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MONITORING CRACK EXTENSION IN FRACTURE TOUGHNESS TESTS BY ULTRASONICS

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ABSTRACT

An ultrasonic method was used to observe the onset of crack extension and to monitor continued crack growth in fracture toughness specimens during three point bend tests. A 20 MHz transducer was used with commercially available equipment to detect average crack extension less than 0.09 mm. The material tested was a 300-grade maraging steel in the annealed condition. A crack extension resistance curve was developed to demonstrate the usefulness of the ultrasonic method for minimizing the number of tests required to generate such curves.

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SUMMARY

An ultrasonic method was applied to observe onset of crack extension and to monitor continued crack growth in fracture toughness specimens during three point bend tests. The pulse-echo technique was employed using a 20 MHz transducer and commercially available equipment. The specimen material, a 300-grade maraging steel in the annealed condition, was chosen for its crack extension characteristics. Specifically, these are that crack extension begins near maximum load and is preceded and accompanied by significant plastic deformation at the crack tip.

The ultrasonic method provided a clear indication of the onset of crack extension in the specimens tested. Cracks were initially detected prior to reaching maximum load, before any clear indication was apparent from the specimen load versus load displacement record. The initially detectable crack extension was less than 0.09 mm. The method also indicated the relative magnitude of larger crack extensions.

A crack extension resistance curve was developed for the test material. The data show that the ultrasonic method can be used to either reduce the number of tests required to generate such a curve or to obtain more useful information from any given number of tests.

INTRODUCTION

Determination of the point of onset of crack extension has been a problem throughout the history of fracture toughness testing largely because of an inability to isolate the process of crack extension from that of plastic deformation. This inability is not critical in the measurement of plane-strain fracture toughness (K_{Ic}) by ASTM Test Method E399-74 (ref. 1), since the method is limited to specimens in which the crack tip plastic region is small compared to certain specimen dimensions. For many technologically important materials, however, the specimen dimensions required by the test method become so great that plane-strain fracture toughness testing becomes impractical. Thus, much effort is presently being expended in developing test methods for determination of a quantity similar to K_{Ic} for materials that exhibit large scale yielding at the crack tip. Any method that could be used to clearly signal onset of crack extension in these materials during fracture toughness testing would be extremely useful as a research test tool. If the method could also be used to monitor continued crack growth, its usefulness would be even greater.

Methods for detecting the onset of crack extension have been used with limited success in the past. Each presents associated difficulties that can be severe depending on the particular application. Optical microscopy and penetrating liquids, for example, reveal the part of the crack open to the specimen surface but give no indication of prior cracking in the middle of the specimen. A technique described in reference 2 measures the electric potential across the crack. A well regulated current supply is required and the potential is measured between two probes straddling the specimen notch opening. This method apparently is not appreciably influenced by crack tip plastic flow except when changes in the shape of the crack result. However, voltage measurement can be affected by such things as probe contact resistance, and interfering signals by devices that radiate a wide band of frequencies. Acoustic emission detection is another technique which has been used in crack toughness tests for many years (ref. 3). This method probably has the greatest inherent sensitivity to crack extension, but often it is difficult to distinguish between noise produced by plastic deformation and noise caused by the crack process. The kind and amount of noise is also influenced by the material being tested and, generally, care must be exercised to exclude interference by emissions from outside the test specimen.

Although ultrasonic methods have been used successfully for monitoring fatigue crack growth in previous investigations (ref. 4 and 5), the method has received little attention in crack toughness testing. The ease with which the ultrasonic technique can be applied and its relative insensitivity to outside interference makes the method an attractive candidate for such an application. Further, the system can also be used on unconventional specimens such as those with internal cracks (e.g. weld specimens with lack of penetration defects) where crack displacement gages are of little use.

The purpose of the present investigation was to obtain preliminary information on the usefulness of ultrasonics for detecting onset of crack extension and monitoring crack growth in fracture toughness tests of a relatively tough material. The pulse-echo technique was employed using a 20 MHz transducer and commerically available equipment. The specimen material was

300-grade maraging steel in the annealed condition. Several tests were terminated when the onset of crack extension occurred, as indicated by the ultrasonic detection system, to confirm the usefulness of the ultrasonic method for signaling crack extension. A crack extension resistance curve for the material was obtained to demonstrate how the ultrasonic method can minimize the number of tests required to develop such a plot.

PRINCIPLES OF CRACK DETECTION BY ULTRASONICS

The principles of ultrasonic wave propagation are described in detail in references 6 and 7. Acoustic energy, in the form of high frequency waves, is transmitted from a transducer into the test specimen. The ultrasonic waves are partially reflected from discontinuities in the specimen. The metal-air interface of a 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 surface area, the intensity of the incident ultrasonic wave, and the crack orientation.

System Design and Operation

A block diagram of the ultrasonic crack detection system used in this investigation is shown in figure 1. As indicated, a commercial ultrasonic flaw detection unit was part of this system. This unit contained a pulse generator used to drive the piezoelectric crystal in the transducer. It also contained amplifiers and a cathode-ray tube that displayed the reflected energy pattern, as well as a time gate and integrator circuitry. An attenuator and an x-y recorder, two components that are not normally a part of the commercial system, were added. The attenuator was inserted between the transducer and the amplifier to control the size of the signal entering the amplifier.

