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CONTINUITY GAGE MEASUREMENT OF CRACK GROWTH ON FLAT AND CURVED SURFACES AT CRYOGENIC TEMPERATURES*

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SUMMARY

A method for measuring instantaneous crack length with a multiple-element foil continuity gage is described. The gage is of particular use in measuring plane-stress crack growth on curved surfaces and at cryogenic temperatures. In order to interpret the output of the gage properly, an experimental calibration program was conducted with through-center-notched aluminum alloy (2014-T6 aluminum), extra-low-interstitial (ELI) titanium alloy (Ti - 5 Al - 2.5 Sn), and stainless-steel (AISI 301) flat-sheet specimens at temperatures to -423° F. The calibration program also included through-cracked aluminum alloy cylinders pressure cycled at -320° and -423° F.

The experimental calibration program showed that the technique used in mounting the gage was critical in obtaining proper operation. In some cases, the fracture of a gage element was caused by the high plastic strain at the crack tip and not to the crack growing through the element. An analytical expression was used to take into account this plastic strain and to minimize the number of test specimens required for an accurate calibration.

INTRODUCTION

Determination of the fracture toughness of a material by using the Griffith-Irwin fracture criterion (ref. 1) requires knowledge of the crack length at the onset of rapid fracture or unstable crack growth. Also, in order to determine the rate of crack growth in materials subjected to cyclic loading requires a means of monitoring the crack length. Srawley and Brown (ref. 2) describe several methods for measuring the instantaneous crack length including cinematography, electrical potential measurement, and displacement (compli-

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ance) gaging. Each of these methods becomes difficult or impractical when the test specimen is immersed in a cryogenic liquid or when it is desired to measure crack growth on a curved surface such as a cylindrical pressure vessel. A multiple-element continuity gage has been developed at the Lewis Research Center for measuring crack growth at cryogenic temperatures both on flat and on curved surfaces. While designed primarily for measuring plane stress crack growth, the gage might be used to measure surface crack growth under plane strain conditions as well. The application and use of the continuity gage are described in this report.

The NASA continuity gage is an electrical-resistance foil gage consisting of multiple elements connected in parallel and is mounted with the elements perpendicular to the expected direction of crack growth. As the crack grows, individual elements fracture near the crack tip, giving an abrupt and easily monitored change in the gage resistance. Because the gage is mounted on the surface of the specimen, the gage elements are, of course, primarily influenced by the behavior of the metal at the surface directly beneath the gage. It would, therefore, be expected that the correlation of the gage element fracture with the position of the crack tip would depend on several factors, such as specimen thickness, amount of tunneling, size of the plastic zone at the tip of the crack, and magnitude of the total strain in the specimen relative to the fracture strain of the gage elements.

In view of the factors that can affect the relation of the gage-output signal to the crack tip location, a research program was undertaken to determine whether or not the continuity gage could be effectively employed in the study of fracture mechanics, and to determine its limitations and the calibration procedures required for its use. This report describes the multiple-element foil continuity gage, its electrical circuitry, and proper gage mounting techniques. The behavior of the gage on 2014-T6 aluminum, ELI Ti - 5 Al - 2.5 Sn, and 301 stainless-steel flat sheet at temperatures to -423° F is reported as well as its behavior on pressure-cycled 2014-T6 aluminum cylinders at -320° and -423° F. Comparisons are made between the results of the experimental program and an analytical method developed in a previous investigation (ref. 3) that relates the crack tip position to the gage response.

CONTINUITY GAGE DESCRIPTION

The continuity gage resembles a conventional metal foil strain gage except that its individual elements are of varying length and are connected in parallel rather than in series. The gage is made of Nichrome V alloy foil, about 0.00015 inch thick, and is mounted on a strippable vinyl backing. The gage configuration is shown in figure 1. Nichrome V alloy was specified over the more common copper-nickel alloys because its

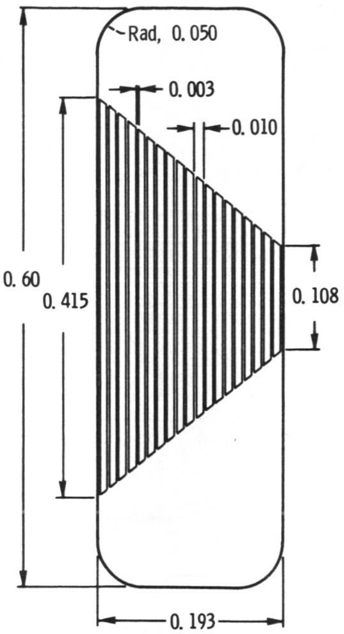


Figure 1. - NASA continuity gage. (All dimensions are in inches.)

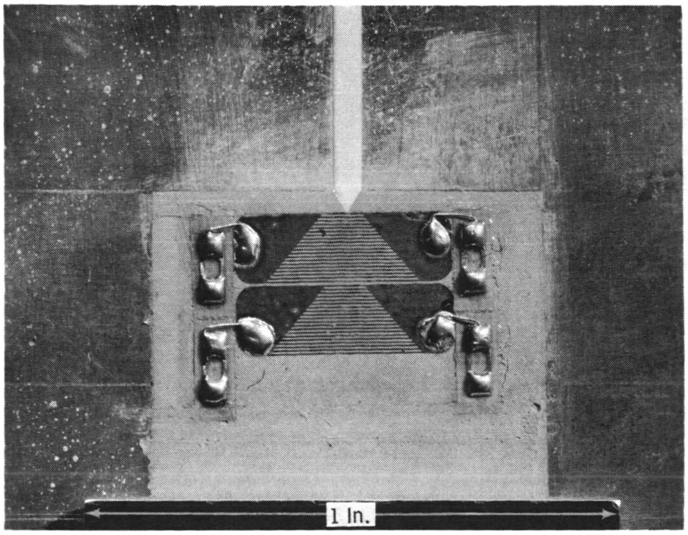


Figure 2. - Multiple continuity gage installation. C-65624

higher resistivity allows shorter filaments for a given resistance, resulting in a more compact gage less subject to breakage and misalinement of filaments in mounting. Also, a previous Lewis study (ref. 4) showed a lesser change in resistance for Nichrome V when it is cooled from room temperature to -423° F.

The continuity gage is bonded to the surface of a fracture test specimen by using a technique described later. The gage is placed with filaments perpendicular to the expected direction of crack propagation with the leading edge of the shortest filament at the tip of the notch or crack. If the slow crack growth is expected to exceed the width of the gage, additional gages are placed alongside the first. An example of such a multiple continuity gage installation at a notch tip is shown in figure 2.

CONTINUITY GAGE CIRCUITRY

The continuity gage is designed to be used with a 1.5-ohm shunt resistor. As the filaments are broken, from the shortest to the longest in turn, the resistance of the assembly increases in a finite and nearly linear stepwise manner. A resistance of 119 ohms is added in series to make the assembly compatible with existing 120-ohm bridge circuitry used for recording strain-gage data. Bridge output is fed to a multichannel direct-recording oscillograph along with an applied-load signal from a load cell or a pressure transducer (fig. 3).

