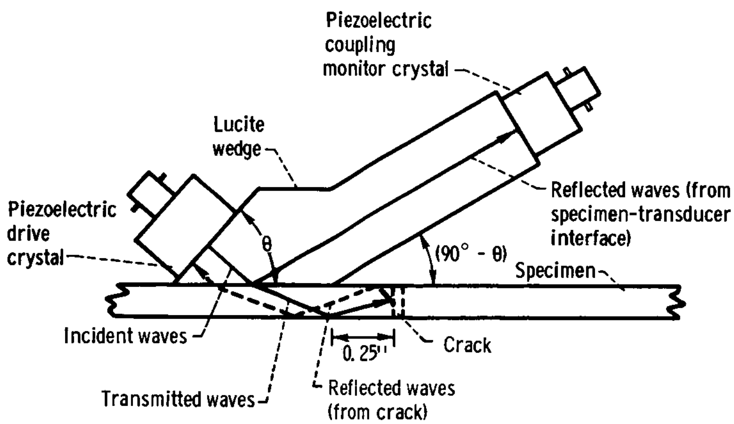
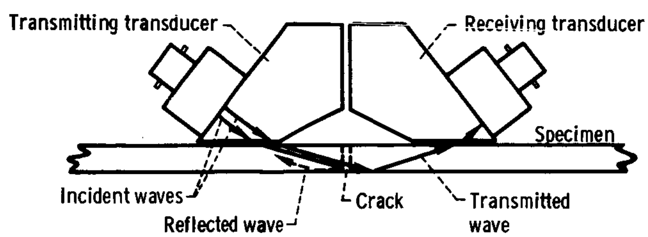


Figure 1. - Crack-detection system.



(a) Transducer used with reflection technique.



(b) Transducers used with through-transmission technique.

Figure 2. - Schematic diagram of ultrasonic transducers used with crack-detection device.

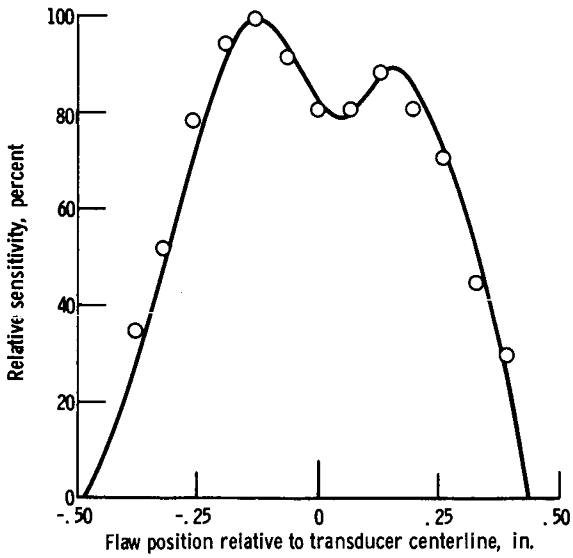


Figure 3. - Variations in sensitivity across typical 1-inch transducer. Distance from flaw, 0.25 inch.

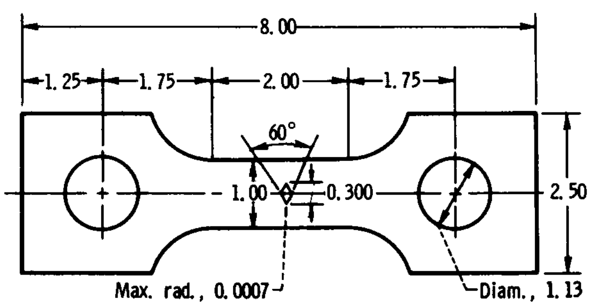


Figure 4. - Notched-sheet fatigue specimen. (Dimensions are in inches.)

