NASA TECHNICAL MEMORANDUM

NASA TM X-67967

NASA TM X-67967

CRACK TOUGHNESS EVALUATION OF HOT PRESSED AND FORGED BERYLLIUM

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TECHNICAL PAPER proposed for presentation at
American Society for Testing Materials Committee on
Fracture Testing of Beryllium
Cleveland, Ohio, December 8-9, 1971

E-6681

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by M. H. Jones[1], R. T. Bubsey[1], and W. F. Brown, Jr.[2]

In a conventional sense beryllium has always been considered a brittle material in that its fracture surfaces appear to be devoid of any evidence of shear lips, impact resistance is extremely low at room temperature, tensile elongation values of one or two percent are frequently reported, and the metal is not formable at room temperature. With these characteristics one would think that beryllium should have a very poor plane strain fracture toughness and that the value could easily be determined by the methods specified in ASTM E 399-70T Tentative Method of Test for Plane Strain Fracture Toughness of Metallic Materials. However, for a number of reasons, attempts to conduct plane strain fracture toughness tests have met with very limited success. The object of the present investigation was to develop methods for overcoming the major difficulties and to produce useful measures of crack toughness for both hot pressed and forged beryllium.

A major problem in fracture testing of beryllium has been the production of fatigue cracks in the test specimens.[(3)] Difficulties arise in maintaining satisfactory control of the crack due to the fact that the stress intensity necessary to start the

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crack in normal fatigue cycling (R>0) is very close to K_{Ic}. It should be noted that Finn et al.[2] have reported success in producing fatigue cracks in four inch wide center-slotted panels of thin (0.040 inch) sheet stock using small elox slots (0.2 or 0.4 inch) as starters. However, this experience is difficult to translate to the production of standard K_{Ic} specimens.

Several approaches have been made to develop plane strain crack toughness data from beryllium specimens which were not fatigue cracked. Harrod et al.[3] have used WOL (wedge opening loading) specimens with machined notches having a two mil root radii. DCB (double cantilever beam) specimens with side grooves have been employed by Harrod et al.[3] and by Albertin[4]. In these cases the crack was initiated from either a two mil radius notch[3] or a chevron notch[4]. A modification of the wedge force technique was used by Harris and Dunegan[5] to crack SEN (single edge notch) specimens. In this method a crack is initiated by impact wedging of a machined notch. The crack is stopped in a compressed zone produced by clamping nuts with an unspecified force on opposite sides of the specimen below the notch.

While the above methods of specimen preparation avoid fatigue cracking they do introduce uncertainties into the result. Thus, there is no evidence which indicates that machined notches will give the same result as fatigue cracks. In fact past experience indicates this would be highly unlikely for a brittle material. The DCB specimen is capable of yielding a series of values of crack toughness for the initiation and arrest of a crack. However, the initiation values correspond to conditions existing at the crack tip after arrest and these may or may not provide crack toughness values equal to those for fatigue cracked specimens. Side grooves are a necessary feature of the DCB specimen but introduce an additional uncertainty into the result. Cracks stopped in a compressed zone are likely to have reinitiation values that are a function of the conditions within this zone. It is likely that plastic flow and/or twining exist in the compressed zone and that for a given applied lateral force the conditions inside the zone and its extent would depend on the specimen thickness and the applied compressive force.

Another difficulty encountered in the plane strain fracture testing of beryllium is associated with its high tensile modulus which results in very steep load displacement records when using the same instrumentation as employed in testing of steel specimens. Such records are difficult to judge for linearity and the load at the secant intercept (ASTM E 399-70T Sec. 8.1.1) sometimes cannot be obtained with useful precision. Most investigators have simply used the maximum load in the test to calculate the toughness value.

Considering the above described difficulties it is doubtful that the published data define an acceptable plane strain crack toughness value for any grade of beryllium. The data of Harris and Dunegan[5] do show a decrease in toughness (based on maximum load) with increasing thickness and an apparent leveling out of the values at the largest thicknesses tested. However, their method of stopping cracks in a compressed zone could well influence this thickness effect. Thus, for the same lateral compressive force the depth of the compressed zone with respect to thickness would decrease with increasing thickness. Furthermore, the shape of the crack front should be a function of both compressive force and thickness.

The purpose of this investigation was to develop appropriate methods of fatigue cracking and test instrumentation that would permit the determination of valid values of plane strain fracture toughness for beryllium. Tests were made at room temperature over a range of thicknesses for both hot pressed and forged stock using specimens containing fatigue cracks or sharp machined notches. While previously reported experimental difficulties were largely overcome, new ones arose and our results reveal various anomalies in the fracture behavior of beryllium that will make the methods of ASTM E 399-70T inapplicable for determination of K_{Ic} values for some forms of this material.

MATERIAL AND PROCEDURE

Material

The beryllium S-200 specimen stock was furnished by Brush Beryllium Company. Specimens were cut from a large pressing (approximately 30 inches in diameter by 32 inches long) or from a forged disk one inch thick by 16 inches in diameter. Standard commercial practice was used to produce the hot pressed material.

The disk was forged at 1400°F with an upset ratio of 3.75 to 1. Oxidation protection was provided by encapsulating the forging in steel. Pertinent information on the chemistry, physical and mechanical properties of these materials is given in Table I. The tensile properties shown in Table I are those obtained by the producer. We obtained essentially the same results for the hot pressed stock but did not determine tensile properties for the forged disk.

Specimens

Three-point bend specimens of the plane proportions specified in ASTM E 399-70T were cut from the stock and machined by Brush Beryllium Company. All specimens were one inch wide except those having a thickness of 0.03 inch which were one-half inch wide. Two types of crack starters were used for fatigue cracking: (1) chevrons with 10 mil maximum radius and (2) slots one-sixteenth inch wide terminating in 0.5 mil radius V notches parallel to the specimen thickness. The latter configuration was also used for specimens containing machined notches. All specimens had integral knife edges for displacement gage attachment. The orientation of the specimens in relation to the surfaces of the stock was not known except for one group cut from the forged disk. These specimens had their long axis in the radial direction and the notches or cracks perpendicular to the disk surface, and as will be discussed later were characterized by crooked fatigue cracks.