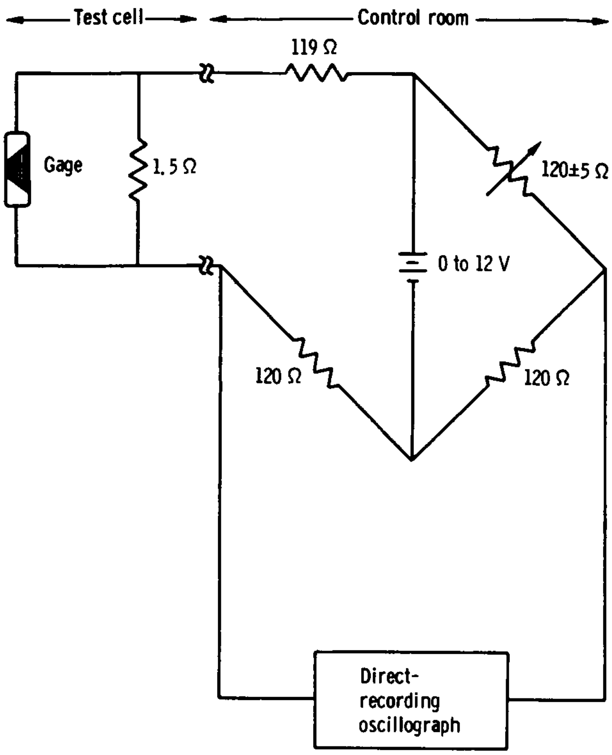


Figure 3. - Typical circuit for continuity gages.

Lead-wire resistance between the continuity gage and the 1.5-ohm shunt resistor should be kept as low as possible, otherwise output and linearity will be reduced. Where tests are conducted in cells remote from the instrumentation, shunt resistors are located on a panel in the cell itself.

OSCILLOGRAPH TRACE INTERPRETATION

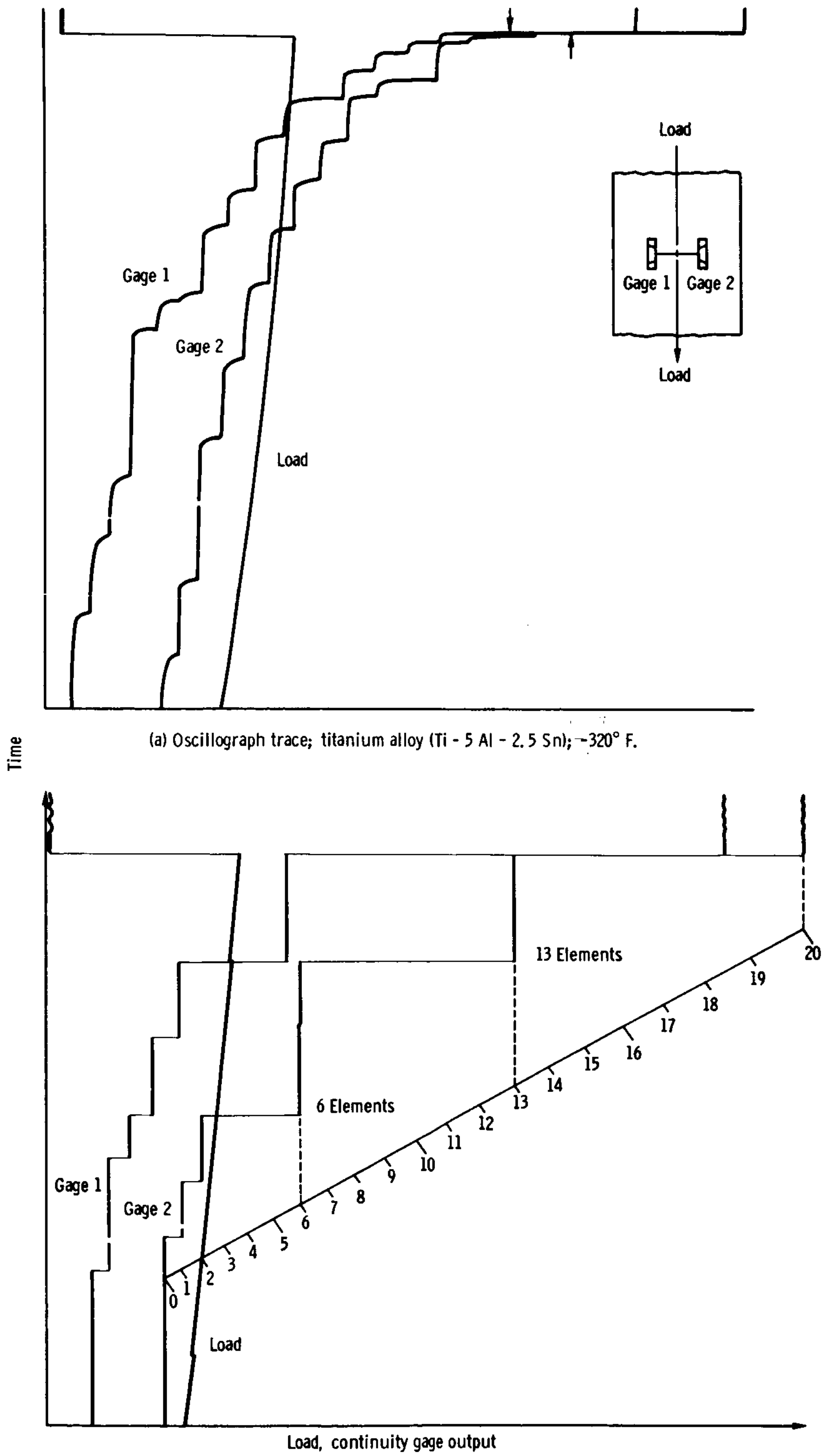
Figure 4 shows oscillograph traces of the gage output for two typical fracture toughness tests of the titanium alloy at -320° and -423° F. At -320° F, each step generally indicates the fracture of a single gage element. The trace indicates that the crack is growing in a continuous manner. The steps are rounded as the element necks down before breaking. Rapid fracture is assumed to start where the gage trace becomes approximately horizontal, as indicated in figure 4(a) by the arrows.

Quite a different type of behavior is exhibited at -423° F (fig. 4(b)). The crack growth is no longer continuous but takes place in abrupt steps that usually increase in magnitude as the load increases. In order to determine the number of gage elements broken in the longer steps, a calibrator similar to that shown in figure 4(c) is used.

The calibration trace was obtained by mounting the gage and cutting each element in order from the shortest to the longest. The gage circuit output was recorded after each element was cut and transferred to a straight line for ease of use. The calibrator is placed on the trace at an angle (fig. 4(b)) so that zero falls on the no-elements-broken line and 20 on the all-elements-broken line. The total number of elements broken after one of the larger steps can be determined easily from the calibrator.

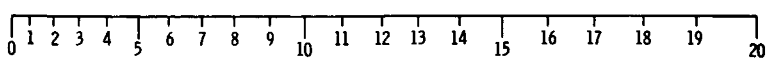
GAGE MOUNTING TECHNIQUES

The ideal adhesive for mounting continuity gages would be of nearly zero thickness, would have a high dielectric constant, and would transfer perfectly the motion of the sub-



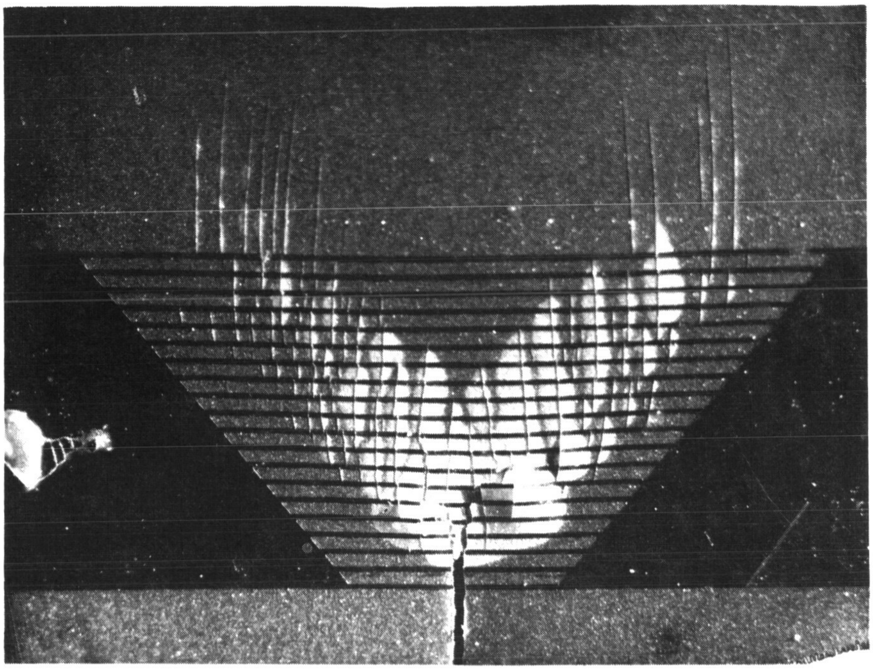
(a) Oscillograph trace; titanium alloy (Ti - 5 Al - 2.5 Sn); -320° F.