Transducer Selection

Theoretically, high frequency transducers, because of their associated short wavelength, are sensitive to smaller flaws than are low frequency (long wavelength) transducers. However, attenuation of ultrasonic energy is greater at the high frequencies. To obtain the optimum sensitivity, therefore, a compromise must be reached between frequency and energy loss in the material, and this generally must be done experimentally. In fracture toughness testing, high sensitivity is not always required. The amount of crack extension necessary to establish K_{Ic} is approximately 2% of the initial crack length (notch plus fatigue precrack), i.e., $\Delta a/a \cong 0.02$. The specimens of this investigation, for example, had an initial crack length of 15 mm; therefore, the crack extension during test had to be observed ultrasonically before it progressed an average of 0.3 mm. This normally is not difficult; however the nature of the crack surface also has an effect on its detectability. If the fracture surface is relatively flat and smooth (as is the case with brittle materials), the cracks are more readily detectable. Ductile fractures that consist of an irregular, highly-plastically-deformed surface are more difficult to detect because they act like acoustic tile and tend to absorb or disperse the energy rather than reflect it. Thus, a transducer with relatively high frequency (20 MHz) was chosen to take advantage of its higher sensitivity to small reflective areas. Lower frequency transducers were also used, but the number of tests were limited and the data are not reported herein.

Transducer Placement For Crack Toughness Tests

Figure 2(a) illustrates the transducer position on a three-point bend specimen of the type used in this investigation. Ultrasonic waves introduced at one end of the specimen travel the length of the specimen with part of the energy reflected at each discontinuity. A discontinuity appears on the cathode-ray tube as a voltage pulse at a position on the horizontal scale which is representative of the time required for the energy to make the round trip from the transducer to the discontinuity and back. Since sound has a relatively uniform velocity in a given metal, the travel time is also representative of distance. The signal received from the region of the fatigue crack at the end of the specimen starter notch was gated, and a proportional dc voltage amplitude was recorded on the x-y recorder during test. Changes in crack length are indicated as changes in voltage amplitude. This is commonly referred to as the pulse-echo technique because only one transducer is used to send and receive ultrasonic energy.

Figure 2(b) shows a different arrangement that might be used on larger specimens of the same type. The intent here is to get as close as possible to the region of the crack in order to minimize losses due to scattering. The major difference is that a second transducer is used to receive the reflected energy and, therefore, it is sometimes referred to as the pitch-catch technique. The geometry of the arrangement prevents most of the energy from bouncing back to the sending transducer. The transmitter (T) and the receiver (R) of course are interchangeable. Another major difference from the method of figure 2(a) is that this method utilizes shear waves instead of longitudinal or compression waves. At any given frequency, shear waves have approximately one half the wavelength and velocity of longitudinal waves. It is necessary to use a wedge between the transducer and the specimen to control the wave mode and angle of entry and the resultant angle-of-refraction of the incident waves at the wedge-specimen interface. A requirement for producing shear waves is that the wedge material must have a longitudinal velocity less than one-half the shear wave velocity in the specimen material (lucite is quite suitable for use with most metallic materials). The optimum lucite wedge angle for steel is approximately 35 degrees.

A second standard type specimen for compact tension tests (not used in this investigation) is illustrated in figure 3. Figure 3(a) shows the position for a single transducer utilizing longitudinal waves. The principles of operation are the same as described for figure 2(a). Figure 3(b) illustrates a two transducer shear wave arrangement with the transducers positioned on the large faces of the compact tension specimen. Again, the principles of operation are the same as described for the three-point bend specimen in figure 2(b), the only difference being in the location of the transducers relative to the crack.

Figure 4 shows a third specimen type which differs from the previous two in that the initial crack is not exposed to the specimen surface. The internal crack could be a lack-of-fusion defect in a weld zone for example. With ultrasonics it would be possible to obtain crack extension information on this potentially-useful specimen type. Here the principles of operation are the same as described previously for similar transducer arrangements (fig. 4(a) and (b)). Still another arrangement can be used with this type of specimen that cannot be used with the previous two.

Figure 4(c) illustrates the use of the through-transmission technique. With this arrangement, the receiving transducer indicates the decrease in ultrasonic energy getting through the specimen as a result of crack extension. For this method to work it is required that specimen surfaces where the transducers are located remain parallel throughout the test.

In fracture toughness specimens where an internal flaw is utilized, it may be desirable to extend the original flaw by fatigue cracking. Since visual observation is not possible, a technique such as ultrasonics could be used to monitor this pre-cracking operation as well as extension during fracture toughness testing. The use of ultrasonics for monitoring fatigue cracks has been previously described in references 4 and 5. The principles are the same whether the cracks are exposed to the surface or not.