Fatigue Cracking

Fatigue cracks were produced by cantilever bending at 2000 cpm using essentially constant end displacement. A load cell of appropriate capacity was placed in series with the loading train and stress intensity factors were calculated from the measured loads using the K calibration for three-point bending[6]. From results reported by Fisher and Repko[7] it would appear that the stress intensities calculated in this way would be an overestimate of the actual values in cantilever bending. We therefore believe that the provisions of ASTM E 399-70T (Section 6.5.2) designed to ensure adequately sharp fatigue cracks were satisfied.

Attempts to grow fatigue cracks using ratios of minimum to maximum tension loads near zero ($R \approx 0.05$) were generally unsuccessful. Under these conditions, if the K_{max} values were restricted to about 50 percent of the expected K_{Ic} value the cracks would not start in a reasonable length of time (500,000 cycles). The results of trials where the maximum tension load was progressively increased were unsatisfactory in that a crack, once started, grew to failure immediately. We found that by fatigue cycling using reversed bending we could start and grow cracks in a controlled manner, using loads whose tension component corresponded to a maximum stress intensity less than one-half that for crack initiation in the subsequent fracture test. However, as the crack grows in reversed bending the increasing area of contact between its faces reduces the effective compressive force at the crack tip. For this reason, it was necessary to use crack starter notches parallel to the specimen thickness rather than chevrons and to use the maximum length of starter notch consistent with meeting the requirements of E 399-70T. Typically, cracks were started in a few thousand cycles and grown to the desired length in 200 to 300 x 10^3 cycles using a compression load two to three times that in tension. The progress of the fatigue crack was followed with the aid of an oil base dye penetrant which was washed from the starter notch before testing.

The specimens from the forged disk which were known to be oriented in a radial direction generally developed fatigue cracks that were considerably out of plane with respect to the plane of the starter notch. As will be discussed later, this behavior had no discernible effect on the measured toughness values.

Testing

Both crack mouth displacement and electric potential measurements were made during the course of most of the fracture tests. These quantities were recorded against the output of a suitable load cell on an X-Y-Y recorder. The measurement and recording of loads and displacements followed the general procedures specified in ASTM E 399-70T. Because of the high modulus of beryllium and the low fracture loads encountered, it was necessary to provide additional gain in the displacement channel over what was normally available from the X-Y-Y recorder. This was accomplished by use of a Keithley Model 149 millimicrovoltmeter in series with the recorder. The Keithley was operated at a gain of 330 and introduced no visible noise into the load-displacement trace. The displacement gage described in ASTM E 399-70T has relatively stiff arms and would apply a stress intensity factor of about 3 ksi-in$^{1/2}$ to the thinnest beryllium specimen tested. This is about one-quarter to one-third of the crack toughness of the material. The displacement gage was therefore redesigned and provided with magnesium arms. This redesign reduced the wedge force by a factor of six. Where appropriate the reported crack toughness values are corrected for wedge force effects.

Constant current for electrical potential measurements was supplied from six lead acid batteries (60 amp-hour capacity) connected in parallel with a water-cooled ballast resistor in series with the specimen. The voltage supplied by these batteries at a 30 amp load did not change by more than 0.1 percent during the course of a fracture test. The current leads were clamped to the ends of the specimens and the potential leads were connected to the displacement gage arms by means of the bolt fastening the arms to an insulating space block which provided electric isolation between the gage arms. A Keithley Model 149 milli-microvoltmeter was used as a voltage amplifier for potential measurements. The initial potential (corresponding to a few pounds of load) was suppressed and the change in potential during the course of the test was recorded on one channel of the X-Y-Y recorder at one microvolt per inch. This corresponded to a gain through the Keithley of 10^5. The general arrangement of equipment and connections has been described previously[8]. For most of the tests described here a Westinghouse Type SW transformer* was placed in series with the AC supply to the Keithleys in order to reduce the effects of various forms of interference riding on the AC lines.

RESULTS AND DISCUSSION

The results are presented in terms of typical test records of crack mouth displacement and electric potential against load and as stress intensity factors calculated from these records using the K calibration given in ASTM E 399-70T Section 8.1.2. The displacement scales shown on the test records were determined by calibrating the displacement gage using a supermicrometer, directly readable to 50 microinches.

Load Displacement Records

Load-displacement records for the hot pressed stock were nonlinear from initial loading to complete fracture of the specimen. Typical curves are presented in Figure 1 for specimens of several thicknesses. In order to permit comparison between records from specimens of different dimensions the curves in Figure 1 have been normalized by plotting a formally computed stress intensity factor K (based on initial crack length) against a displacement δ normalized to an $a/W = 0.5$ and a $W = 1$ inch (see Appendix A). The curves shown in Figure 1 exhibit three characteristics which blend imperceptibly into one another as the specimen thickness decreases. The initial portion shows relatively small change in displacement with increasing K (applied

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* This is a passive interference suppressor, voltage stabilizer, and line filter.

load). Following the initial portion there is a more gently curved region, the curvature of which increases with decreasing thickness. This region is terminated by the appearance of steps which are associated with cracking. The separation of the curves for specimens of various thicknesses is associated with decreasing transverse constraint as the thickness decreases and the associated effect of plasticity.

Load-displacement records for the forged disk specimens were different from those of the hot pressed material in that the only pronounced nonlinearity observed was associated with the initial portion of the test record. With the exception of one 0.06-inch-thick specimen, all others gave test records which exhibited a maximum load and abrupt failure well within the deviation from linearity corresponding to the 5 percent secant line. For the one exceptional specimen, discontinuous cracking occurred under rising load.

Electrical Potential Records

The electrical potential records for the specimens from hot-pressed stock consistently exhibited anomalous behavior. A typical test record is illustrated in Figure 2 which shows the electrical potential and displacement traces against load for a 0.25-inch-thick specimen. The potential initially decreases to a minimum value and then rises smoothly until discontinuous jumps are produced by cracking. The minimum is observed at load levels which are well below those producing evidence of cracking and considerable potential rise is noted before the discontinuities associated with cracking are observed. The magnitude of the initial decrease in potential varied from about 0.5 to 2 percent of the potential measured at the start of the test. As will be discussed later, this loss in potential is affected by preloading and is almost completely recoverable on unloading.

The electric potential records for the forged disk specimens generally showed very small potential change throughout the test. However, a few specimens exhibited anomalous but inconsistent potential changes.