(b) Oscillograph trace; titanium alloy (Ti - 5 Al - 2.5 Sn); -423° F.

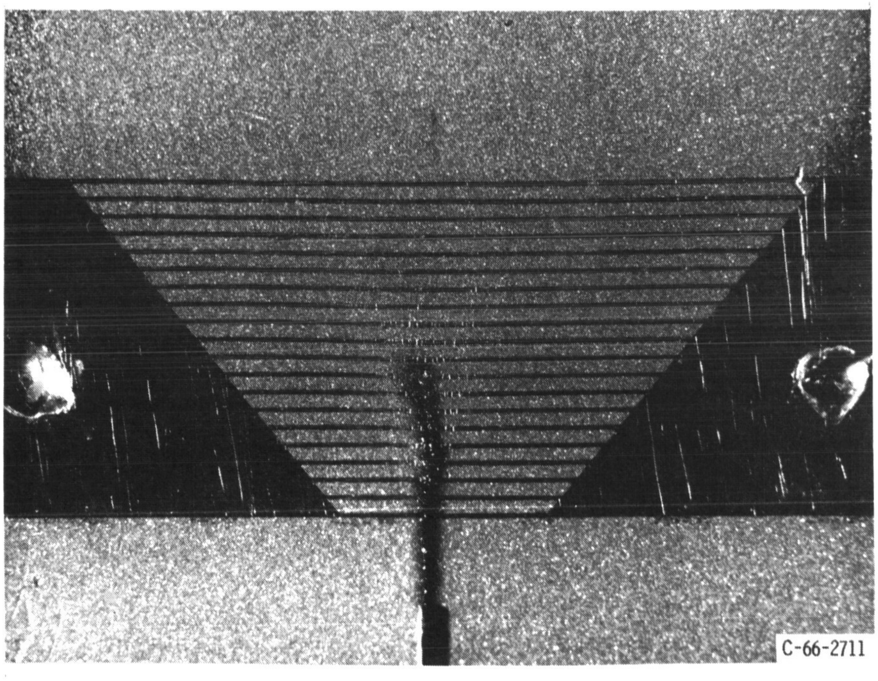


(c) Continuity gage calibrator.

Figure 4. - Typical continuity gage output.



(a) Epoxy adhesive; crazing.



(b) Polyester adhesive; no crazing.

Figure 5. - Influence of adhesive used in mounting continuity gage. Titanium alloy (Ti - 5Al - 2.5 Sn); -320° F.

strate to the gage. Such an adhesive is, of course, not available at present, but the development of mounting techniques was oriented toward approaching this ideal.

Initially, the continuity gage was mounted on 2014-T6 aluminum specimens by using the same technique as that used for applying strippable-backed foil strain gages with an epoxy adhesive used as the mounting cement (refs. 4 and 5). Because this is a well-known technique, it is not described in detail herein. This technique gave satisfactory results at room temperature. However, when used on the titanium specimens tested at -320° and -423° F, it proved to be unsatisfactory because of extensive crazing in the epoxy cement (fig. 5(a)). Crazing takes place when the ductility of the cement is exhausted and, in this case, was a result of the low ductility of the epoxy cement relative to that of the titanium. A more ductile cement was required for satisfactory service on more ductile materials.

A polyester adhesive, designated G-207 by Goodyear Aerospace Corporation, proved to be a satisfactory cement. It demonstrated a ductility at least equal to that of the titanium alloy at -320° F (fig. 5(b)). Since the technique used in mounting the continuity gage with this adhesive was critical to its satisfactory operation, especially at -423° F, the mounting procedure developed at Lewis is described in detail in the appendix. For best results, it was necessary to keep the total thickness of the gage mount to 0.0015 inch or less. It is recommended that a specimen be tested as soon as possible after the gage is mounted, since additional curing at room temperature causes a reduction in the ductility of the cement at -423° F. Because of the low strength of the polyester at room temperature, it should not be used at or above this temperature.

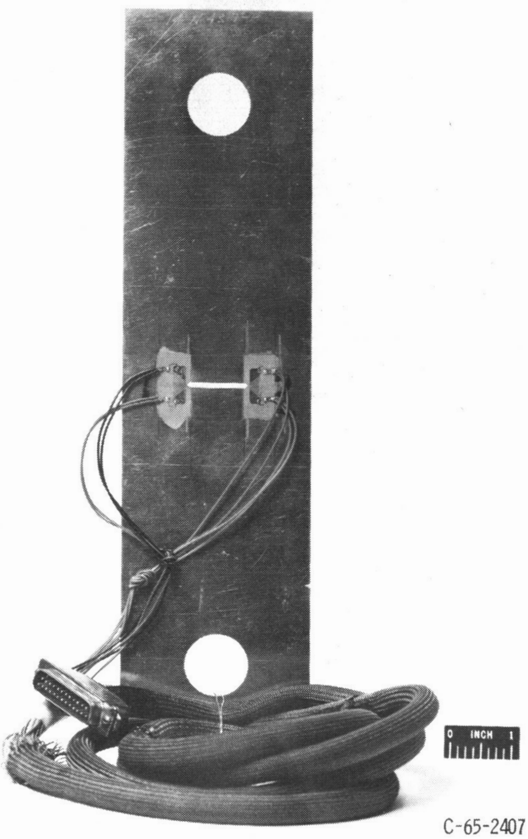


Figure 6. - Calibration test specimen.

EXPERIMENTAL CALIBRATION PROCEDURE

Specimen Preparation and Testing

In order to interpret the output of the continuity gage properly, an experimental calibration program was undertaken with both single-cycle-uniaxial and multicycle-biaxial test specimens. The single-cycle phase was conducted with 0.060-inch 2014-T6 aluminum sheet, 0.020-inch ELI Ti - 5 Al - 2.5 Sn sheet, and 0.020-inch 301 stainless-steel sheet. The calibration specimen (fig. 6) was 3 inches wide by 12 inches long with

TABLE I. - NOTCH PREPARATION AND MOUNTING CEMENTS USED

IN CONTINUITY GAGE CALIBRATION

Material	Form	Notch preparation	Mounting cement
2014-T6 aluminum	Sheet	Machined	Epoxy
	Cylinder	Machined	Epoxy
	Sheet	Machined	Polyester
	Sheet	Electrical discharge plus fatigue	Polyester
Ti - 5 Al - 2.5 Sn	Sheet	Electrical discharge plus fatigue	Polyester
301 Stainless steel	Sheet	Electrical discharge plus fatigue	Polyester

an initial center notch of either 0.5 or 1.0 inch.

The through-the-thickness notches were prepared in one of two ways. The first method consisted of machining the notch to the desired length. Notch-root radii of approximately 0.0002 inch were obtained by this method. The second method consisted of placing a through-the-thickness electrical-discharge notch in the specimen and low-stress fatiguing it to the desired length. Table I shows the notch preparation methods and gage mounting cements used in the calibration program.

