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Elevated Temperature Crack Propagation

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Elevated Temperature Crack Propagation

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SUMMARY

This paper is a summary of two NASA Contracts on high temperature fatigue crack propagation in metals. The first evaluated the ability of fairly simple nonlinear fracture parameters to correlate crack propagation. Hastelloy-X specimens were tested under isothermal and thermomechanical cycling at temperatures up to 980°C (1800°F). The most successful correlating parameter was the crack tip opening displacement derived from the J-integral.

The second program was more extensive. It evaluated the ability of several path-independent integrals to correlate crack propagation behavior. Eight integrals were first evaluated from a theoretical standpoint. Inconel 718 specimens were tested under isothermal, thermomechanical, temperature gradient, and creep conditions at temperatures up to 650°C (1200°F). The integrals formulated by Blackburn (J^*) and by Kishimoto ($\tilde{J}$) correlated the data reasonably well under all test conditions.

INTRODUCTION

This paper reviews and summarizes two NASA Contracts on high temperature fatigue crack propagation in metals, with application to aircraft turbine engine hot-section components. The first contract was begun in 1980. Its objectives were (1) to determine those engine hot-section components for which linear elastic fracture mechanics (LEFM) analysis methods are inadequate, and (2) to evaluate the ability of then-current nonlinear fracture parameters to correlate crack propagation. Hastelloy-X specimens were tested under isothermal and thermomechanical cycling. Maximum test temperature was 980°C (1800°F) and peak loads were well beyond yield.

The second contract, begun in 1983 as a part of the NASA HOST (HOt Section Technology) Program, was more extensive. This contract consisted of a basic program and an option program. The basic program evaluated the ability of several path-independent integrals to correlate time-independent crack propagation. Eight integrals were first evaluated from a theoretical standpoint. Computer simulations of the tests to follow were run to determine whether the integrals were indeed path-independent under the proposed test conditions. Inconel 718 specimens were tested under isothermal, thermomechanical, and temperature gradient conditions. Maximum test temperature was 650°C (1200°F) and peak loads were also well beyond yield.

The option program was incorporated into NASA's Earth-to-Orbit Propulsion Technology Program. It extended the previous studies to time-dependent behavior using similar procedures. Rate versions of selected integrals were evaluated from a theoretical standpoint. Computer simulations of the tests to follow were run. Specimens were tested under static

loading, strain cycling with hold time, and thermomechanical loading with hold time. Also, data from the first contract were re-analyzed to see if a better correlation could be obtained using path-independent integrals.

FIRST CONTRACT

Approach

The first contract was awarded to Pratt & Whitney Aircraft (Commercial Products Div.). The Principal Investigator was G.J. Meyers. First, an "engine survey" was conducted to determine those areas of a turbine engine hot section where LEFM methods are not adequate to predict crack propagation rates. The survey was based on experience with the JT9D engine, an advanced commercial turbofan.

Isothermal and thermomechanical fatigue (TMF) cyclic tests were conducted. The test matrix (strain range, temperature) is shown in Fig. 1 and the TMF cycles in Fig. 2. Most of the TMF tests were out-of-phase (OP), but one in-phase (IP) test and one "faithful cycle" test were run. The "faithful cycle" is a simplification of results from a finite element analysis of a combustor liner louver.

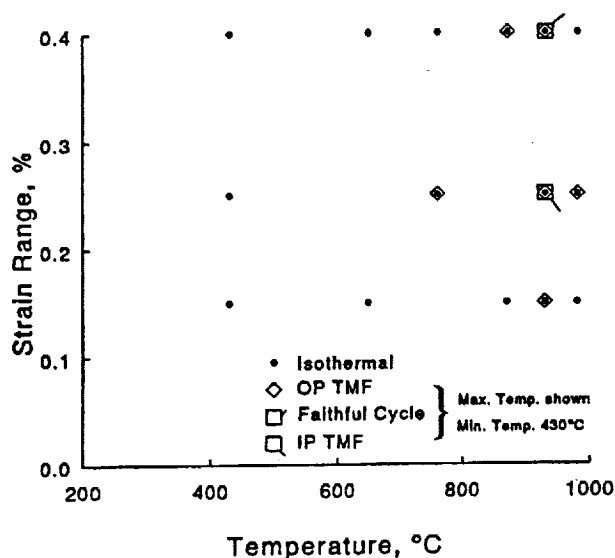


Fig. 1 - Hastelloy-X test matrix.