Crack Toughness and Effect of Notch Radius

For the tests on the hot pressed stock it was not possible to analyze the recorded data to yield K_{Ic} values because of the above described nonlinearity in the load displacement records. For this material K_{max} was calculated based on the maximum load and these values are plotted against thickness in Figure 3 along with K_i values calculated from the first crack indications apparent from the test records (e.g. see Fig. 2). The K_{max} values increase with decreasing thickness for specimens of the same width and are reduced by decreasing the width. This trend of K_{max} with thickness is commonly observed in steels and aluminum alloys. In these materials it is associated with a fracture mode transition which is characterized by the development of shear lips and thickness reduction at the fracture. In contrast, for the beryllium specimens we were not able to measure any thickness reduction and the fracture surfaces were always flat and perpendicular to the longitudinal axis of the specimen. Within the limits of scatter the K_i values are nearly constant over the entire thickness range investigated and for a thickness of 0.50 inch K_i is nearly equal to K_{max}. Based on this behavior a plane strain crack toughness of about 10 ksi-in$^{1/2}$ could be defined for the hot pressed stock.

The K_{max} values for specimens of hot pressed stock with sharp machined notches were in all cases considerably above those for fatigued cracked specimens. Electric potential measurements were not made for the sharp notched specimens and therefore no K_i values were determined.

As mentioned previously the test records for specimens from the forged disk exhibited only small amounts of nonlinearity, and it was therefore possible to calculate K_Q values. These are plotted in Figure 4 against the specimen thickness. Most of the fatigue cracks deviated from the starter notch plane by substantial amounts as indicated by the φ values marked next to the plotted points. This behavior is probably associated with the forging texture and may represent fracture on prism planes. The measured angles varied over a wide range, but this variation appears to have no systematic influence on the K_Q values. This behavior is in contrast with the substantial effects of crack angle reported by Fisher and Repko[7]. The K_Q values appear to rise with decreasing thickness and this effect is most pronounced in the thickness range below 0.25 inch. While all data except that for the 0.06 inch thick specimens met the ASTM E 399-70T requirements in terms of crack length, thickness and linearity of the load displacement records, only the two largest thicknesses were within the specified limits of W/B. Neglecting the fact that most fatigue cracks deviated substantially from the starter notch plane*, the data for the two largest thicknesses define a crack toughness of about 11 ksi-in$^{1/2}$ for the forged disk material.

Values of K_{max} determined from forged disk specimens with machined notches were higher than those obtained from the fatigue cracked specimens; however, this difference is less than observed from the hot pressed materials. Two tests on specimens with a three mil notch radius indicated this notch produced about the same K_{max} values as the 0.5 mil radius notch.

SPECIAL TESTS ON HOT PRESSED STOCK

When a decrease in potential (apparent increase in conductivity) during the initial portion of loading (see figure 2) was first encountered, we judged it to be caused by some difficulty with the equipment and unloaded the specimen after the potential began to decrease rapidly**. Upon reloading the potential increased until the previous load was reached, and then on further loading the potential again decreased. To further study this anomalous behavior which characterized the

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*ASTM E 399-70T, Section 7.2.4 specifies that if the greatest angle between the fatigue crack surface and the plane of symmetry of the notch exceeds 10 degress the test is invalid.

** Results of some additional tests are described in Appendix B which show similar electrical behavior for a titanium alloy. They also indicate that the anomalous electrical behavior observed for beryllium is not likely associated with some experimental difficulty.

hot pressed stock, a specimen was subjected to a series of loadings and unloadings at increasingly higher values of the applied load. The results of typical cycles are illustrated in Figure 5 which shows plots made by an X-Y-Y recorder of load and electrical potential vs. displacement (X axis). The current supply voltage drift during any one loading cycle was less than 0.03 percent. The final cycle carried the specimen to failure and this test record is shown in Figure 6. Before this last cycle the batteries were recharged and the supply voltage drift during the test was about 0.1 percent. It should be noted that the first load cycle is not shown in Figure 5. During this 50-pound preload, the potential continuously decreased and on unloading returned essentially to its initial value at zero load.

A number of interesting observations may be made from these cyclic loading experiments. These are summarized in the following section and represent behaviors which we have not encountered previously and for which we have no satisfactory explanation.

Load-Displacement Records

As mentioned previously, all fracture tests on hot pressed beryllium specimens exhibited nonlinear load-displacement records (see Figure 1). As shown in Figure 5 the effect of preloading does not eliminate the initial nonlinearity (hook) in these records but does produce a region of essentially linear behavior extending to the maximum load of the previous cycle. The unloading traces shown in Figure 5 are linear over a greater range than the loading traces and have a somewhat lower slope so that a negative residual displacement appears*. We have observed a similar hook in the initial portion of the load displacement records for most of our fracture tests on many materials. However, as described in Appendix C, this commonly observed behavior is probably not due to the same effects of those producing the hook in the test records of the beryllium specimens.

Using the unloading traces in Figure 5, apparent values of elastic modulus were calculated from the displacement relationships given by Gross et al.(11) These values are shown in Figure 7 as a function of the preload level. The apparent modulus decreases with successive load cycles from an unaccountably high value of 53×10^6 psi to 43×10^6 psi, a value near that generally reported(15) for hot pressed beryllium.

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*Experiments were made on an aluminum specimen using the same instrumentation as employed in the tests on beryllium. The results of this experiment showed a small positive residual displacement (10 micro-inches) when the aluminum specimen was loaded and then unloaded in the elastic range. This positive residual was independent of the applied preload and was apparently associated with a slight hysteresis in the clip gage.

Electrical Potential Records

Following any load cycle, the potential exhibits an initial increase and then remains essentially constant until the maximum load of the previous cycle is reached after which it begins to decrease. During loading to failure, Figure 6, this decrease is interrupted by cracking which causes a large and discontinuous increase in potential. On unloading during any cycle the potential first recovers at a rate which is nearly equal to its rate of decrease during loading, but the recovery is only partially complete before the potential assumes a nearly constant value with decreasing load. Recovery to near the initial value takes place during the last stage of unloading. This recovery is nearly complete for the lowest load cycles but as the loads increase a progressively larger residual loss in potential remains. It is interesting to compare the behavior during the cyclic loading experiment with that observed for the same thickness (0.25 inch) specimen under continuously increasing load (see figure 2). The potential in the cyclic loading test always decreased when the preload level was exceeded even though this level was well above that corresponding to a large recovery in potential in the continuously loaded test. It should be mentioned that a second 0.25-inch thick specimen was tested under continuously increasing load and the potential minimum occurred at the same load as in the first test.

