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MINIATURE SPECIMEN TECHNOLOGY FOR POSTIRRADIATION FATIGUE CRACK GROWTH TESTING

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SUMMARY

Current magnetic fusion reactor design concepts require that the fatigue behavior of candidate first wall materials be characterized. Fatigue crack growth may, in fact, be the design limiting factor in these cyclic reactor concepts given the inevitable presence of crack-like flaws in fabricated sheet structures. Miniature specimen technology has been developed to provide the large data base necessary to characterize irradiation effects on the fatigue crack growth behavior. An electrical potential method of measuring crack growth rates is employed on miniature center-cracked-tension specimens (1.27cm x 2.54cm x 0.061cm). Results of a baseline study on 20% cold-worked 316 stainless steel, which was tested in an in-cell prototypic fatigue machine, are presented. The miniature fatigue machine is designed for low cost, on-line, real time testing of irradiated fusion candidate alloys. It will enable large scale characterization and development of candidate first wall alloys.

INTRODUCTION

Current magnetic fusion reactor design concepts require that the fatigue behavior of candidate first wall materials be characterized. Fatigue crack growth may, in fact, be the design limiting factor in these cyclic reactor concepts given the inevitable presence of crack-like flaws in fabricated sheet structures. Currently, an insufficient amount of data on the effect of irradiation on the fatigue crack propagation (FCP) behavior of materials exists from which to draw design criteria.

Some postirradiation FCP testing has been done with conventional specimens[1,2,3]. Conventional specimens are too large to permit high volume irradiation, especially in the fusion materials test facilities currently being built. Conventional test techniques are also limited by the design of commercial fatigue test equipment and visual measurement of crack extension neither of which is conducive to high volume, low cost, in-cell testing.

Miniature specimen technology designed for high volume, low cost, postirradiation testing has been developed to provide the necessary volume of data. This technology is based on a miniature weldable center-cracked-tension (CCT) specimen and an electrical potential (e.p.) technique of measuring crack length. A miniature fatigue machine designed for high volume, in-cell operation has also been developed as part of this technology.

Using the miniature specimen technology, a baseline study on 20% cold-worked 316 stainless steel was initiated. Twenty percent cold-worked 316 stainless steel is the reference alloy for the fusion materials development program. Ambient and elevated temperature results are reported.

EXPERIMENTAL TECHNIQUE

Miniature Specimen

The miniature center-cracked tension specimen (CCT) is 1.27cm by 2.54cm (0.5 inches by 1.0 inches) and approximately 0.06cm (0.024 inches) thick, Figure 1, Type 3. It is election beam welded to larger pull tabs for fatigue testing. A 0.38cm EDM slit is used as a starter notch. The specimen was developed in three steps, Figure 1,[4] by testing a 5.1cm (2 inch) wide 0.051cm (0.020 inch) thick sheet specimen (Type 1b), a thinner, 2.54cm wide, gage section specimen of the same type (Type 1a), and finally a tab specimen (Type 3). The results obtained from these specimens were compared with tests using conventional specimens,[4] Figure 2. The miniature specimen produced the same results as 10 conventional specimen geometries for 304 stainless steel tested in air at room temperature.