The calibration procedure consisted of loading the specimen in tension until a predetermined number of gage elements separated. The specimen was then unloaded and the extent of actual crack growth was determined.

Determination of Actual Crack Growth

The extent of actual crack growth was determined either visually or by marking the fracture surface. For the titanium specimens tested at -320° F, a large amount of plastic flow took place at the crack tip that did not allow the crack to close when unloaded. Hence, a visual examination was all that was required to determine the extent of actual crack growth. In all other cases, the crack closed tightly when unloaded and necessitated marking the fracture surface.

The first marking technique consisted of forcing the notch open in a jig, inserting dye, and pressurizing to 1000 pounds per square inch. The specimen was heated in order to dry the dye and was then broken open to measure the extent of dye penetration. For the uniaxial test specimens, this technique was abandoned in favor of fatigue marking (the second technique), since the crack could be accidentally extended by forcing it open excessively, or the dye might not penetrate to the crack tip if the notch were not forced open enough. The fatigue-marking technique consisted of low-stress fatiguing the previously

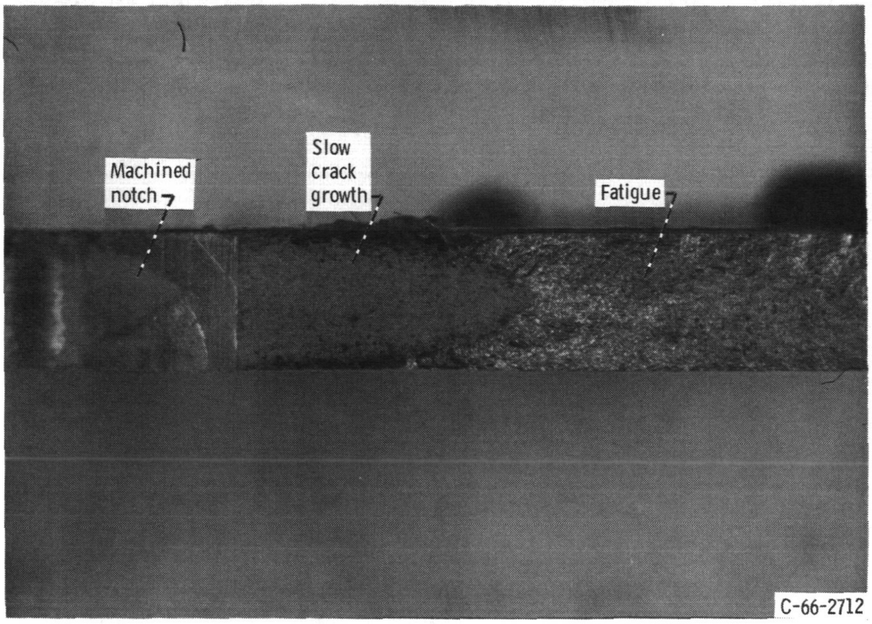


Figure 7. - Determination of extent of crack growth by fatigue marking. 2014-T6 aluminum.

loaded specimen to failure. The clear demarcation between the slow crack growth and the fatigued portion is shown in figure 7. The aluminum specimens were marked with dye in some cases and by fatiguing in the remainder. The titanium specimens tested at -423° F and the stainless-steel specimens tested at -320° and -423° F were fatigue marked in all cases.

Cyclic Calibration

The cyclic calibration was obtained as a part of biaxial cyclic crack growth studies performed at Lewis. Cylindrical pressure vessels machined from 2014-T6 aluminum tube stock, each containing either two or three through-the-thickness machined notches, were cycled to failure at various stress levels. Continuity gages were mounted to measure crack growth at each notch. The notch or notches through which the failure did not occur were used to determine the relation between the continuity gage indication of growth and the actual crack growth. The dye-marking technique described in the preceding section was used to determine the actual crack growth.

ANALYTICAL CALIBRATION

The necessity for a detailed calibration of the continuity gage for each material and notch length would severely limit the usefulness of the gage. Therefore, an analytical calibration was devised that requires only a few tests for each material thickness to verify its accuracy. This calibration is of use when the plastic zone at the crack tip is large enough to cause a gage element to break before the crack actually reaches it. It assumes that a gage element will break when the strain in the plastic zone exceeds the fracture strain of the element. The expression is derived in reference 3 and states:

$$\frac{a}{a_g} = \left\{1 + \left[1 + \left(\frac{2}{\pi}\right)^4 \left(\frac{\epsilon_{fg}}{\epsilon_{yY}} - 1\right)\right]^{-2} \left[\frac{W}{\pi a} \text{arc sin}\left(\sin \frac{\pi a}{W} \sec \frac{\pi \sigma}{2\sigma_{yY}}\right) - 1\right]\right\}^{-1} \tag{1}$$

where

a	actual half-crack length
a_g	gage indication of half-crack length
W	sheet width
ϵ_{fg}	gage failure strain
ϵ_{yY}	strain at elastic-plastic interface
σ	gross stress in specimen when gage element breaks
σ_{yY}	stress at elastic-plastic interface

Because of the biaxial nature of the stress at the crack tip, ϵ_{yY} was taken as $\left[\left(1 - \nu^2\right)/E\right]\sigma_{yY}$ where ν is Poisson's ratio, E is the modulus of elasticity, and σ_{yY} is taken as the 2 to 1 biaxial yield strength.

The validity of the analytical expression was verified with data obtained from the experimental calibration of the titanium and stainless-steel sheet. Because of the texture hardening exhibited by the titanium alloy, σ_{yY} for this alloy was obtained from a single burst test of a cylindrical pressure vessel. For stainless steel, σ_{yY} was assumed to be 1. 15 times the uniaxial yield strength.

The gage failure strain ϵ_{fg} was obtained by mounting a gage on a tensile specimen, loading it until the gage elements fractured, and noting the strain in the specimen. Tests were conducted by using both titanium and stainless-steel tensile specimens at -320° F and with stainless steel at -423° F. In all cases the gages were mounted with the polyester adhesive.

The calculation of ϵ_{yY} requires the knowledge of Poisson's ratio and modulus of elasticity. With 301 stainless steel, these material properties are not constant but vary continuously with the stress. Therefore, values for ν and E for the 301 stainless steel were selected to give a good fit with the experimental data.

ALTERNATE GAGE CONFIGURATIONS

The design of the current NASA continuity gage was influenced by the conditions under which it was to be used as well as by physical and electrical considerations. Burst tests of precracked subscale pressure vessels immersed in liquid hydrogen were to be conducted in remote test cells; hence, lead-wire resistance could not be ignored. For reasons of cost and expediency, the dimensions of the gage were held within the scope of then current foil strain-gage production technology. Previous studies of strain gages at cryogenic temperatures (refs. 3 and 4) indicated that a strippable backing was preferable. Filaments had to be long enough to allow for slight branching of a crack, but not so long as to present extreme difficulty in handling and mounting. The output and linearity of the gage and its circuit were to provide at least a 0.1-inch step in the oscillograph trace as each filament breaks.