Electrical potential measurements were made on smooth specimens cut from the same hot pressed stock as were the cracked bend specimens. Load cycling in tension or in compression to near the 0.2 percent yield strength produced no anomolous behavior. The electrical potential varied in a linear manner consistent with the changing cross section of the specimen under load.

Contributing Factors

There are three factors that could contribute to the unusual deformation and electrical behaviors observed in the fracture tests on hot pressed beryllium, namely: microcracking, microplasticity, and twinning. Microcracking might be expected in view of the very low basal plane fracture propagation energy of 7000 ergs per cm^2 (K= 1.3 ksi-$in^{1/2}$) reported by Govila and Kamdar[10]. While decrease in modulus with increasing preload level (figure 7) could be associated with microcracking, the electric potential records do not show any evidence of cracking. Thus, cracking should produce an increase in potential on loading and a decrease in potential on unloading. Microplasticity at low loads could result from localized slip on basal planes and this could contribute to nonlinearity in the load-displacement records. Tuer and Kaufman[16] report a value of about 2000 psi for the critical resolved shear stress for basal slip and, as pointed out by London[17], this value is only 300 psi for very pure crystals. Beryllium exhibits a considerable anisotropy of mechanical and electrical properties[16,12] and twins readily[9]. Therefore it might be expected that twinning could play an important role in establishing the observed behaviors. However, we were unable to find a concentration of twins adjacent to the fracture surfaces by examination (500X) in polarized light of sections normal to the fracture. The twinning that was observed was scattered throughout the body of the sample rather than being concentrated near the fracture and might have been due to polishing. It is, of course, possible that more advanced metallographic techniques would reveal twin concentration in the region of the fracture.

It is evident that a satisfactory understanding of how various metallurgical factors could interact to produce the observed unusual mechanical and electrical behaviors will require a considerably more sophisticated approach to the problem than represented by this investigation. We hope that the results presented will stimulate further studies by specialists in physical metallurgy.

COMPARISON WITH PUBLISHED RESULTS

We are not aware of any published data on the crack toughness of forged beryllium that would be suitable for comparison with the results obtained in this investigation for the forged disk stock. The results of a number of investigations of vacuum hot pressed materials have been reported and room temperature data from these studies are summarized in Table III which also gives the crack toughness values obtained in this investigation. With the exception of the results reported by Harrod et al.[(3)] the orientation of specimens in relation to the block pressing direction was not specified. However, no substantial directionality effects would be expected and this is confirmed by the data of Harrod et al. which shows a difference of about 10 percent between the crack toughness measured in the pressing direction and normal to this direction. Table III gives both the range of crack toughness values reported and the average. It should be noted that in the case of the DCB specimen the ranges reported represent the spread of the initiation and of the arrest values obtained from all the specimens tested.

A useful comparison of the data in Table III is complicated by a number of factors: (1) the specimens used varied both as to type and method of cracking and some were not cracked at all, (2) different grades of material were tested which are different in impurity content and perhaps in other ways, (3) the thicknesses varied and this will influence the reported toughness values when they are based on maximum load, and (4) the basis for determining the load used in the K calculation was not the same throughout. It is quite obvious that the available data are by no means sufficient to characterize the crack toughness of any grade of vacuum hot pressed beryllium for specification purposes. However, some interesting observations may be made on the basis of the data shown in Table III.

The average value of 10 ksi-in$^{1/2}$ for the crack toughness obtained in this investigation is among the lowest listed in this table. It may be compared to a value of 23 ksi-in$^{1/2}$ reported by Harris and Dunegan[5] for 0.5-inch thick specimens of 200 grade stock having essentially the same yield strength. While the toughness values from both studies were based on maximum load, our results indicate that maximum load at this thickness corresponds very closely to the initiation of detectable cracking. The considerably lower toughness which we obtained for S 200 grade is likely due to the fact that a "sharper" crack was produced by the fatigue loading than was produced by stopping a crack in a compressed zone. In tests on N50A stock, Dunegan et al.[14] used this latter method of cracking but employed acoustic techniques to determine the load used for calculation of the K values. As will be noted from Table III the toughness values so obtained for 0.1-inch thick specimens did not differ significantly from those based on the maximum load.

Evidence that natural cracks can produce lower toughness values than machined notches is also provided by the data of Harrod et al.[3]. One-inch-thick WOL specimens with 2 mil notch root radii and 0.25-inch thick DCB specimens were cut from the same S 200 stock and, as noted in Table III, the DCB specimens gave significantly lower toughness values. Unfortunately, the available data do not permit a comparison of the results obtained (for the same stock) from DCB specimens with those obtained from specimens prepared and tested in accordance with ASTM E 399-70T.

The data given in Table III do not support the idea that an increase in purity of the hot pressed stock is accompanied by an increase in the crack toughness. Thus, there is essentially no clear difference in the toughness values reported by Harrod et al.[3] for S 200 grade and those reported by Albertin[14] for the higher purity brake block. Both these investigators used DCB specimens* and tested material of nearly the same yield strength. The same conclusion can be made on the basis of the data reported by Harris and Dunegan[2] for S 200 stock as compared with the higher purity N50A grade. In this case, 0.30 to 0.35-inch thick specimens of N50A had a lower yield strength and lower toughness than 0.35 or 0.50-inch thick specimens of S 200 grade.

CONCLUSIONS

In formulating the following conclusions, particular emphasis has been placed on identifying those points which are of importance to the development of practical fracture test methods for beryllium. However, it should be kept in mind that we tested only hot pressed stock and a forged disk. It is likely that the fracture properties of beryllium will be strongly influenced by fabrication history and that investigation of other forms should be undertaken before fracture test methods for beryllium are formulated.

1. Beryllium fracture toughness test specimens were successfully fatigue cracked using reversed cycling with a

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* The first crack initiation value reported by Albertin was not included in Table III because it corresponded to initiation from the tip of the chevron notch and as might be expected was considerably lower than subsequent values.

compression load two to three times the tension load. Typically, cracks were started in a few thousand cycles and grown under satisfactory control to the desired length in 200,000 to 300,000 cycles with the maximum stress intensity in fatigue less than one-half the K value for crack initiation in the subsequent fracture test.