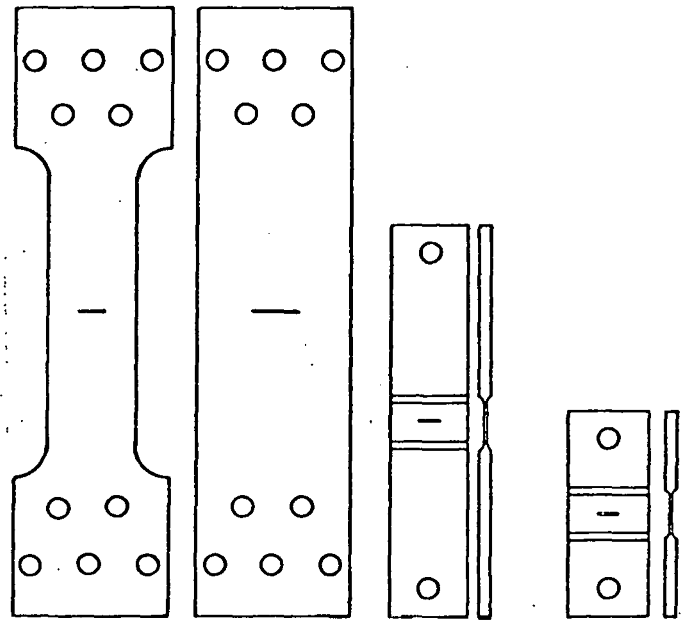

Fig. 1: Miniature Specimen Development

Electrical Potential Technique

The electrical potential technique entails passing a constant d.c. current through a miniature center-cracked specimen under load, Figure 3, and measuring the potential difference between two points on either side of the crack. As the crack propagates the current path increases and accordingly the output voltage increases. By measuring the potential difference at two distanees, Y_1 and Y_2, from the crack, a voltage ratio V_1/V_2 can be obtained which eliminates material dependent parameters which may vary from test to test to test or under irradiation conditions. This is a direct result of Ohm's Law which for our specimen geometry can be written as:

$$V_i = f(a, Y_i) \qquad \text{Equation 1}$$

or

$$\frac{V_1}{V_2} = \frac{f\,(a,\, Y_1)}{f\,(a,\, Y_2)} \qquad \text{Equation 2}$$

where V_i is the potential difference measured at a distance Y_i from the crack, a the half crack length, and $f(a, Y_i)$ a geometric function.

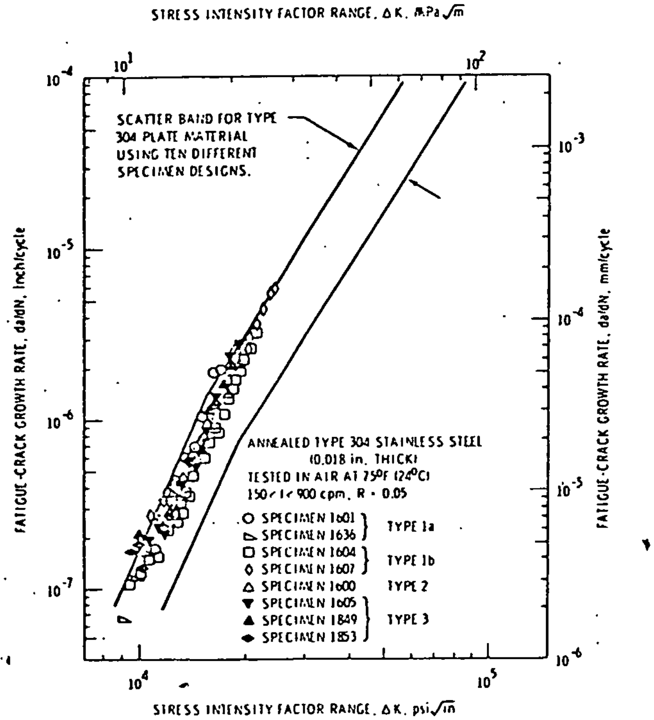

Fig. 2: Miniature Specimen Characterization

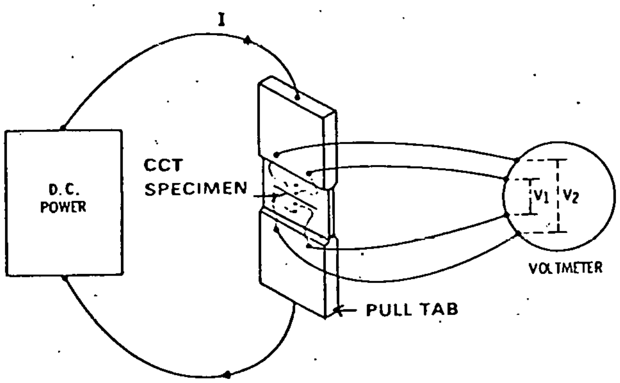

Fig. 3: Electrical Potential Measurement Details

Potential probes are placed so that one voltage, V_2, is extremely sensitive to small crack extension. Another voltage, V_1, is measured to account for changes in current and resistivity. By calculating a ratio of these voltages, V_1/V_2, potential drops due to time dependent phase and structural changes as well as long term current fluctuations are eliminated. Simultaneous measurement of two potential drops eliminates time consuming theoretical and individual specimen calibrations required in previous experiments.[5,6,7]