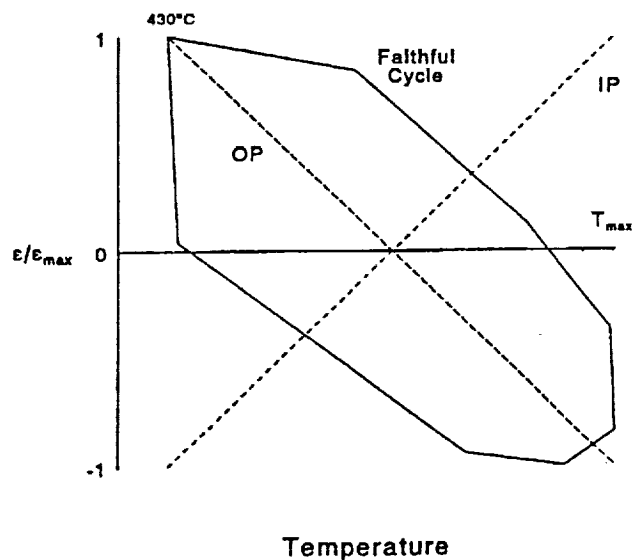


Fig. 2 - Hastelloy-X TMF cycles.

Tubular specimens with through-thickness circumferential cracks (Fig. 3) were made of Hastelloy-X, a typical combustor liner material. Isothermal tests were run in an electric furnace. TMF specimens were heated by induction coils and cooled by forced air. Most tests were conducted with zero mean strain. Displacements were measured over the gage length only (i.e., crack mouth displacements were not measured). Crack lengths were measured optically.

The parameters that were compared were the stress intensity factor, the strain intensity factor, the J-integral (Rice, 1968), and the crack tip opening displacement (CTOD).

Tomkins' (1975) model was also evaluated. The stress and strain intensity factors for the cracked tubular specimen were based on an analysis by Erdogan and Ratwani (1970). The same stress intensity factor was used to compute the elastic portion of the J-integral, and the plastic portion used an expression by Shih and Hutchinson (1976) for a small crack in a flat plate. A simplified crack tip opening displacement (CTOD) was calculated using the Dugdale (1960) model. For some of the isothermal tests, CTOD was also calculated from the J-integral and the strain hardening coefficient.

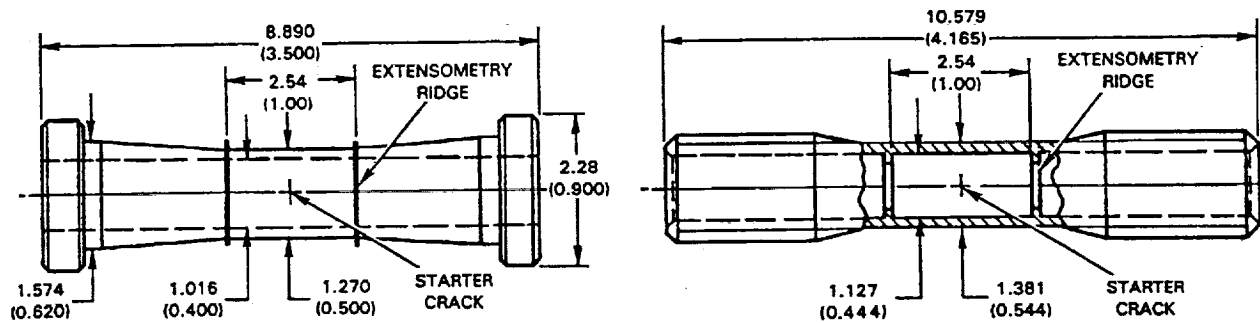


Fig. 3 - Hastelloy-X tubular test specimens. Dimensions in cm (in.).

Results

The results of this contract were reported by Meyers (1982). Portions of this work have also been reported by Jordan and Meyers (1986, 1989).