Under other conditions, however, alternate configurations and circuits are possible that may yield equally good results. For example, a gage could have filaments of equal length and resistance, as shown in figure 8(a). Such a gage could be constructed by shunting the filaments of a conventional strain gage with fine wire or with conductive cement, and such methods were used in the preliminary stages of this program. If n is the number of filaments remaining (unbroken), R is the resistance of each and every filament, R_L is the resistance of lead wires plus the galvanometer, and E is the applied voltage, by conventional series-parallel resistance equations

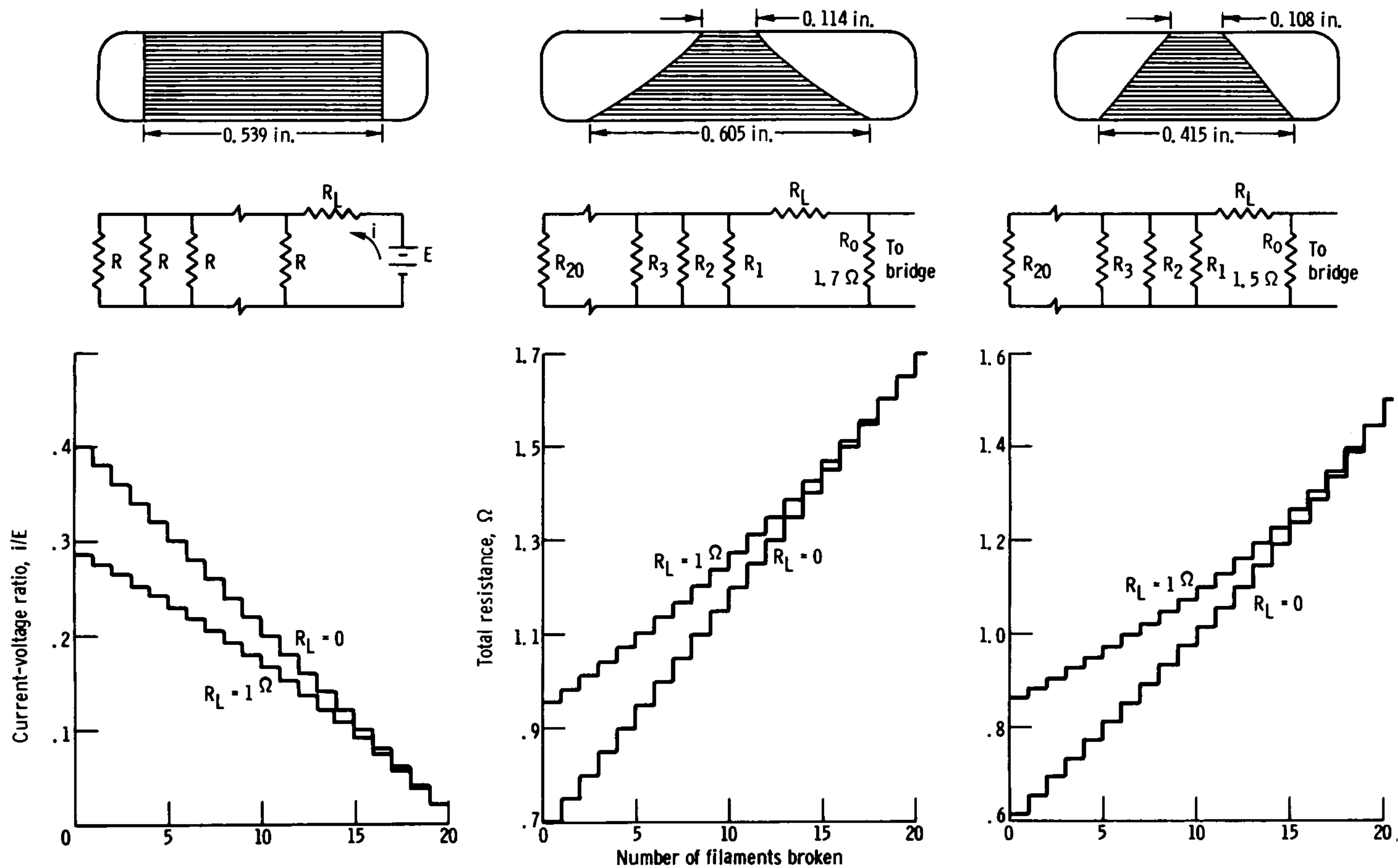
$$i = \frac{E}{\frac{R}{n} + R_L}$$

If

$$R_L << \frac{R}{n}$$

then

$$i \approx n \frac{E}{R}$$



(a) Equal-resistance configuration.

(b) Linear-output configuration.

(c) NASA configuration.

Figure 8. - Dimensions, equivalent circuit, and electrical characteristic of NASA configuration and typical examples of alternate configurations. (Dimensions based on 0.003-in.-wide by 0.00015-in.-thick filaments; resistivity, 106×10^{-6} ohm-cm.)

Thus, under ideal conditions, current drop will be nearly proportional to the number of filaments broken. For the example shown in figure 8(a), R was taken as 50 ohms.

It is also possible to design a configuration for use in a bridge circuit that will give equal-resistance increments (neglecting lead-wire resistance). It is easier to assume arbitrarily a value for the external shunt resistance, and then compute successively the resistances required to reduce overall resistance by the desired amount. If N is the total number of filaments, n is the number of filaments remaining ($0 \leq n \leq N$), R_o is the resistance of the external shunt resistor, R_n is the resistance of the n^{th} filament, $\overline{R}_n$ is the resistance of R_o and n filaments in parallel, and ΔR is the resistance increment equal to $\overline{R}_n - \overline{R}_{n-1}$, it can be determined that, to give equal-resistance increments,

$$R_{n+1} = \frac{\left(\overline{R}_n\right)^2}{\Delta R} - \overline{R}_n$$

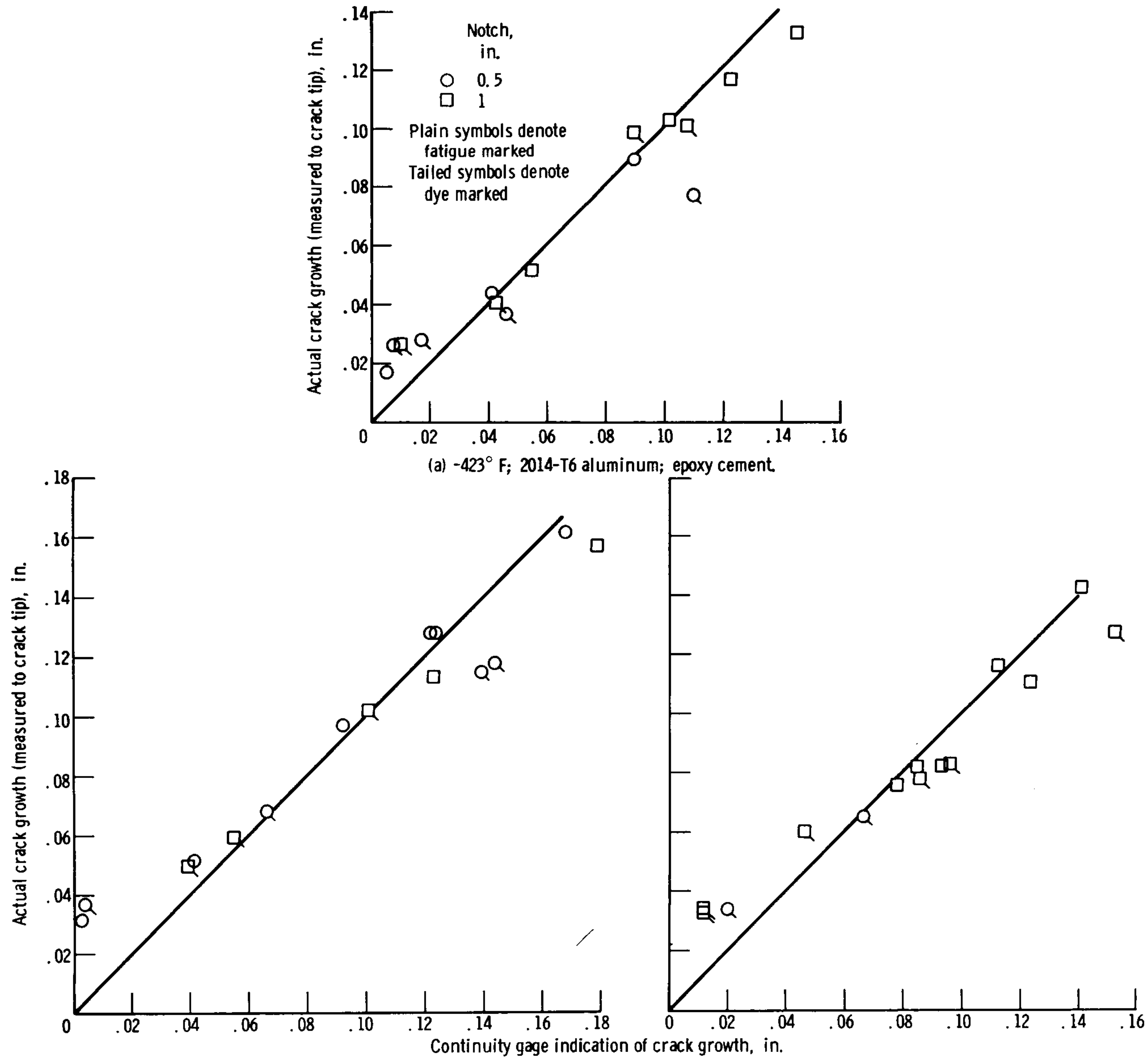
The shortest filament (first to break) is represented by R_N, and the longest by R_1. A bridge circuit is often useful since resistance of lead wires between the shunt resistor R_o and the remainder of the bridge can be balanced out. However, resistance of the leads from the gage to the shunt resistor must be considered. A typical example of this influence can be seen in figure 8(b).