Instead, a simple calibration curve relating voltage ratio V_1/V_2 to half crack length can be generated, Figure 4. Once a calibration curve has been established for a particular specimen geometry and probe placement, crack length can be determined in subsequent tests by simple measuring the voltage ratio. This can be accomplished without interrupting the test. Data obtained by this technique exhibit excellent agreement with a theoretical solution for the potential drop across a crack in a center-cracked specimen proposed by H. H. Johnson.[8] For the miniature specimen and potential probe placement, this function can be written in the following form:

$$\frac{V_1}{V_2} = \frac{\cosh^{-1}\left(\frac{\cosh \pi Y_1}{\cos \pi a}\right)}{\cosh^{-1}\left(\frac{\cosh \pi Y_2}{\cos \pi a}\right)} \qquad \text{Equation 3}$$

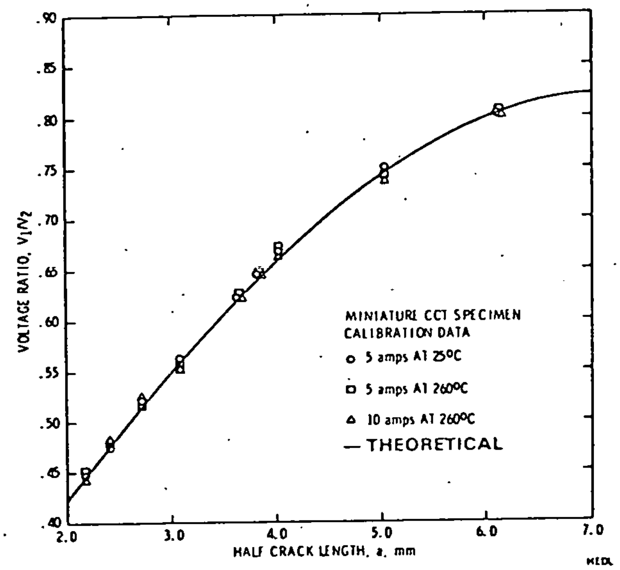

Fig. 4: Calibration Curve, Voltage Ratio Versus Half Crack Length

The theoretical solution emphasizes that the measured voltage at Y_2, farthest from the crack, is more sensitive to probe positioning than Y_1. The magnitude of error in crack growth rate generated by an error in lead placement was determined using Equation 3, Figure 5. The accumulated error in voltage ratio measurements as a function of lead placement error over an