MATERIAL AND TEST PROCEDURE

Specimen Material

The specimen material used in this study was a 300-grade maraging steel in the annealed condition (0.2% offset yield strength, 731 MN/square meter; ultimate tensile strength, 1041 MN/square meter). This material was chosen for its specific crack extension characteristics, i.e., crack extension begins prior to maximum load, with extension preceded and accompanied by significant plastic deformation in and adjacent to the immediate crack tip region. Annealed 300-grade maraging steel is representative of a material whose plane-strain fracture toughness (K_{Ic}) determination is extremely restricted under the specimen size requirements of ASTM Test Method E399-74. The plane strain fracture toughness in the annealed condition has not been determined, but a specimen thickness in excess of 12 cm would probably be necessary. The specimen size limitations result from the need to scale the specimen to the volume of plastically deformed material in the crack tip region. This scaling is necessary so that the test approximates the elastic model on which the ASTM Test Method is based.

Three-point bend specimens (fig. 2) were utilized in this investigation. The specimens were approximately 13 cm long and had a square cross section, 2.5 cm on a side. The specimens were notched half-way through the cross section and a fatigue crack was propagated another 0.25 cm to make a total initial crack length of 1.5 cm. The specimen end surface to which the ultrasonic transducer was coupled was machined flat and perpendicular to the specimen longitudinal axis within 0.0025 cm, full indicator reading. Surface finish was better than 32 RMS.

Fracture Testing Procedure

Preliminary fatigue cracking and subsequent loading of the bend specimens were performed in accordance with the applicable sections of ASTM Test Method E399-74 (ref. 1). Specimen displacement was recorded by means of a piston and cylinder device which incorporated a standard double-cantilever beam displacement gage as the transducer (fig. 5). This device measured displacement at the specimen knife edges in the direction of the applied load. A small error is incurred by designating this displacement as the actual load displacement. This error is not of significance for the purposes of this paper. Crack mouth displacement was also recorded using a second double-cantilever beam gage mounted between the specimen knife edges.

After loading each specimen to extend the crack a specified amount as estimated by ultrasonics, the load was removed and the specimen placed in an air furnace for 3 hours at 430 °C to heat tint the fracture surfaces. After fracturing the specimen in three-point bending, the fatigue crack and additional crack extension incurred during the crack toughness test were clearly evident. The fractured surfaces were photographed at approximately 4X, and the crack areas were measured with a planimeter. The average crack extension is the projected crack area divided by the specimen thickness. The intent was to obtain a different degree of crack extension in each of a series of specimens to provide data for developing a crack resistance curve which is described in a later section of this paper.

Application of Ultrasonic System

The transducer-specimen arrangement used for this investigation was as shown in figure 2(a) and figure 5. Glycerine was used as a coupling agent for transmitting ultrasonic energy from the transducer to the specimen. The transducer was clamped to one end of the specimen via a yoke clamp (fig. 5). Longitudinal waves traveled the entire length of the specimen. The reflections of these waves from the fatigue crack at the root of the notch were observed as a spike on the cathode-ray tube. The same reflected signal, after passing through the time gate, also was recorded on an x-y recorder (fig. 1). The voltage output was recorded on a scale of one inch per volt and was plotted against load displacement. The amplifier suppression (reject) was adjusted to minimize the electronic noise level. The amplifier gain was adjusted to near its maximum setting. If the signal from the starter notch (fatigue crack) exceeded approximately 20% full scale on the cathode-ray tube, external attenuation was inserted between the transducer and the amplifier until the amplitude was reduced to that level. The x-y recorder was then zeroed. Somewhat greater sensitivity can be achieved by using the amplifier suppression to lower the signal level, thereby permitting a higher effective gain setting (by using less external attenuation). This resulted in a greater increase in recorded voltage level per unit of crack extension.

When utilizing the ultrasonic method for detection of the onset of cracking, care must be taken to prevent contamination of the specimen crack surfaces. Such things as cutting oil or dye penetrant can cause greater ultrasonic transmission across the crack and resultant erratic response to crack extension.

RESULTS AND DISCUSSION

A series of room temperature tests were made to explore the usefulness of the ultrasonic technique for detecting the onset of crack extension in crack-toughness specimens. Since the method's greatest potential may be in its application to subsized (according to ASTM Standard E399-74) specimens, the material tested was a ductile, tough form of maraging steel described in a previous section.

Detection of Crack Extension

Figure 6 shows four sets of curves which are typical of results recorded on an x-yy' recorder during the crack toughness tests. Both ultrasonic output voltage and the applied load were plotted against load displacement (displacement of the specimen in the direction of loading). Each set of curves was taken from a different test and each test was intended to provide a different degree of crack extension. Note that all of the ultrasonic output curves have a similar shape although the overall voltage level differs from specimen to specimen.

When the load is first applied, the output voltage increases very rapidly from zero to the point marked A on the curves. This is followed by a period of gradual increase followed by another abrupt but nonlinear increase at point B (figs. 6b, c, d). The rapid rise during the early part of the test is due to the nature of the fatigue pre-crack. The crack is tight at this stage having been produced at a relatively low cyclic load level resulting in minimal plastic deformation at the crack root. A large portion of the opposing crack surfaces are in contact with each other, squeezed together by residual stresses and resulting in partial transmission of the sound energy. When a relatively small load is applied (as in the early part of the test), the crack surfaces separate causing more energy to be reflected back to the transducer with a corresponding increase in output voltage. Differences in the amount of voltage rise for different specimens can be attributed to variables such as fatigue crack closure force, fatigue crack geometry, slight changes in amplifier gain setting, and others. However, these factors do not adversely affect the capability of the ultrasonic system to detect onset of crack extension which takes place later in the test.