The NASA configuration (fig. 8(c)) is more suitable for remote testing than the equal-resistance gage (fig. 8(a)) and more compact than the linear-output gage (fig. 8(b)) yet provides sufficient output and linearity for practical purposes.

RESULTS AND DISCUSSION

Aluminum Sheet Calibration

Figure 9 shows the results of the uniaxial experimental calibration program. In all cases, the 45^o line indicates exact agreement between actual and gage indication of crack growth. The data shown in figures 9(a) to (c) were obtained by mounting continuity gages on 2014-T6 aluminum specimens with the epoxy adhesive. These specimens were tested at -423^o F, -320^o F, and room temperature. Both 0. 5- and 1. 0-inch notch specimens were tested. The tailed symbols indicate dye marking, while the remaining points were obtained by fatigue marking. The actual crack growth was determined by measuring with an optical comparator to the furthest point of crack penetration, or, in other words, to the tip of the crack tunnel. At the lower stress levels, where the crack had just started to grow, the continuity gage underestimated the crack growth because the crack had tun-

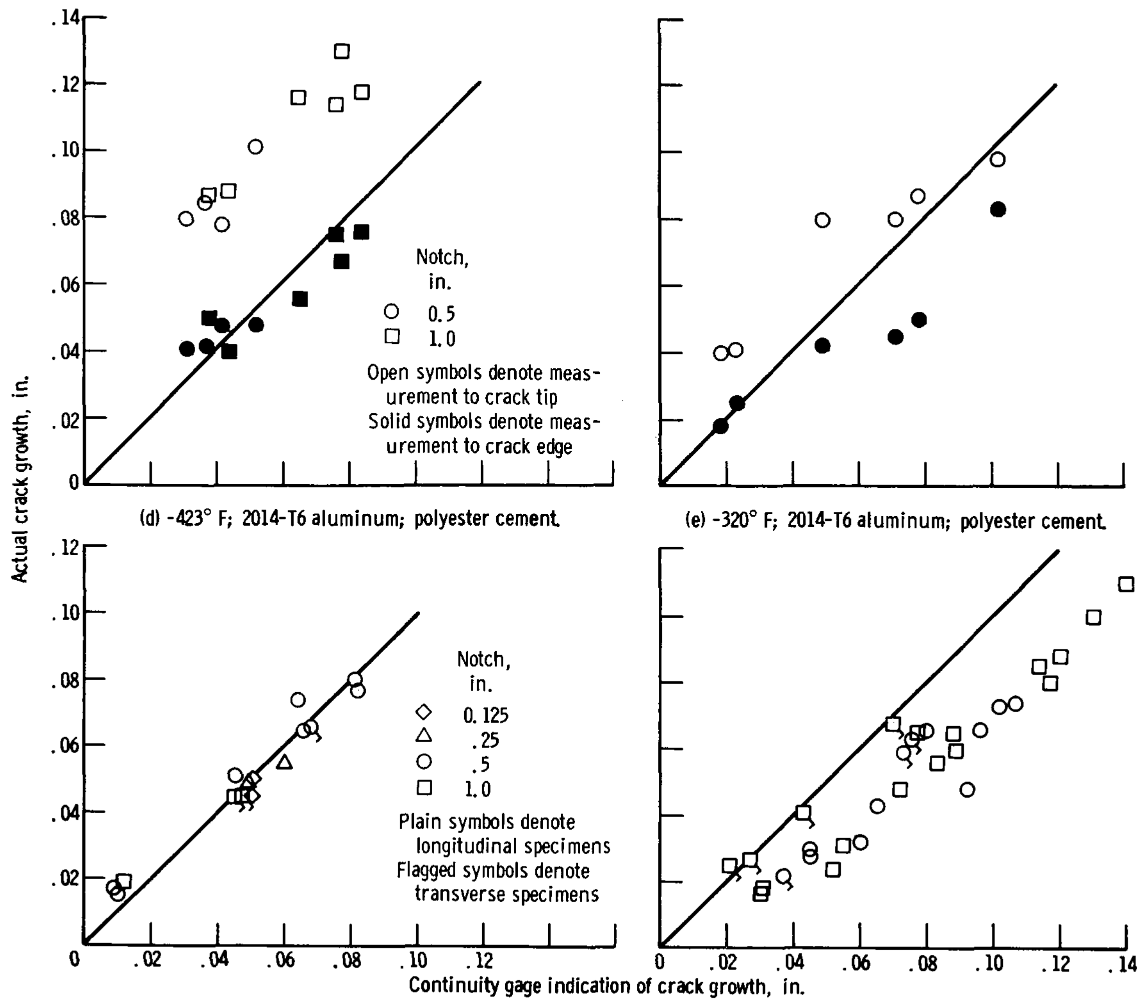


(a) -423° F; 2014-T6 aluminum; epoxy cement.

(b) -320° F; 2014-T6 aluminum; epoxy cement.

(c) Room temperature; 2014-T6 aluminum; epoxy cement.

Figure 9. - Continuity gage calibration.



(d) -423° F; 2014-T6 aluminum; polyester cement.

(e) -320° F; 2014-T6 aluminum; polyester cement.

(f) -423° F; titanium alloy (Ti - 5Al - 2.5Sn); polyester cement.

(g) -320° F; titanium alloy (Ti - 5Al - 2.5Sn); polyester cement.

Figure 9. - Continued.

neled beneath the gage. At higher stress levels and at cryogenic temperatures, the strain ahead of the crack attained a magnitude sufficient to make the epoxy cement craze and cause premature fracture of the gage elements (fig. 5(a), p. 6). At room temperature the high strain caused the gage element alone to fracture.