Results of the engine survey indicated that cyclic nonlinear material behavior seldom occurs in turbine disks, seals, spacers, and cases. For these components, LEFM analysis is adequate. Life prediction for blades and vanes is generally based on crack initiation life, with a correction factor based on engine experience. Since a 3D strain and temperature analysis of a blade or vane would be difficult and costly, nonlinear analysis would only be used for investigating serious safety concerns. The combustor liner, however, is fairly simple to analyze and is a high-maintenance-cost item. Nonlinear analysis would be most useful in this case.

Experimental results are not totally consistent, as can be seen in Fig. 4. The 'spread' is the greatest ratio (over the test range) of the fastest growth rate to the slowest, at the same value of the correlation parameter. Surprisingly, the stress intensity factor collapsed the OP TMF growth rates as a function of strain range (bar 2) rather well. But, as expected, it did not do well overall. The CTOD based on the J-integral was the best overall. The other methods all failed to collapse the isothermal growth rates as a function of temperature (bar 3). Three forms of Tomkins' model were applied to some of the isothermal data, but the correlation was no better than for the strain intensity factor and it was not carried further. An attempt was made to predict the TMF behavior from the isothermal data by integrating the instantaneous crack growth rate (as a function of temperature) over the tensile portion of the cycle. The prediction was good for an IP TMF test but only fair for the OP TMF and the "faithful cycle" test.

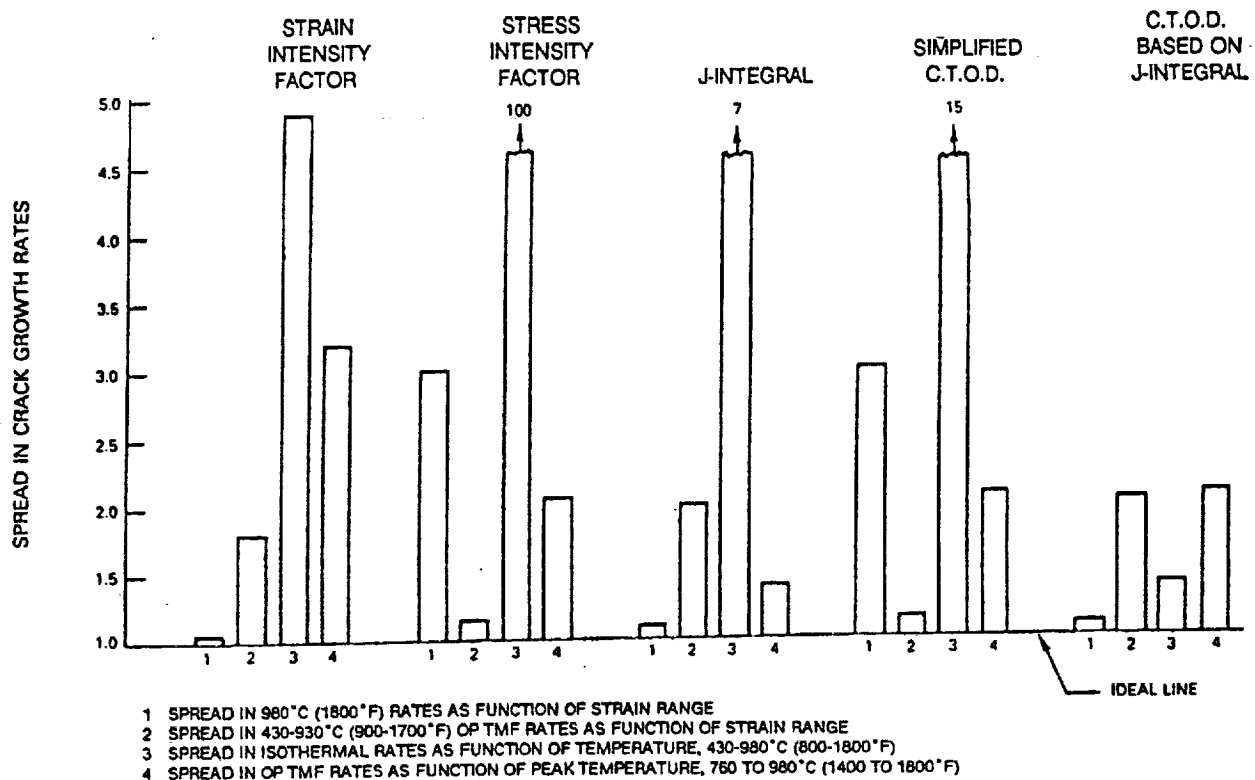


Fig. 4 - Spread of crack growth rates for various fracture parameters.