The second stage of less rapidly increasing voltage cannot be explained so simply. It may be true that smaller portions of the crack surfaces near the root require high loads to separate them but this explanation is probably only valid near the knee of the curve. The most plausible explanation is that the remaining voltage change is associated with plastic deformation and may be proportional to the amount of deformation that occurs prior to crack extension. Plastic deformation in the material tested herein results in work hardening which can cause an acoustic impedance mismatch with the surrounding material and subsequent reflection of ultrasonic energy. The effect of course would be expected to vary with the frequency of the sound, with more energy being reflected at the higher frequencies. It is not likely that enough microcracking occurs during this stage of the test to cause significant reflection of energy.

This leaves the third and most important stage of the output voltage versus load displacement curves. This is the stage that represents crack extension and is clearly distinguished from the rest of the curve by an abrupt increase in slope (point B). The curves of figure 6 illustrate the effect of the onset of crack extension and crack growth on voltage. The curves of figures 6(b), (c), and (d), all exhibit the abrupt change which is characteristics of stage 3. The average crack extension is indicated on the figure. The photographs show the fracture surface of each specimen. Figure 6(a) did not exhibit this abrupt voltage change up to the point where the test was stopped. Subsequent examination of the specimen revealed that some cracking had occurred but was so minimal that it was not measurable by the procedure described previously for crack growth determination. Figure 6(b) shows a change of approximately 0.5 volt corresponding to an average crack extension of 0.09 mm (0.0036 in.) and provides an indication of the sensitivity of the method. Note that the load curves in both figures 6(a) and (b) were still rising when the tests were terminated, giving no definable indication that cracking had begun. Figures 6(c) and (d) illustrate that for greater crack growth the ultrasonic output voltage continues to increase but at an unpredictable rate. This is probably due to the ductile nature of the crack.

It is not apparent from the photographs of figure 6, but the surfaces formed during the crack toughness test (black zone) contain a multitude of re-entry surfaces. This is more clearly shown in the electron photograph in figure 7. Only the surface of a crack nearly normal to the direction of ultrasonic wave travel will cause energy to be reflected directly back to the transducer. The total effective (projected) crack surface, however, contributes to the load displacement. Thus if formation of fresh crack surface normal to the direction of ultrasonic wave travel is not continuous, then ultrasonic voltage output cannot be expected to be continuous either. This could account for the irregular nature of the latter part of the ultrasonic output curves in figures 6(c) and 6(d). Less ductile materials with smoother fracture surfaces would produce more uniform ultrasonic response in this third stage.

Crack Toughness Test Results

Figure 8 shows a plot of crack extension resistance versus crack extension incurred during crack toughness tests of annealed 300-grade maraging steel. Commonly referred to as an R curve, the plot describes an energy derivative as a function of crack extension and is used to measure cracking resistance of materials whose size in a given application is insufficient for the requirements of ASTM Test Method E399-74. The energy derivative used in figure 8 is the nonlinear elastic measure, J, whose fundamental units are in terms of energy per unit area. (References 8 and 9 give a more detailed background on the use of J as a developing fracture criterion).

The purpose of presenting this curve is to illustrate the usefulness of the ultrasonic method as a tool for either reducing the number of tests needed to develop an R curve or for gleaning more information from any given number of crack toughness tests. The data in figure 8 represent a total of five tests. Each test is arbitrarily assigned a number from one through five so that the data points can be easily identified. Note that there are two data points plotted for each test. One of the data points for each test falls on the ordinate at the origin of the curve, and the other data point corresponds to the total crack extension at the time the test was terminated. The x-yy' recordings for three of the tests (1, 2, and 4) were previously shown in figures 6(b), 6(c), and (d), respectively. It is evident that the information from tests 1 and 2 used to plot those data points which define the curve at small crack extensions would have been difficult to obtain without ultrasonics because the load versus load displacement curves of figures 6(b) and 6(c) do not by themselves, give positive indication that cracking was in progress. The ultrasonic voltage output, however, gave a clear indication that crack extension had begun and also provided qualitative information as to the relative size of the newly formed crack surfaces. The latter information is obtained by observing that as crack size increases the voltage continues to increase (fig. 6). By using ultrasonics, the experimenter was able to stop each test when the crack reached the prescribed length most useful in characterizing the plot of figure 8. Without ultrasonics, the experimenter must rely on experience or intuition to assess the amount of crack extension during the test. In many cases this results in running unnecessary, repetitive tests. Thus with the aid of ultrasonics in testing, the experimenter cannot only economize on the number of tests required to characterize material behavior, but he can also control the experiment to use the available specimens to their best advantage.