Figures 9(d) and (e) show data obtained by mounting the gages on aluminum alloy specimens with the polyester adhesive and then testing at -423° and -320° F. At -320° F, only notches of 0.5 inch were tested, while at -423° F both 0.5- and 1.0-inch notch specimens were tested. These specimens were fatigue marked in all cases. The extent of actual crack growth was measured both at the surface of the specimen directly beneath the gage as well as to the tunnel tip. At -423° F, the gage indication of crack growth agreed very closely with the actual growth directly beneath the gage. The difference between the open symbols and the solid symbols indicates the amount of tunneling. The average tun-

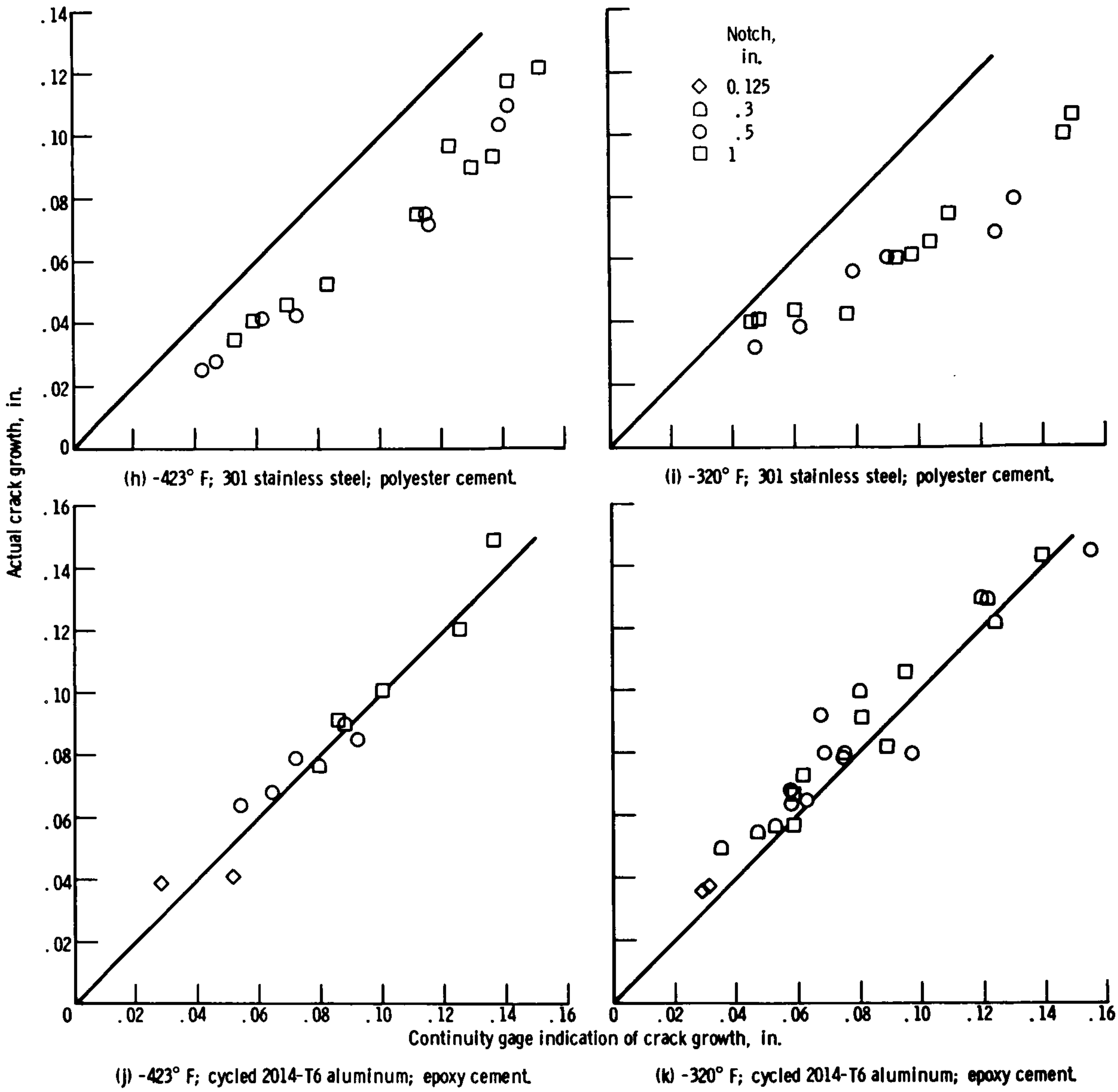


Figure 9. - Concluded.

nel length here was about 0.04 inch and, once established, did not vary appreciably as the stress increased. If the tunnel is assumed to be parabolic in shape, the correct crack growth would be the sum of crack growth on the surface and two thirds of the tunnel length. For initial notches of 1.0 inch or greater, however, the error incurred by neglecting tunneling is small. At -320° F, the continuity gage overestimated the crack growth at the surface due to the increased ductility of the aluminum alloy at this temperature.

Titanium Sheet Calibration

Figures 9(f) and (g) show data obtained by mounting the continuity gage on the titanium-alloy specimens with the polyester adhesive and testing at -423° and -320° F. Both longitudinal (with respect to the direction of rolling) and transverse specimens were tested. At -423° F, where specimens with 0.125- and 0.25-inch initial notches were tested in addition to the 0.5- and 1.0-inch notched specimens, good agreement was obtained between the continuity gage indication of growth and the actual crack growth. Tunneling did not take place in the titanium alloy specimens. At -320° F, where the titanium alloy was much more ductile, the continuity gage, in general, again overestimated the extent of actual crack growth. This overestimation was the case except for the 1.0-inch notch transverse specimens, where agreement between the actual and gage indication of crack growth was good. This agreement could be a result of the plastic zone at the crack tip being smaller than that which occurred with the longitudinal specimens.

Stainless-Steel Sheet Calibration

Figures 9(h) and (i) show data obtained by mounting the continuity gage on 301 stainless-steel specimens with the polyester adhesive and testing at -423° and -320° F. At both temperatures, the continuity gage overestimated the extent of actual crack growth, which indicates that the plastic zone is of sufficient size to cause premature failure of a gage element in both cases. It might be expected that the overestimation would be less severe at -423° F because of the reduced ductility of the stainless steel at this temperature. The degree of the overestimation was not reduced, however, and this is partially explained by the fact that the ductility of the foil element is slightly reduced. Also, in some cases, instead of forming an enclave of general yielding at the crack tip, a narrow line of yielding would branch off from the crack tip causing premature failure of the gage elements. This instability has been observed and discussed previously as "catastrophic shear" in references 6 and 7.

Aluminum Cylinder Calibration

Figures 9(j) and (k) show the results of the calibration obtained from the pressure cycled aluminum-alloy cylinders at -423° and -320° F. Cylinders containing initial notch lengths of 0.125, 0.3, 0.5, and 1 inch were tested. The actual crack growth was measured to the furthest point of crack penetration.

In general, the agreement between the actual crack growth and the gage indication is

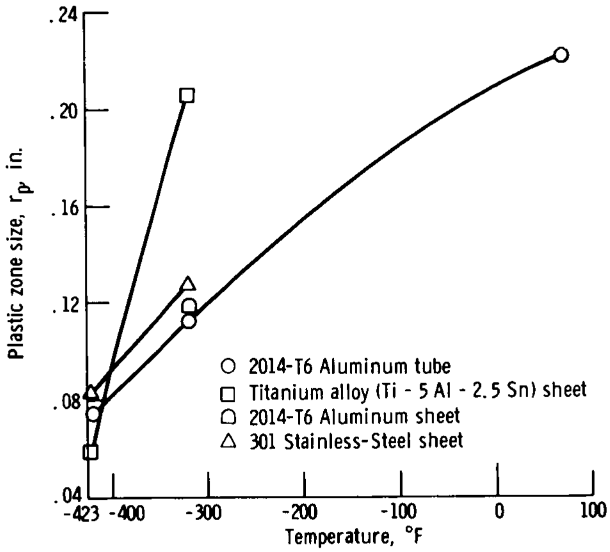


Figure 10. - Effect of temperature on plastic zone size (eq. 2). Specimen width, 3.0 inches; crack length, 1.0 inch.

quite good. It would be expected that the cyclic agreement would be better than that obtained from the single-cycle calibration because the stress levels in the cyclic tests were lower. Hence, a smaller plastic zone was formed.