After the conclusion of this contract, it was apparent that a more fundamental approach to elevated temperature crack propagation was needed. There were a number of J-like path-independent integrals which looked promising but which had not been critically evaluated. Also, the phenomenon of crack closure (Elber, 1971) should be considered in any evaluation.

SECOND CONTRACT, BASIC PROGRAM

Approach

The second contract was awarded to GE Aircraft Engines. The Principal Investigator for the basic program was J.H. Laflen. First, eight path-independent integrals were evaluated from a theoretical standpoint. Those included were denoted J (Rice, 1968), J_w (Wilson and Yu, 1979), J_G (Gurtin, 1979), J_θ (Ainsworth et al., 1978), J^* (Blackburn, 1972), $\hat{J}$ (Kishimoto et al., 1980), and the ΔT_p and ΔT_p^* integrals by Atluri et al. (1983). The Atluri integrals are based on the incremental theory of plasticity, the rest on the deformation theory.

The path-independence of the integrals under isothermal cyclic loading, thermomechanical loading, and cyclic loading with a temperature gradient was first investigated analytically.

The model used was an edge-cracked strip under uniform end displacements. Analyses were made using CYANIDE, a General Electric nonlinear finite element program. Gap elements were used to model crack closure. A postprocessor was written to calculate each integral along several integration paths. The last four integrals mentioned above were all found to be acceptably path-independent.

For testing, an analog material was desired which can be tested at lower temperatures (to ease instrumentation problems) while retaining many of the important characteristics of a combustor liner material. These characteristics include significant variation in elastic modulus, large changes in short-time creep rates, and absence of phase transformations within the test temperature range. Inconel 718 in the temperature range 430-650°C (800-1200°F) was selected.

To meet the program requirements, special consideration was given to the type of test specimen to be used. The specimen should be suitable for isothermal and TMF testing under tension-compression loading and should permit the establishment of a temperature gradient in the direction of crack propagation. Displacements at the load point and at the crack mouth must be measured. For these reasons, the buttonhead single-edge-crack specimen shown in Fig. 5 was chosen.

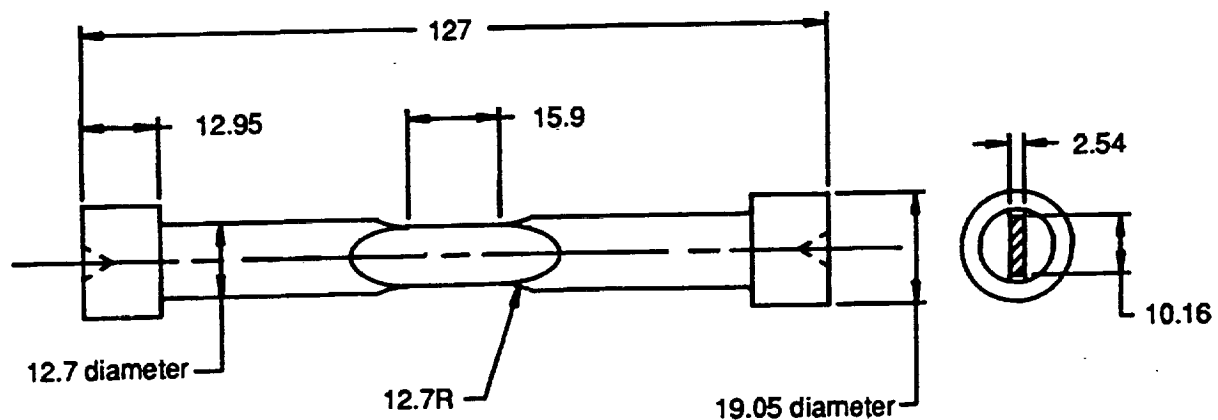


Fig. 5 - Buttonhead single edge crack specimen. Dimensions in mm.

Elastic-plastic 3D finite element analyses of the specimen were performed over the range of crack lengths to be tested. They showed that the displacements at the ends of the gage section were not uniform but, rather, varied linearly. This was confirmed by experimental measurement. Thus it was necessary to model only the gage section, with end displacements varying linearly, in two dimensions.