As noted earlier, the use of ultrasonics for the detection of onset of crack extension results in two R curve data points instead of one. The additional point is obtained for every specimen and falls on the ordinate, where crack extension for all practical purposes is zero. This is evidenced by the cluster of data points at the origin of the curve in figure 8. This point would be almost impossible to obtain without the use of some detection device and can be of importance in defining the shape of the R curve. The relatively small size of this cluster also suggests that the reproducibility of the ultrasonic system is good, although this conclusion must be qualified in that the spread in data also includes material variations. The spread contained in the cluster of data at zero crack extension, when converted to the more familiar fracture toughness quantity K (where $K^2 = EJ$, E = Youngs modulus), ranged from 135 to 154 $MN/m^{3/2}$. This represents a variation of ± 7% based on the average value of 143 $MN/m^{3/2}$.

CONCLUDING REMARKS

The application of ultrasonics to the detection of the onset of crack extension appears to have considerable potential in fracture toughness testing. It has been shown herein that an ultrasonic system in its simplest form can be used to significantly reduce the testing effort required to generate data for an R curve for a particular material. Multiple tests, however, still have to be performed since one test provides a maximum of two data points. This limitation could be circumvented by calibrating the device to provide a capability for measuring accurately the size of the crack continuously during its progression. Thus, a complete R curve could be generated for every specimen.

A number of variables must be considered for proper calibration, among them being the shape of the crack front and how it affects the ultrasonic response, particularly as it changes shape during propagation. Another variable is the texture of the crack surface. It was pointed out in the previous section that the material used in this investigation produced crack surfaces that were very rough. This kind of surface produces a different ultrasonic response for a given crack size than would a smooth crack surface normally encountered in more brittle materials. It is apparent, therefore, that a different calibration may have to be performed for each material. It is probable that calibration might be more readily performed for a brittle material than for a tougher material because the crack surfaces are easier to simulate. Therefore, although calibration of the ultrasonic system is feasible, the payoff must be measured in terms of cost and effort for the particular program to which it will be applied.

The system described herein requires no complicated calibration for obtaining qualitative crack size data for a given material. However, if the possibility of electronic repairs or transducer changes in the middle of a program are foreseen, it would be desirable to have a reference standard on which to periodically set up the system electronics. Metal reference standards containing built-in flaws are commercially available.

SUMMARY OF RESULTS

An ultrasonic method was applied to detect onset of crack extension and monitor continued crack growth in three-point bend fracture toughness specimens. The pulse-echo technique was employed using a 20 MHz transducer and commercially available equipment. Fracture toughness tests were performed according to ASTM E399-74 procedures. The specimen material was 300-grade maraging steel in the annealed condition. This material was chosen for its specific crack extension characteristics, which are that crack extension begins near maximum load and is preceded and accompanied by significant plastic deformation in and adjacent to the immediate crack tip region. The following results were obtained:

1. A clear indication of the onset of crack extension was provided by a significant change in slope of the ultrasonic voltage versus load displacement record.

2. Crack extensions of 0.09 mm or less were detected; this was well before any clear indication of cracking was apparent on the load versus load displacement record.

3. The ultrasonic system was capable of providing qualitative information on the relative size of cracks that extended beyond the size of those initially detected.

4. For every specimen tested, ultrasonics provided an additional data point on the ordinate of the crack extension resistance (R) curve. Thus, fewer tests are required to complete construction of such plots than with current test procedures.

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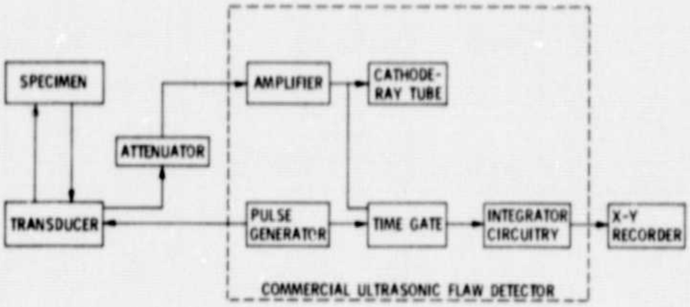
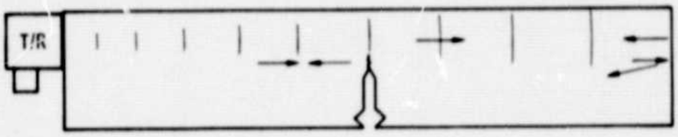
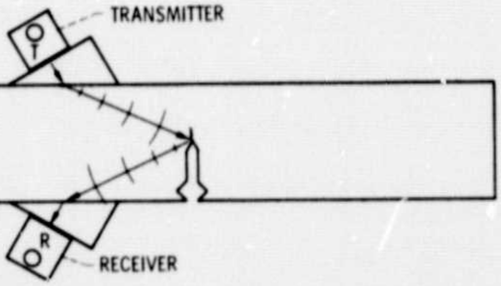


Figure 1. - Crack-detection system.



(a) SINGLE TRANSDUCER PULSE-ECHO TECHNIQUE UTILIZING LONGITUDINAL WAVES.



(b) TWO TRANSDUCER PITCH-CATCH TECHNIQUE UTILIZING SHEAR WAVES.