Effect of Plastic Zone Size

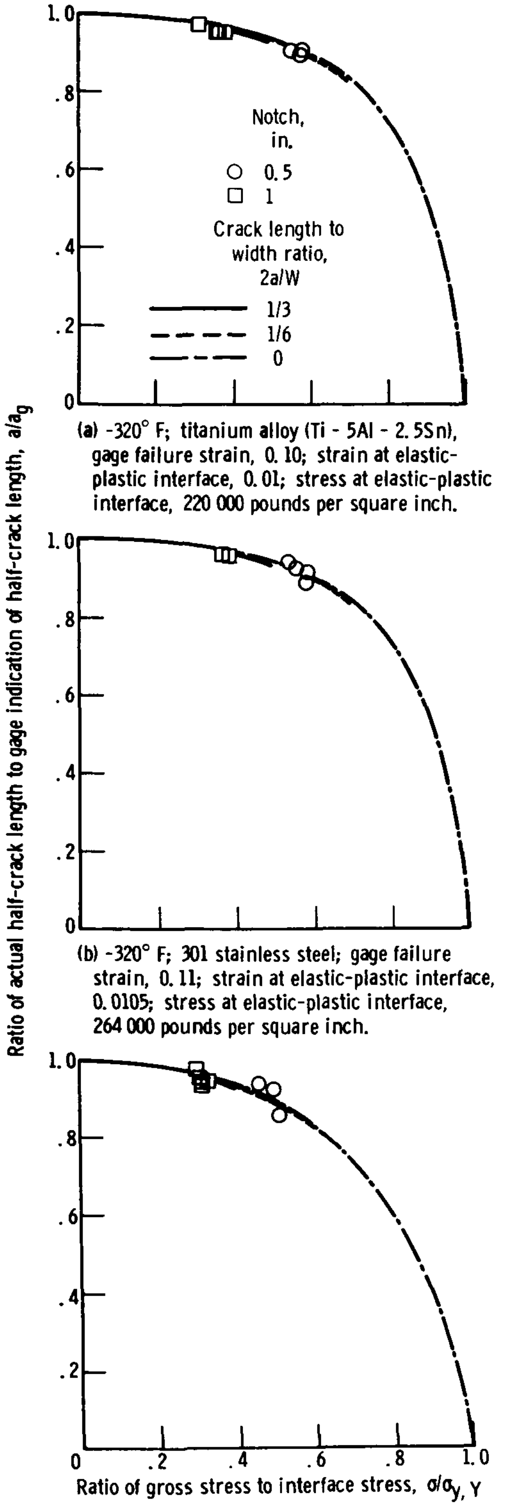
The experimental calibration program showed that the magnitude of the plastic strain at the crack tip governs the behavior of the continuity gage. The larger the plastic zone, the more likely it is for the continuity gage to overestimate the extent of crack growth. Figure 10 shows the relative magnitude of the plastic zone at the onset of rapid fracture for three materials at three temperatures. The plastic zone size r_p was obtained from the following equation (ref. 8):

$$r_p = \frac{1}{\pi}\left(\frac{K_{CN}}{\sigma_y}\right)^2 \tag{2}$$

In order to compare the materials on an equal basis, the uniaxial 0.2 percent yield strength σ_y and nominal fracture toughness K_{CN} for a 3-inch-wide specimen with a 1-inch notch were used. At -423° F, the plastic zone size of both the aluminum and titanium alloys is about 0.035 inch. The experimental calibration (figs. 9(d) and (f)) showed that good agreement could be obtained between the actual crack growth at the material surface and the gage indication. The plastic zone is larger for all three materials at -320° F, and the experimental calibration (figs. 9(e), (g), and (h)) shows the gage overestimating the crack growth. An indication of the behavior of the continuity gage on any sheet material can be obtained by computing the plastic zone size of the material and comparing it with those in figure 10. The smaller the plastic zone, the better the agreement should be between the gage indication and actual crack growth. The upper limit on the size of the plastic zone, where the continuity gage is no longer of use, has not been determined.

Analytical Calibration

Figure 11 compares the derived expression for the ratio of actual half-crack length



(a) -320° F; titanium alloy (Ti - 5Al - 2.5Sn), gage failure strain, 0.10; strain at elastic-plastic interface, 0.01; stress at elastic-plastic interface, 220 000 pounds per square inch.

(b) -320° F; 301 stainless steel; gage failure strain, 0.11; strain at elastic-plastic interface, 0.0105; stress at elastic-plastic interface, 264 000 pounds per square inch.

(c) -423° F; 301 stainless steel; gage failure strain, 0.09; strain at elastic-plastic interface, 0.015; stress at elastic-plastic interface, 305 000 pounds per square inch.

Figure 11. - Analytical continuity gage calibration (eq. (1)).

to gage-indicated half-crack length (eq. (1)) with the experimental data obtained from the titanium-alloy calibration program at -320° F and the 301 stainless-steel calibration program at -320° and -423° F. The close agreement between the derived expression and the experimental data for both materials at -320° F indicates that the analytical calibration can be a useful tool in properly interpreting the continuity gage output.

Figure 11(c) shows the data for 301 stainless steel at -423° F. As mentioned previously, catastrophic shear, a second mode of failure, was detected in some of these specimens tested at -423° F. Such failures were premature relative to the conventional mode of failure and caused the associated data to fall below the conventional mode data. The analytical expression given is unable to take into account this partially understood phenomenon.

CONCLUSIONS

The NASA continuity gage can be an effective tool in the measurement of crack growth on flat and curved surfaces at cryogenic temperatures provided that proper gage-mounting techniques are employed. A calibration program is necessary to ensure correct interpretation of the gage output.

The analytical calibration, which shows close agreement with the experimental data obtained from ELI Ti - 5 Al - 2.5 Sn and 301 stainless steel, can be used to minimize the number of specimens required for an accurate calibration for a given material, sheet thickness, and temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 29, 1966,
124-08-08-19-22.

APPENDIX - CONTINUITY GAGE MOUNTING PROCEDURE

WITH POLYESTER ADHESIVE

For satisfactory operation of the continuity gage at cryogenic temperatures using the polyester adhesive, the following procedure was developed:

(1) Mask the surface where the gage is to be mounted and then blast with 50-micron dental abrasive.

(2) Demask the surface and clean off the dust.

(3) Remask the surface for spraying the cement.

(4) Mix the cement in the following proportions: 2 grams of polyester (G-207B), 0.08 gram of catalyst (G-207C), 2.5 grams of toluene, and 3 grams of methylethylketone.

(5) Apply this mixture to the masked surface with an airbrush type spray gun using a spray pressure of 5 pounds per square inch. The amount of methylethylketone in the mixture and the spray pressure can be varied to suit the individual spray gun. Spray until the surface is no longer dull.

(6) Bake in a 150° to 170° F oven for 8 hours.

(7) Spray the surface with a light gage mounting coat of G-207.

(8) Air dry for 15 minutes.

(9) Remove the vinyl backing from the gage by applying a strip of cellophane tape to the exposed surface of the gage. Strip off the vinyl backing. With the gage now adhering to the tape, apply it to the sprayed area. With thumb pressure remove all air under the gage.

(10) Remove the cellophane tape and cover gage with 0.005-inch clear polytetrafluoroethylene plastic. Tape the ends of the plastic to hold it in place and squeeze out the air once more with thumb pressure.

(11) Place a metal-backed 1- by 1.25- by 0.25-inch soft silicone rubber pad over the gage and clamp lightly (~ 30 psi). Excessive clamping pressure will cause the gage elements to break.

(12) Repeat step (6).

(13) Remove the clamp, pad, and polytetrafluoroethylene plastic and make solder connections.

(14) Spray a light overcoat of G-207.

(15) Repeat step (6).

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