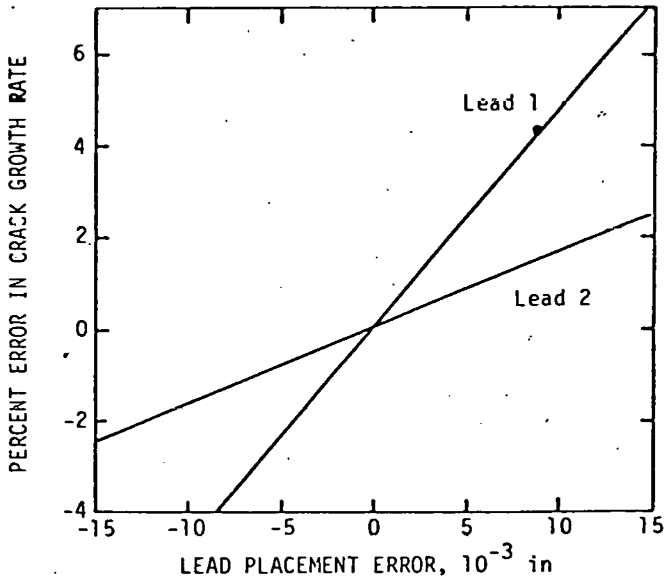

Fig. 5: Lead Placement Error

entire test was considered, that is crack growth from 0.38cm to 2.03cm. For a 1.27 x 10^{-2}cm (5 mil) error in lead placement, a 0.8% error in crack growth measurement was generated from lead 1 and 2.4% from lead 2. This corresponds to a 2.5% error in calculated fatigue crack growth rate, da/dN. For a 2.54 x 10^{-2}cm (10 mil) error in probe positioning the error generated in crack growth measurements is 1.5% and 4.8%, for lead 1 and 2 respectively. This is a 5.1% error in the calculated crack growth rate da/dN. This magnitude of error is comparable with that associated with typical visual measurements. The effect of horizontal error in lead placement is more difficult to assess although it is expected to be much less than the error associated with vertical positioning.

Test Apparatus

Tests were performed with the miniature fatigue machine designed for the CCT specimen, Figure 6. The testing system consists of three modules; a servo-hydraulic actuating component, a furnace and environmental control unit, and an electronic control and data acquisition system.

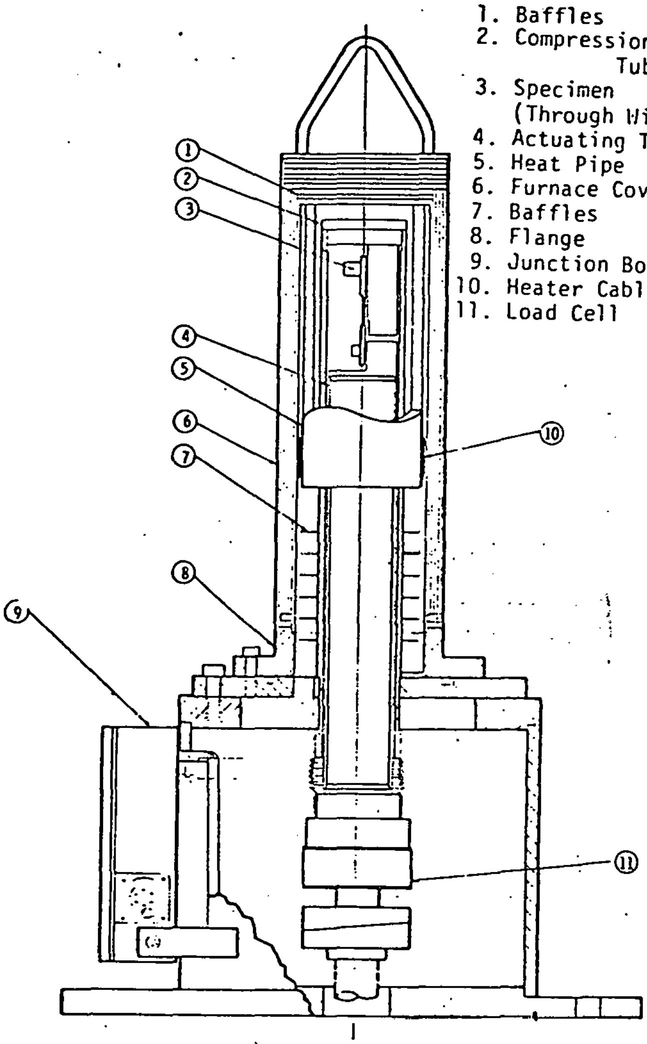

Fig. 6: Miniature Fatigue Machine Skematic

The servohydraulic system consists of the hydraulic actuator, servovalve, and load frame. The test frame and assembly have been optimized for easy in-cell operation. The assembly stands 100cm (39 inch) high and is 36cm (14 inch) in diameter. Specimens are inserted through a window in the compression tube which acts as a fixed support for the specimen.

Elevated temperature testing capabilities are provided by a resistance heating cylindrical furnace which fits over the load frame. Temperature can be controlled to within ± 1°C across the specimen. A portable vacuum station and inert gas line supply a helium atmosphere to the furnace chamber. The leads used for e.p. crack growth measurements are fed out of the chamber through a porthole to a junction box where they are joined to the data acquisition system.