2. In worked beryllium, textures may be produced which result in fatigue cracks that are out of plane with the starter notch. Substantial deviations of this type were observed in our tests on forged disk stock; however, they produced no systematic influence on the measured fracture toughness.

3. Because of the high modulus and low fracture loads which characterize beryllium, it is necessary to use extra amplification in the clip gage output channel beyond that normally available from X-Y recorders. Without this amplification, the load-displacement trace cannot be adequately examined for deviations from linearity.

4. Specimens of hot pressed stock exhibited load-displacement records which were nonlinear throughout their course. This nonlinearity decreased with increasing specimen thickness but was sufficiently pronounced for the thickest specimen (0.5 inch) that the initial slope of the test record could not be unambiguously established. For this reason, the procedures of ASTM E 399-70T Tentative Method of Test for Plane Strain Fracture Toughness of Metallic Materials could not be applied. Specimens from the forged disk exhibited linear load-displacement records and with one exception the maximum load

in the test occurred before five percent deviation in linearity was reached.

5. Fractured specimens of both hot pressed and forged stock showed essentially no reduction of thickness and the fracture surfaces were flat and normal to the load axis. However, the stress intensity factor at maximum load K_{max} increased with decreasing thickness while the stress intensity factor K_i corresponding to the first crack indications was essentially independent of thickness.

6. Values of K_{max} obtained with very sharp (0.5 mil) machined notches were higher than corresponding values from fatigue cracked specimens. In this respect the behavior of beryllium is in line with that observed for brittle steels and titanium alloys.

7. For reasons discussed in this paper, valid K_{Ic} values could not be determined for either the hot pressed or forged beryllium stock. However, the data do define a value of about 10 ksi-in$^{1/2}$ for crack initiation in both these forms under plane strain conditions and for the loading rates specified in ASTM E 399-70T for plane strain fracture toughness tests.

8. Load-displacement and electric potential records for the hot pressed beryllium specimens exhibited several anomalies. Included among these were negative residual crack mouth displacements for specimens which were loaded in the "elastic range" and then unloaded, and a decrease in electrical potential (increase in conductivity) with increasing load which is recoverable on unloading.

APPENDIX A: PROCEDURE USED FOR NORMALIZING LOAD-DISPLACEMENT CURVES

The load-displacement curves for specimens of various thicknesses are best compared after normalizing them to account for variations in specimen plane dimensions. This may be accomplished by reducing the load-displacement records to a plot of K vs δ where δ is the displacement normalized to an a/W = 0.5 and W = 1 inch. For the three-point bend specimen with a 4W span

$$K = \frac{4\,P}{B\,W^{\frac{1}{2}}}\,Y$$

and

$$v = \frac{P}{E\,B}\,F$$

where P is the applied load, W the specimen width, B the specimen thickness and E the elastic modulus. Y and F are functions of a/W where a is the initial crack length. Values for Y can be found in ASTM E 399-70T Section 8.1.3.2 and values of F are given by Gross et al.[11] Substituting for P

$$v = \frac{K\,W^{\frac{1}{2}}\,F}{4\,E\,Y}$$

For W = 1 inch and a/W = 0.5, F/Y = 13.4. Therefore the normalized displacement

$$\delta = \frac{13.4\,Y}{W^{\frac{1}{2}}\,F}\,v$$

where v is the measured displacement for a particular specimen and the remainder of the terms take values corresponding to the plane dimensions of the specimen. Curves of K vs δ obtained in this way will coincide provided the specimens behave in a linear elastic manner and the constraint is constant. Separation of the curves in Figure 1 is in part due to decreasing constraint with decreasing thickness and in part to nonlinear behavior which increases with decreasing thickness.

APPENDIX B: ELECTRICAL POTENTIAL MEASUREMENTS ON A TITANIUM ALLOY

A test was made on a titanium bend specimen with the object of determining whether the anomalous electrical behavior observed for beryllium would also characterize another hexagonal metal. A one-inch thick specimen of standard proportions (E 399-70T) was cut from alpha-beta forged and mill annealed Ti-6Al-4V plate, fatigue cracked in bending ($R \approx 0.1$) and instrumented in the same way as were the beryllium specimens. A second set of potential leads was clamped to the specimen near the crack mouth in order to determine whether the method of potential sensing through the clip gage used with beryllium specimens might have introduced some spurious effects. The results of this test are given in Figure B-1 which shows the load and the electrical potential as a function of the crack mouth displacement. The electrical potential rises rapidly as the load is applied due to the opening of the fatigue crack which was produced by tension-tension loading and is therefore closed at the start of the fracture test. It should be noted that this initial rise in potential was not observed for the beryllium specimens because they were fatigued in reversed cycling and therefore the crack faces were not in contact at the start of the fracture test. Following the initial rise, the potential remains constant over a rather narrow load range and then passes through a pronounced minimum as was observed for the beryllium. The traces for each method of potential sensing are essentially identical.

High sensitivity potential measurements were also made on aluminum (5083-0 and 6061-T6) bend specimens of standard proportions. These revealed no trace of the potential minimum observed for the beryllium and titanium stock. Tests on these aluminum alloys produced potential records which show the expected abrupt rise followed by a region of constant potential which terminates in a steady rise due to crack extension.

APPENDIX C: NONLINEARITIES IN LOAD-DISPLACEMENT RECORDS AT SMALL DISPLACEMENTS

Frequently in plane strain crack toughness tests a small nonlinearity or "hook" is observed in the initial portion of the load-displacement record. This hook gives the appearance of a decreasing specimen stiffness with increasing load and has been attributed to seating of the specimen and the clip gage (ASTM E 399-70T Note 6). Some further information concerning this nonlinearity can be obtained from precision displacement measurements that we made on fatigue cracked and on slotted specimens during a compliance investigation. The general geometry of these aluminum alloy specimens is shown in Figure C-1. One specimen contained a fatigue crack extending from the edge to the center of the width. The fatigue cracking procedures outlined in ASTM E 399-70T were followed with the exception that shallow side grooves were used to guide the crack. An oil base dye penetrant was used to mark the progress of crack growth. After fatigue cracking the crack starter and the side grooves were removed and integral knife edges provided for attachment of the displacement gage. The other specimen was provided with a square bottomed narrow slot (0.01-inch wide) having a length of one-half the specimen width. Signals from the load and displacement transducers were read from a digital voltmeter, and the resulting data are plotted in Figure C-1 which shows the behavior on loading and unloading within the elastic range.