The instrumentation that was used is shown in Fig. 6. An extensometer on the specimen centerline is used for strain control. The backface extensometer, combined with the control extensometer, is used to determine the linear displacement gradient. The crack-mouth opening displacement (CMOD) gage is used in determining crack closure and the DC potential drop method to determine crack length. These measurements were recorded continuously using a computerized data acquisition system.

Isothermal, IP and OP TMF, and temperature gradient cyclic tests were conducted over the range 430-650°C (800-1200°F). The test matrix is shown in Fig. 7. The specimens were induction heated to establish and maintain the desired temperature. For the temperature gradient tests, air was blown on the back face. The resulting steady-state gradient was approximately trilinear, as shown in Fig. 8, and was reasonably uniform along the gage length. The crack was grown under cyclic loading from an initial length of about 0.5 mm to a final length of 8-12 mm. Cyclic rate for all tests was 0.6 cpm.

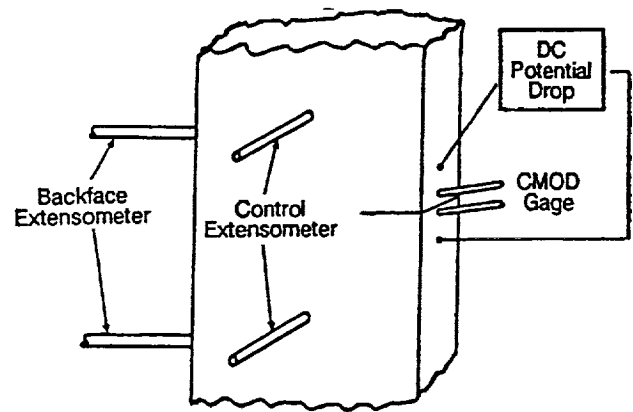


Fig. 6 - Displacement instrumentation.

The path-independent integrals were calculated from the test measurements as follows. At selected intervals, the crack length was determined from electric potential measurements. The control and backface displacements at minimum and maximum load determined the boundary conditions. These conditions along with the cyclic stress-strain curve served as inputs to the CYANIDE nonlinear finite element program. A postprocessor calculated the path-independent integrals from the finite element output.

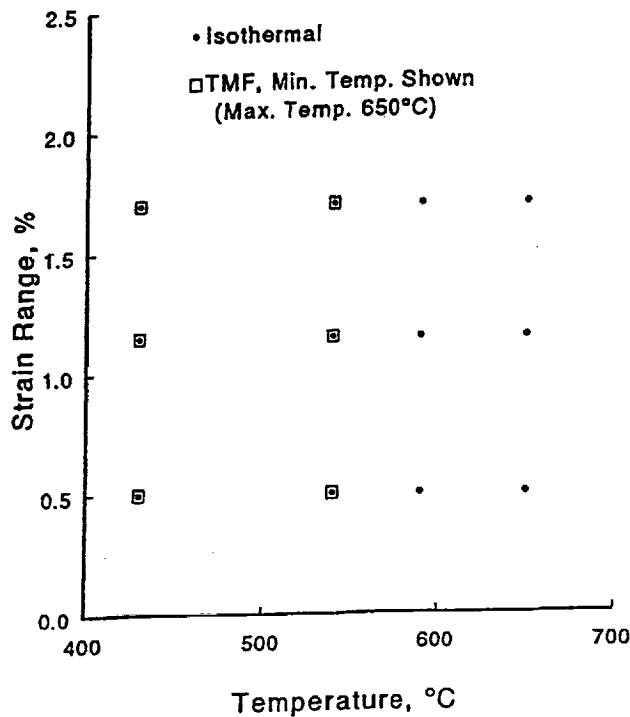


Fig. 7 - Test matrix for basic program.