Load control is exercised through a flat load cell using an MTS feedback controller. The controller interfaces with the data acquisition system through a 16 bit parallel interface and TTL counter which provides eight digit count accuracy.

The data acquisition system consists of a desk top computer (HP9845) and digital voltmeter which monitor changes in potential across the specimen through a scanner/multiplexor joined to the specimen probes at the junction box. The data acquisition system has been designed to monitor a number of test stations. Equipped with scanning/multiplexing capabilities, the computer will be able to monitor up to 50 test stations. Individual MTS controllers and TTL counters will allow test conditions at each station to be controlled independently.

By scanning and accessing each individual counter, the computer can be triggered to take e.p. measurements at predesignated count intervals, and therefore, determine the fatigue crack growth as a function of the number of cycles. Since the e.p. measurements are averaged at cued count intervals, the computer can continuously monitor each test without interrupting the load cycle.

On line measurements substantially increase the amount of data which can be accumulated during a test; and test time is reduced. This automized measuring capability will enable postirradiation tests to be monitored continuously, in-cell with a high degree of accuracy. Substantial savings in capital investment cost and technical labor are also accrued.

Testing

Fatigue crack growth testing was performed on 20% cold worked (CW) 316 stainless steel, the reference alloy for the fusion first wall materials development program, using the miniature CCT specimen and in-cell prototypic test machine. Test conditions are detailed in Table 1.

Table 1

Test Conditions

Temp°C	Atmos.	Max. Load(lbs)	Stress Ratio	Freq. (H_z)	Wave-form	Orien-tation
25	air	400	0.05	15	Sine	WR*
260	air	300	0.05	15	Sine	-
315	helium	350	0.05	15	Sine	WR
595	air	475	0.05	0.167	Sine	WR

*Rolling direction perpendicular to stress direction, parallel to crack.

To compare test results generated using the miniature specimen technology with conventional techniques, tests were performed on 20% CW 316 SS in air at 25°C and at 593°C and in helium at 315°C. An additional test was performed on solution annealled 316 SS at 260°C in air to determine the effect of thermal emf's on the electrical potential measurements. The voltage ratio (V_1/V_2) was measured at input currents of 5 and 10 amps at 260°C and 25°C. Open circuit voltage measurements of the system were also taken.

Crack length measurements were made using the e.p. technique. To minimize the effects of thermal emf's at elevated temperatures on the measured potentials, 0.13mm (0.005 inch) 316 SS wire was used for the probes. These probes were joined to larger 0.76mm (0.030 inch) 316 SS wire leading out of the furnace to the junction box. A constant 5 amp d.c. current was supplied to the specimen from a 50 volt Hewlett Packard power supply through a 4 ohm resistor. Occasional visual measurements of crack length were made with a traveling microscope to confirm the e.p. measurements.

RESULTS

All data was analyzed using a linear elastic fracture mechanics approach where the crack growth rate (da/dN) is described as a function of the effective stress intensity at the crack tip (K). The effective stress intensity factor for the CCT specimen is,[4]

$$K=[\sigma\sqrt{\pi a}][1-0.025(\alpha)^2+0.06(\alpha)^4][\sec(\pi\alpha/2)]^{1/2}$$

where σ = applied stress, a = half-crack length, α = 2a/W, and W = specimen width. Results were plotted as da/dN vs ΔK, where ΔK = K max-K min.

Questions do arise when using electrical potential measurements at elevated temperatures. Other investigators have found that thermal emf's which fluctuate with slight temperature changes can interfere with crack growth measurements.[11] In this investigation, the effect of thermal emf's was reduced by using probes of similar composition as the specimen. The sensitivity of the electrical potential measurements in a relationship to the thermal emf's was examined by measuring V_1/V_2 at 5 and 10 amps at 260°C and 25°C, and by taking open circuit voltage measurements of the system to monitor fluctuations in thermal emf's. This was done to determine whether the accuracy of the potential measurements was a function of the applied current and whether increasing the input current would allow measurements to be made in materials where thermal emf's could not be eliminated. It was postulated that by increasing the current, and hence the magnitude of the potential drop, thermal emf's would become a smaller proporation of the potential measurements.