Figure 2. - Ultrasonic transducer arrangement for use with a three-point bend specimen.

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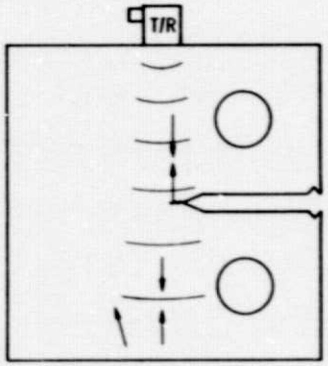
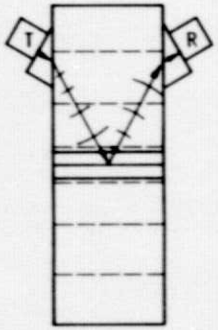
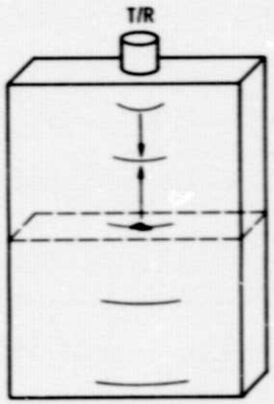


(a) SINGLE TRANSDUCER PULSE-ECHO TECHNIQUE UTILIZING LONGITUDINAL WAVES.



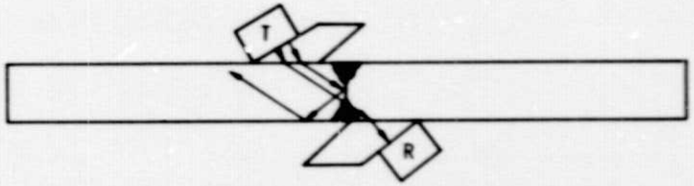
(b) TWO TRANSDUCER PITCH-CATCH TECHNIQUE UTILIZING SHEAR WAVES. (EDGE VIEW).

Figure 3. - Ultrasonic transducer arrangement for use with the compact tension specimen.



(a) SINGLE TRANSDUCER PULSE-ECHO TECHNIQUE UTILIZING LONGITUDINAL WAVES.

(b) SINGLE TRANSDUCER PULSE-ECHO TECHNIQUE UTILIZING SHEAR WAVES (THIN SPECIMENS).



(c) TWO TRANSDUCER THROUGH-TRANSMISSION TECHNIQUE UTILIZING SHEAR WAVES.

Figure 4. - Ultrasonic transducer arrangement for use on specimens with internal cracks (as in welds).

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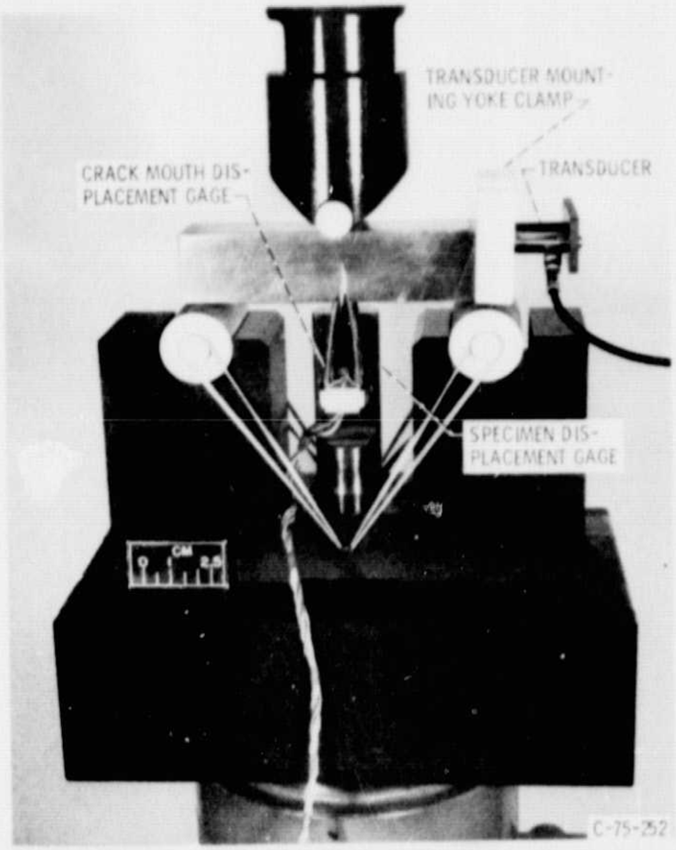
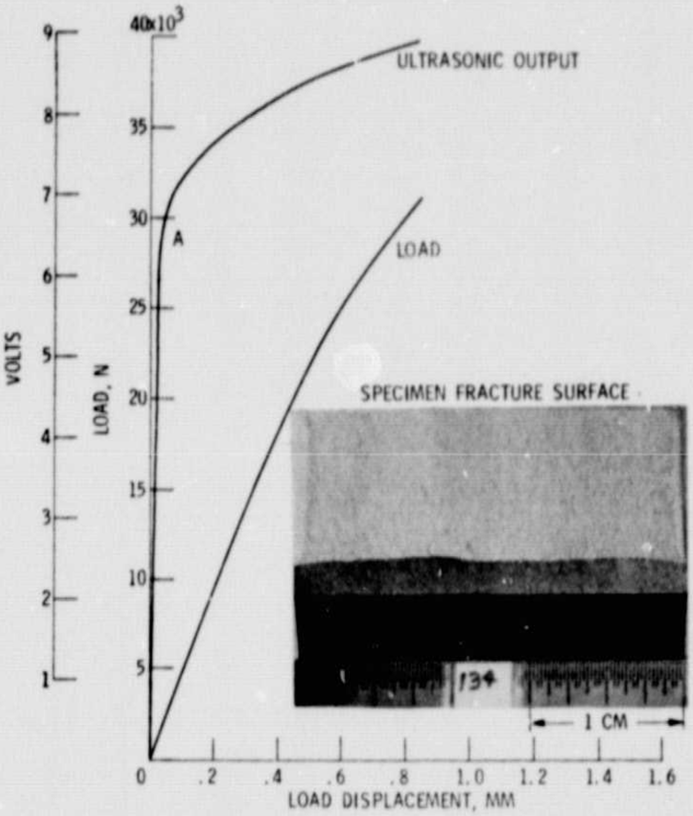