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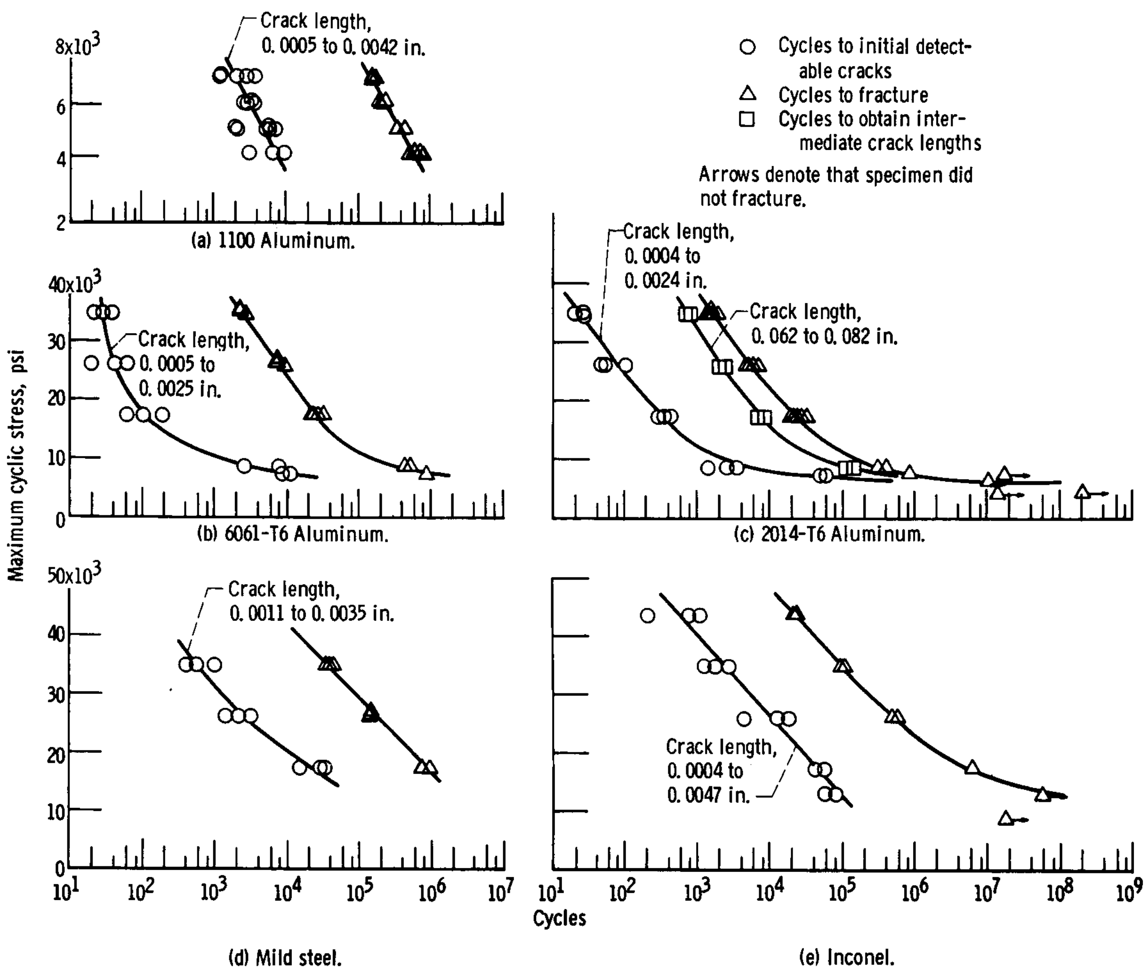

Figure 5. - Stress-life (S-N) curves showing cycles to first detectable cracks and cycles to fracture for center-notched sheet specimens. Ratio of minimum to maximum stress, 0.14.

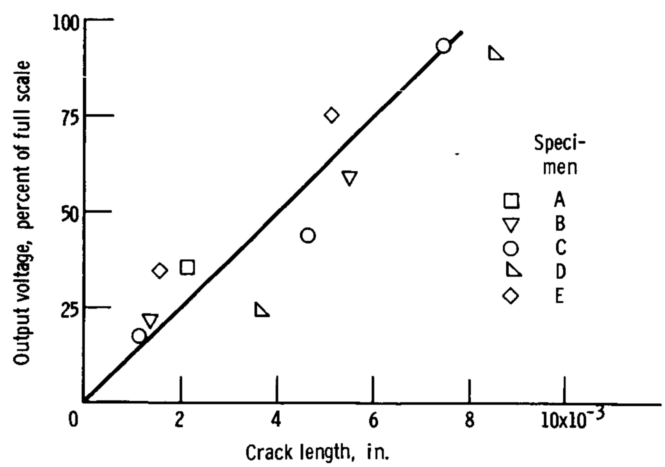

Figure 6. - Crack-detection characteristics for 2014-T6 aluminum.