Figure 4 shows the effect of current on the potential drop measurements. For 316 SS, current values in the range of 5 to 10 amps had no effect on the sensitivity of the measurements. Thermal emf's were found to be less than .3% of the measured potentials at both 5 and 10 amps. Resistance heating of the specimen was observed at input currents greater than 10 amps.

Crack growth was monitored both visually and with the e.p. method on an initial Path A 316 SS room temperature test. Both visual and e.p. measurements agree with data obtained using conventional test techniques and a CT specimen, James,[9] Figure 7.

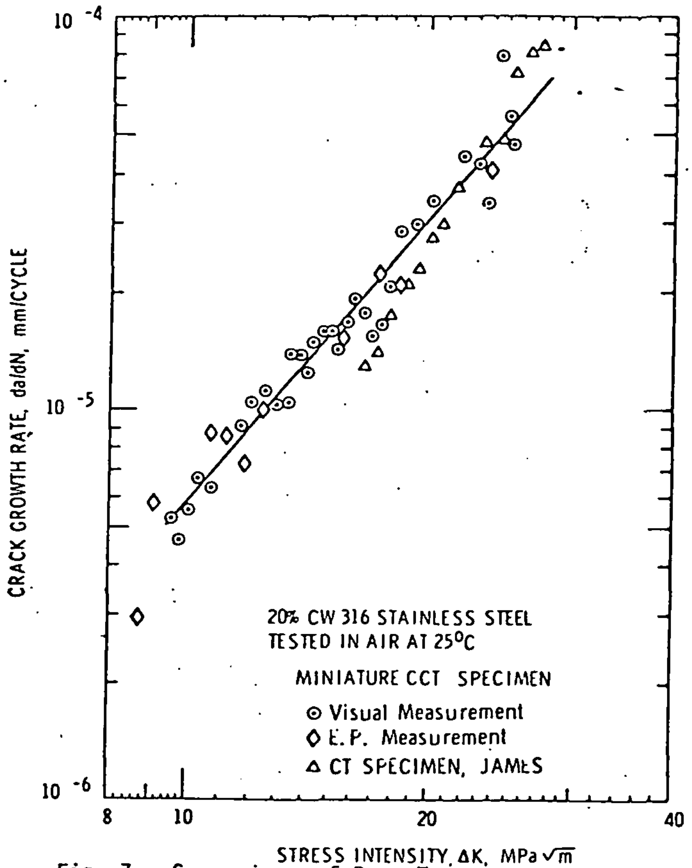

Fig. 7: Comparison of Room Temperature Fatigue Crack Growth Rates for CCT Specimen (e.p. and Visual Measurements) and CT Specimen (Visual), James.[9]

Results of the 315°C test in helium are compared with a conventional test, CT specimen, in air[9] in Figure 8. Although data from the miniature CCT specimen extends into a lower crack growth regime, agreement is excellent in the 10^{-5} to 10^{-4} mm/cycle region. Environment does not appear to effect the crack growth behavior of 316 SS at this temperature.

The 593°C test was performed in air for direct comparison with Shahinian,[10] Figure 9. The single-edge notch cantilever (SENC) specimen data agrees with the miniature CCT specimen results in the 2 x 10^{-4} to 5 x 10^{-4} mm/cycle regime. Further tests will be conducted to extend this region of comparison to a higher crack growth regime.

CONCLUSIONS

1. Miniature specimen technology has been developed to provide the large data base necessary to characterize irradiation effects on the fatigue crack propagation behavior of candidate fusion first wall materials. This technology has been designed for high volume, low cost in-cell operation.

2. Tests on 20% cold-worked 316 stainless steel have confirmed the accuracy and reliability of the miniature specimen technology in characterizing the fatigue crack propagation behavior of materials at ambient and elevated temperatures.