Figure 5. - Three-point bend test device with specimen and ultrasonic transducer in place.



(a) INSIGNIFICANT CRACK EXTENSION

Figure 6. - Load displacement curves showing ultrasonic voltage output and applied load.

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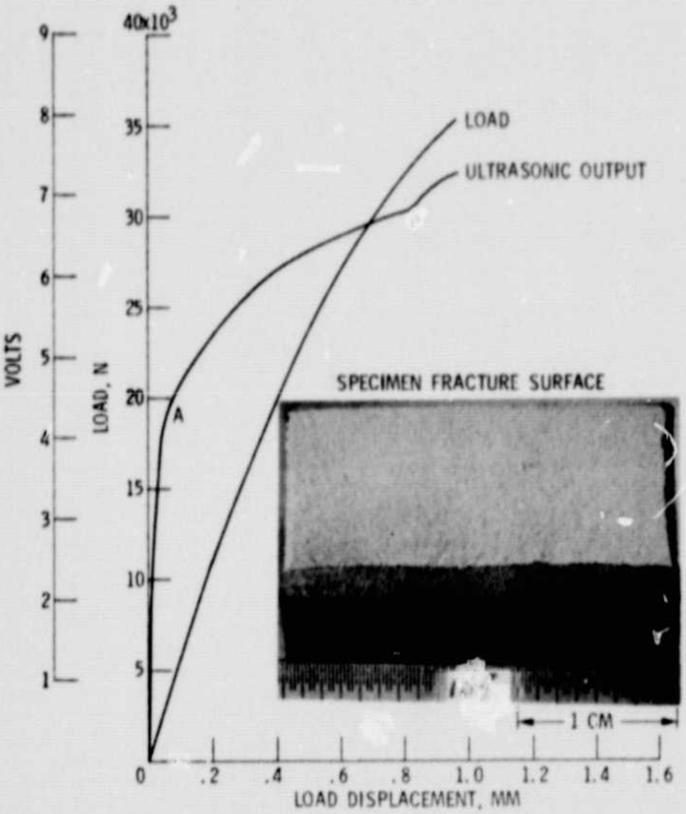
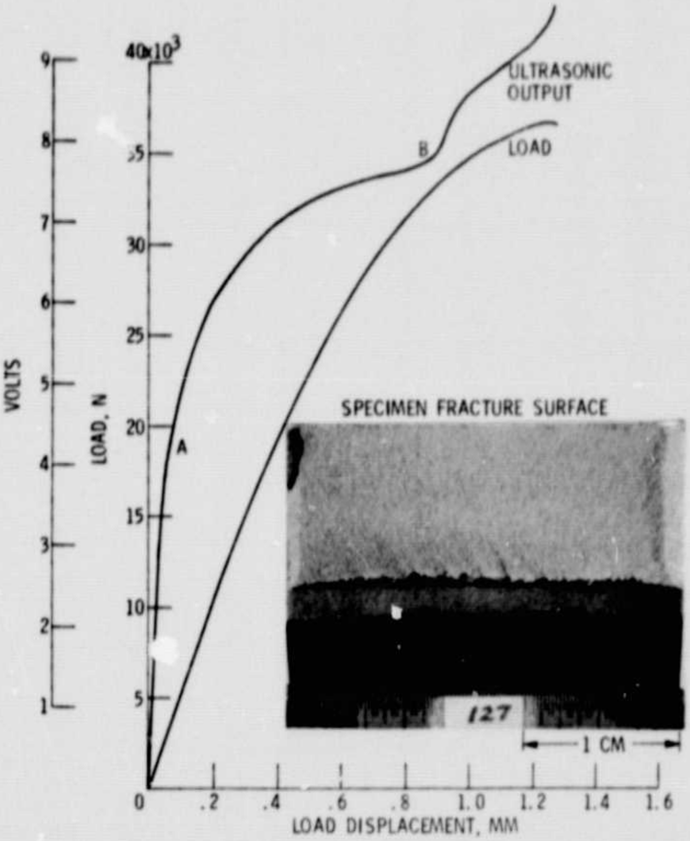