The specimen with the machined slot shows linear behavior on both loading and unloading. The specimen with the fatigue crack exhibits an initial nonlinearity (hook) which fades out at small displacements and shows completely reversible displacements on unloading. We thought perhaps dye penetrant remaining in the fatigue crack could be responsible for the nonlinear effects due to surface tension forces and therefore removed the crack tip with an 1/8-inch diameter drill so that the crack faces could be cleaned while completely separated by elastic loading. The crack surfaces were flushed with acetone and dried in an air stream. Subsequent displacement measurements showed the hook was still present. In the case of these aluminum specimens we believe that the hook was associated with the forces necessary to separate the crack faces and not due to difficulties with seating of the specimen and the clip gage. It is our opinion that in most plane strain crack toughness tests, these same forces act to produce a hook in the load-displacement records of specimens that have been fatigue cracked in tension-tension. The magnitude of the effect will, of course, depend on the length of the fatigue crack, and it should be noted that we employed a very long crack.

However, it is doubtful that the hook observed in the load-displacement records for the hot pressed beryllium can be explained in the same way for the following reasons: (1) The crack in the beryllium specimens is probably open after fatigue cycling because of the relatively high compression loads that were used. Electrical potential measurements confirm this because they do not show a sharp rise in potential at the start of the fracture test which would be characteristic of the opening of a tight crack. (2) The displacements in the beryllium specimens were not completely reversible on unloading. (3) Relative to the size of the fatigue crack the hook was much larger in beryllium than in aluminum specimens.

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TABLE I. - CHEMICAL COMPOSITION AND PROPERTIES OF SPECIMEN STOCK

Form	Composition, ppm							Grain size microns	Degree of orientation	Density, lb/in.[2]	Tensile properties			
	BeO	Fe	C	Al	Mg	Si	Be				Ultimate strength, ksi	0.2% yield strength ksi	Elong. percent (4D)	R.A. percent
Hot pressed block no. 2340	16700	1100	1070	750	40	250	Bal.	13	1N	0.067	45.7	39.1	1.2	1.3
Hot pressed block No. 2172	16500	1180	1000	700	40	300	Bal.	12	1N	0.067	46.7	36.3	1.0	1.3
Forged disk No. 209-2-8341	17100	1280	1300	400	110	260	Bal.	21	4N	0.067	85.4	60.7	11.1	17.0

TABLE II. - SUMMARY OF CRACK TOUGHNESS VALUES REPORTED FOR VACUUM HOT PRESSED BERYLLIUM

Type of Be	Thickness, in.	Reference source	σ_{YS} ksi	Specimen type	Type of notch or crack	Basis for K calc.	Number of specimens tested	Crack toughness, K ksi $\sqrt{in.}$			
								Initiation		Arrest	
								Range	Avg.	Range	Avg.
S-200	0.50	5	40	SEN[a]	b	Maximum load	2	20 - 26	23		
	0.35	5	40	SEN[a]	b	Maximum load	3	13 - 23	17		
	0.25	3	33	DCB[c]	c	Maximum load	2	14 - 15	15	12 - 13	12
	1.0	3	33	WOL[d]	d	Maximum load	9	17 - 25	20		
	0.25 to 0.5	present Invest.	39	Bend	Fatigue	See text	5	10 - 11	10		
N 50A	0.1	5	29	SEN[a]	b	Maximum load	9	18 - 22	20		
	0.1	14	29	SEN[a]	b	e	6	18 - 21	19		
	0.30 to 0.35	5	29	SEN[a]	b	Maximum load	3	11 - 15	13		
Brake grade Block - Lot I	0.25	4	31	DCB[f]	Chevron	Maximum load	3	10 - 14	12	7 - 11	8
Lot II	0.18	4	31	DCB[g]	Chevron	Maximum load	1	14 - 15	14	12 - 14	13

[a]SEN; $W = 1.5$ in., $0.2 < a/W < 0.45$.
[b]Wedge induced crack stopped in compressed zone.
[c]DCB; $W = 7$ in., $B_n = 0.13$ in., $a_o = 1$ in. notch rad. = 2 mils.
[d]WOL; $W = 1.125$ in., $a_o = 0.5$ in., notch rad. = 2 mils.
[e]Acoustic emission.
[f]DCB: $W = 5$ in., $B_n = 0.19$ in., $1.5 < a_o < 2$ in.
[g]DCB; $W = 5$ in., $B_n = 0.13$ in., $a_o = 1.5$ in.

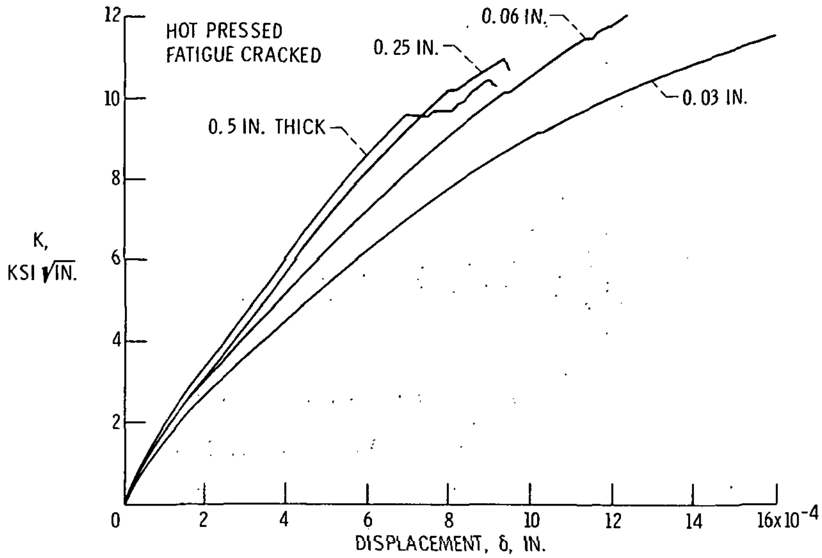

Figure 1. - Normalized load versus displacement records for beryllium bend specimens of several thicknesses from hot pressed stock.