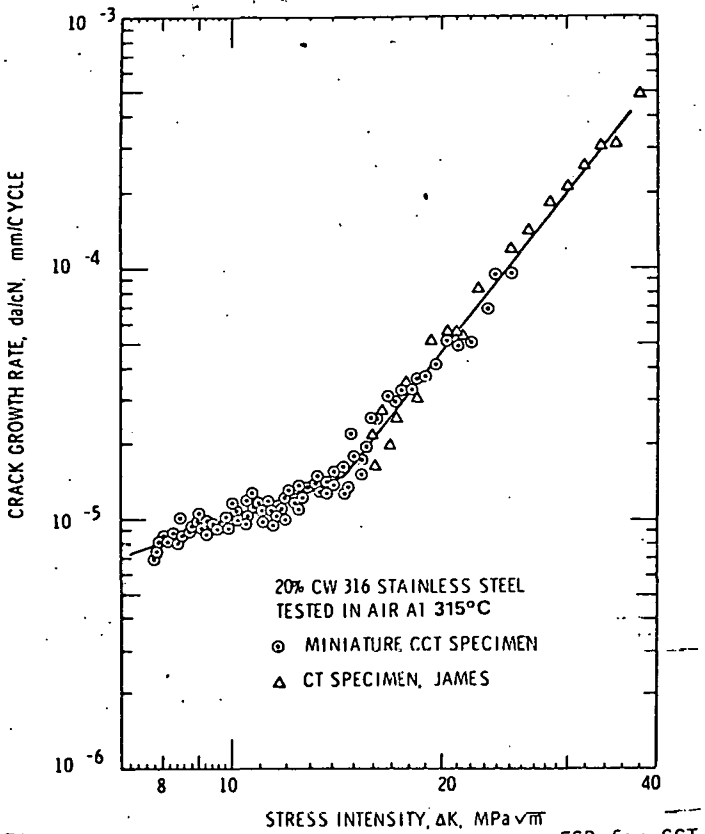

Fig. 8: Comparison of Elevated Temperature FCP for CCT Specimen (e.p. Method) and CT Specimen (Visual Method), James.[9]

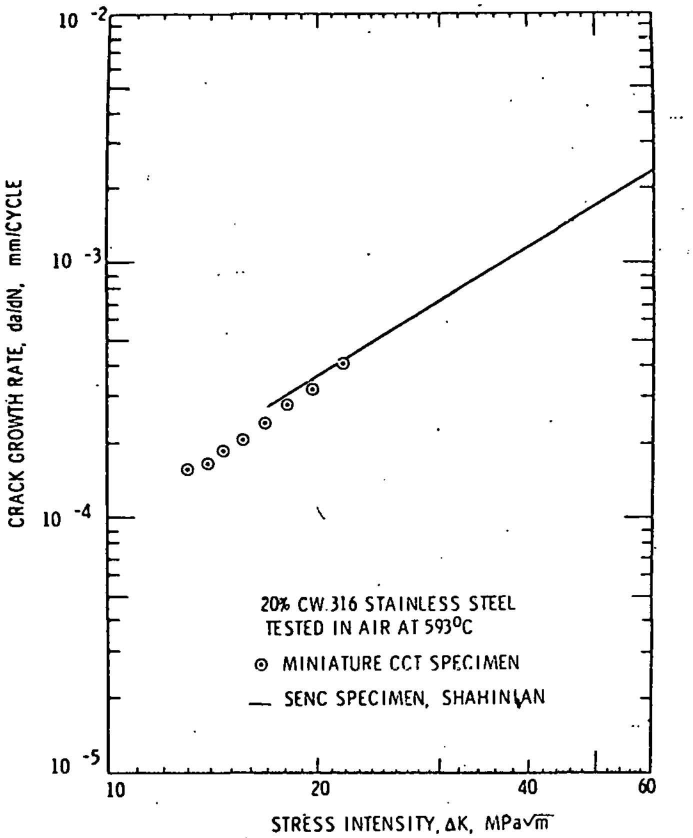

Fig. 9: Comparison of Elevated Temperature FCP for CCT Specimen (e.p. Method) and SENC Specimen (Visual Method), Shahinian.[10]

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