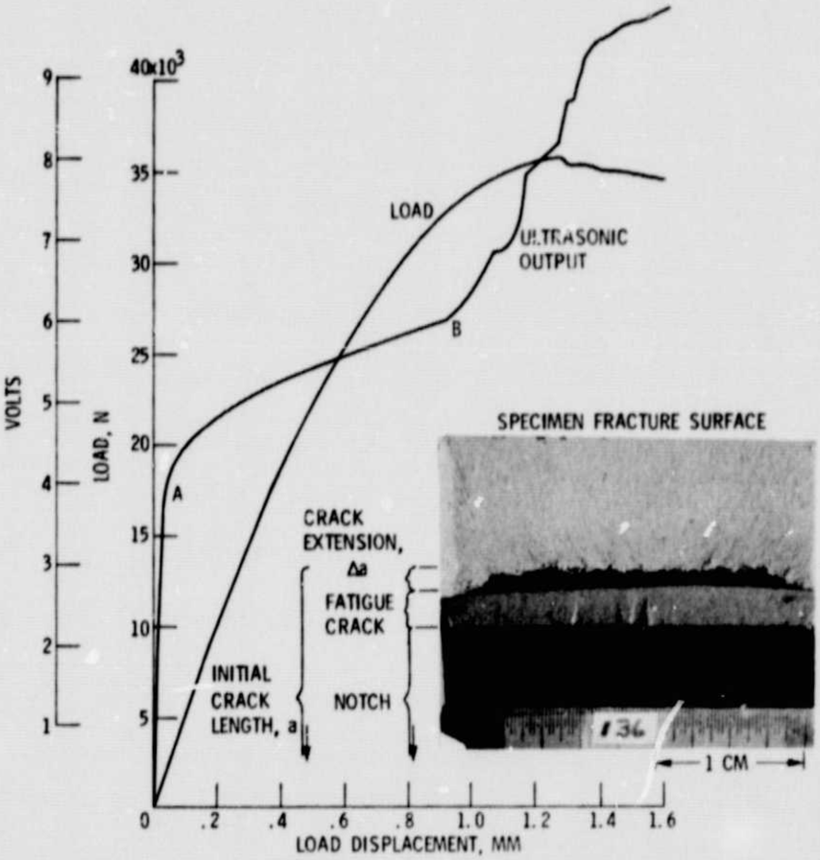
(b) CRACK EXTENSION 0.09 MM (0.0036 IN.).

Figure 6. - Continued.



(c) CRACK EXTENSION 0.36 MM (0.014 IN.).

Figure 6. - Continued.



(d) CRACK EXTENSION 0.92 MM (0.036 IN.).

Figure 6. - Concluded.

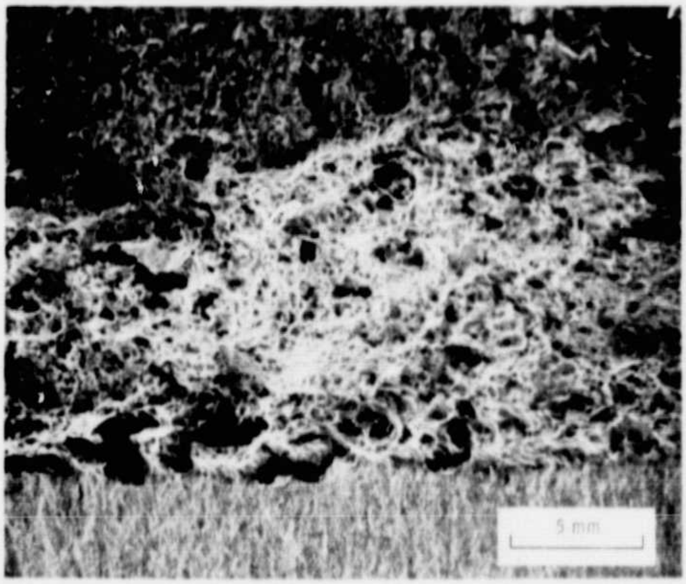


Figure 7. - Scanning electron photograph showing rough ductile nature of the crack surface produced by bending load (top) compared to the relatively smooth fatigue precrack surface (bottom).

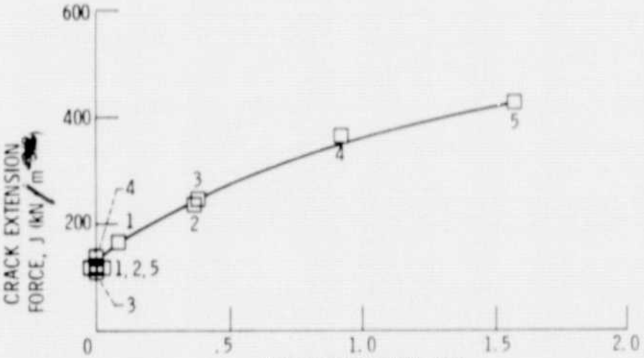


Figure 8. - Crack extension resistance for an annealed 300-grade maraging steel.

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