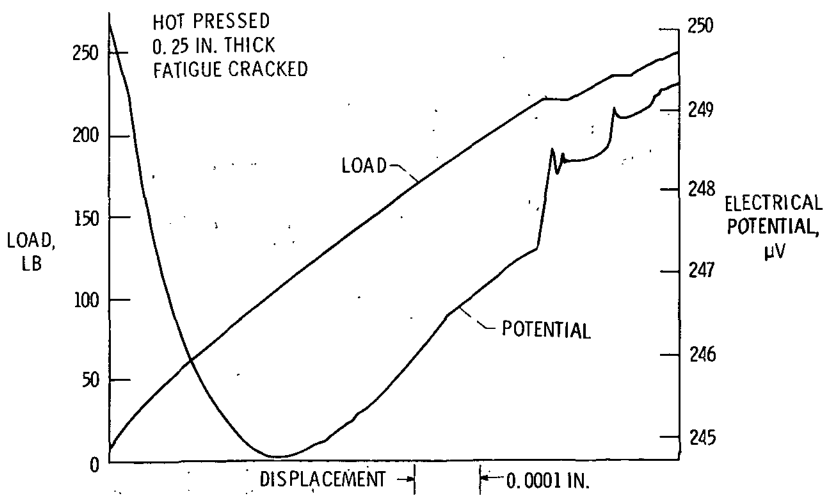

Figure 2. - Load and electrical potential records for a 0.25-inch-thick beryllium bend specimen from hot-pressed stock.

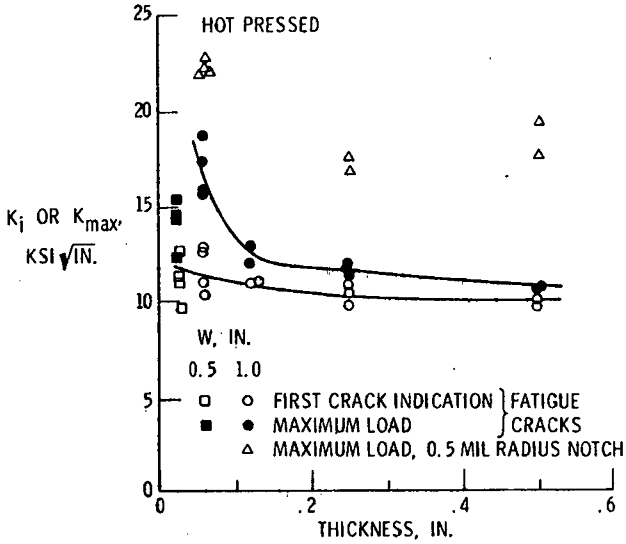

Figure 3. - Effect of thickness on toughness of fatigue cracked or sharply notched beryllium bend specimens cut from hot pressed stock.

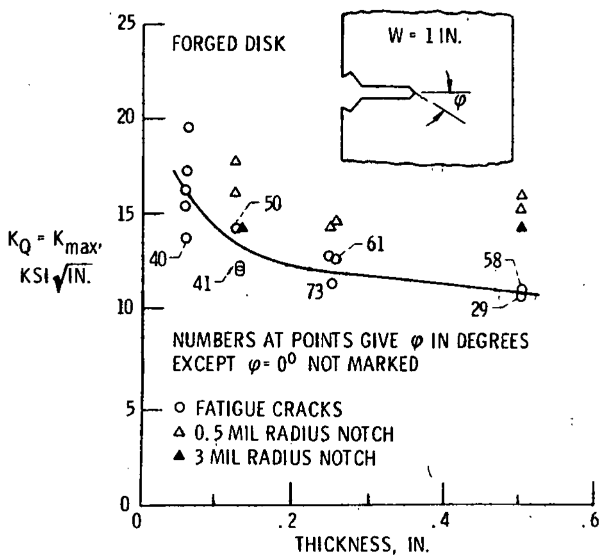

Figure 4. - Effect of thickness on toughness of fatigue cracked or sharply notched beryllium bend specimens from a forged disk.

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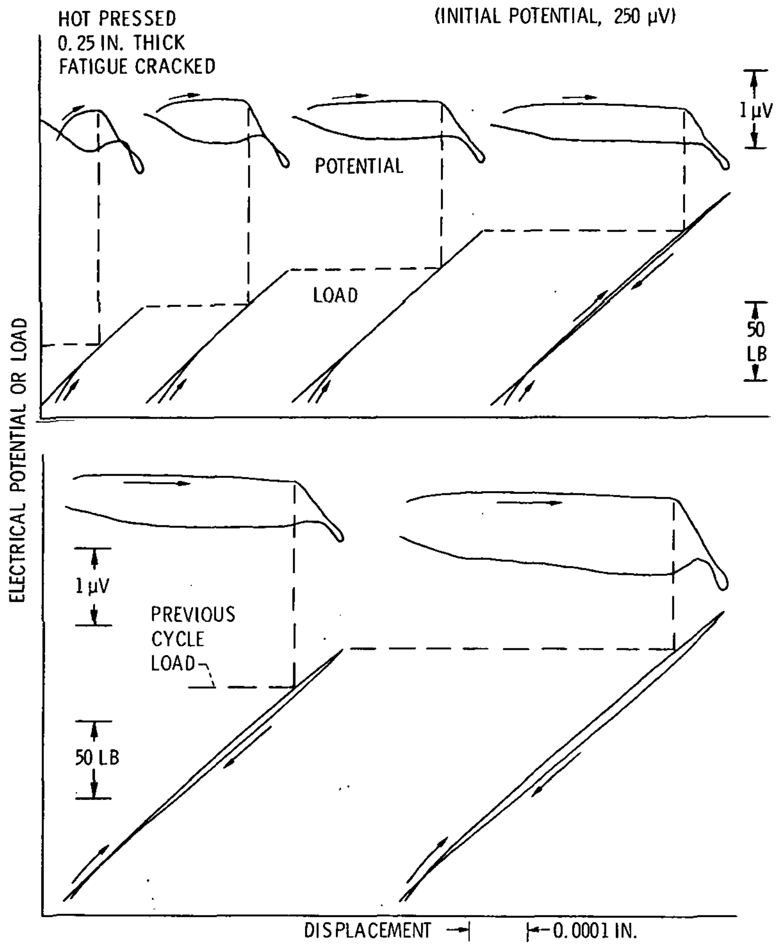

Figure 5. - Load and electrical potential versus displacement records for cyclic loading of a bend specimen from hot pressed stock.

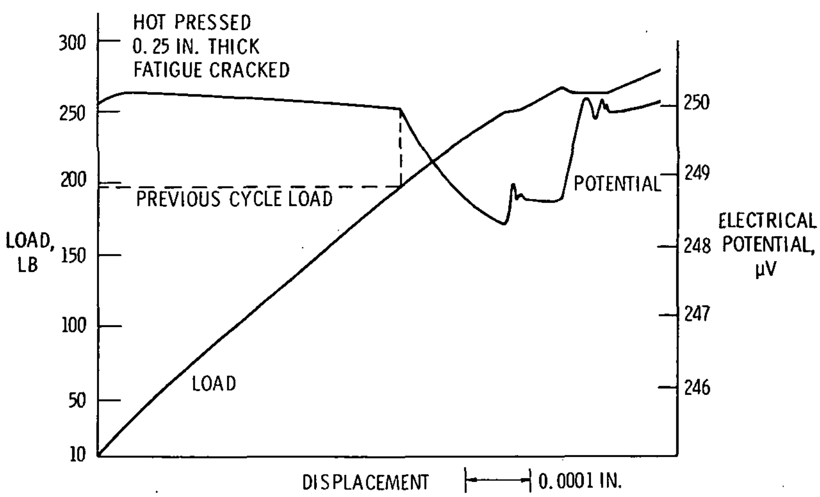

Figure 6. - Load and electrical potential versus displacement records for final loading cycle of the series shown in figure 5.

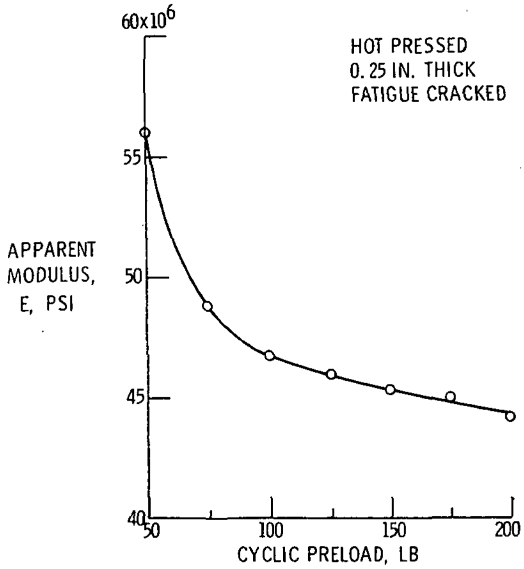

Figure 7. - Apparent elastic modulus as a function of the cyclic preloads used in the test represented by figure 5.

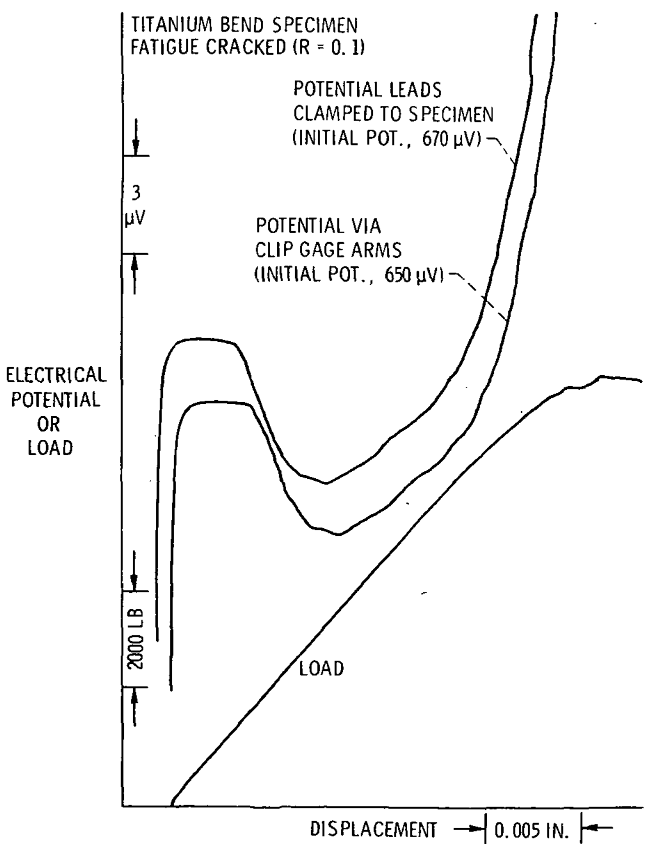

Figure B-1. - Load and electrical potential versus displacement records for a one-inch-thick annealed Ti-6Al-4V bend specimen.

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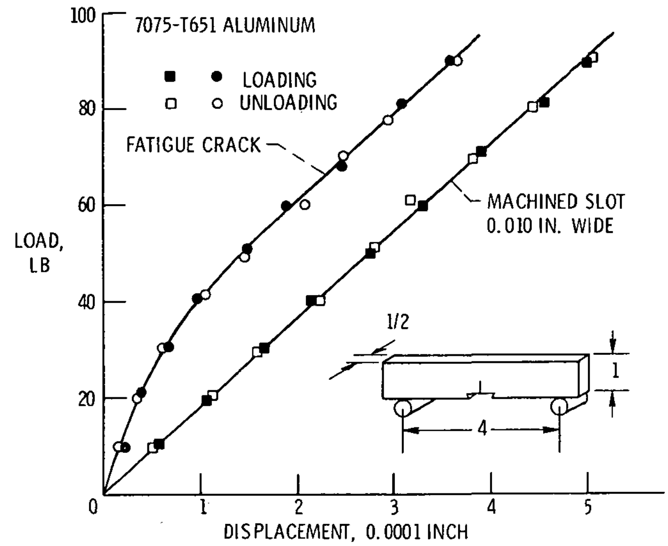

Figure C-1. - High sensitivity load and elastic displacement measurements for a fatigue cracked and for a slotted 7075-T6 aluminum bend specimen.