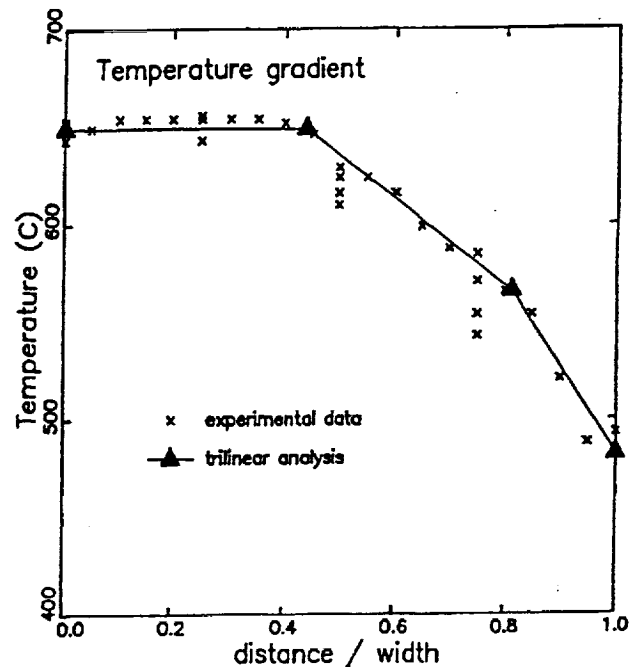


Fig. 8 - Trilinear temperature gradient.

Results

The results of the basic program have been reported by Kim (1985), Yau et al. (1985), Malik et al. (1987), and Kim et al. (1990a). Portions of this work have also been reported by Kim and Orange (1988), Kim et al. (1990b), and Kim and Van Stone (1990).

The evaluation of the path-independent integrals was reported in detail by Kim (1985) and by Kim and Orange (1988). The results are summarized in Table 1. For engineering application, a path-independent integral must satisfy three requirements. First, the integral must be calculable without great difficulty and must be reasonably path-independent. Second, it must be possible to determine the value of the integral from measurements made on a test specimen. Third, the integral must consolidate various types of crack propagation data into a single curve.

Table 1. - Evaluation of Path-Independent Integrals

Integral	Capable of Handling:				Integral Type	Experimental Measurement?
	Non-Proportional Cyclic Loading	Thermal Strain	Material Inhomogeneity	Elastic-Plastic Strains		
J	No	No	No	Yes	Line	Yes
J_W	No	Yes	No	No	Line + Area	Yes
J_G	No	Yes	No	No	Line	Yes
J_θ	No	Yes	No	Yes	Line + Area	Yes
J^*	Yes	Yes	Yes	Yes	Line + Area	No
$\hat{J}$	Yes	Yes	Yes	Yes	Line + Area	No
ΔT_p	Yes	Yes	Yes	Yes	Line + Area	No
ΔT_p^*	Yes	Yes	Yes	Yes	Line + Area	Yes

Note in Table 1 that six integrals are comprised of a line integral plus an area integral. The first four are not suitable for the situations characteristic of turbine engine hot sections. The last four integrals seemed the most promising and were selected for further evaluation. But note also that three of the four cannot be measured experimentally. That is, since they cannot be expressed as a rate of change of potential energy they cannot be evaluated from load-point displacement measurements alone. Nor can they be evaluated by measuring strains around a contour remote from the crack tip, as was done with strain gages by King and Herrmann (1981). Full-field stress-strain measurements would be required.

The final report for the basic program was given by Kim et al. (1988). Crack closure was found not to be a significant factor in these experiments. The crack opening load was very near the minimum load. Iyyer and Dowling (1985) found a similar trend in tests of 4340

steel with small surface cracks under fully reversed loading at high plastic strain levels.

As expected, the elastic stress intensity factor did not correlate the isothermal crack growth rates as a function of cyclic strain level. Data for 540°C are shown in Fig. 9. But all four integrals correlated these tests quite well. That is, crack growth rate data for all three strain levels could be fitted to the same straight line. An example (for the Atluri integral ΔT_p^*) is shown in Fig. 10. The three other integrals were equally successful. Each point in Fig. 10 represents a separate finite element calculation, thus there are fewer than in Fig. 9. The TMF and temperature-gradient tests were completed under this program, but their analysis was deferred to the option program and were reported by Kim and Van Stone (1992). However, they will be discussed here for consistency. Three integrals (Atluri's ΔT_p^* , Blackburn's J^* , and Kishimoto's $\hat{J}$) correlated the TMF data quite well. An example (for Kishimoto's $\hat{J}$) is shown in Fig. 11. Atluri's ΔT_p integral did not do quite as well.

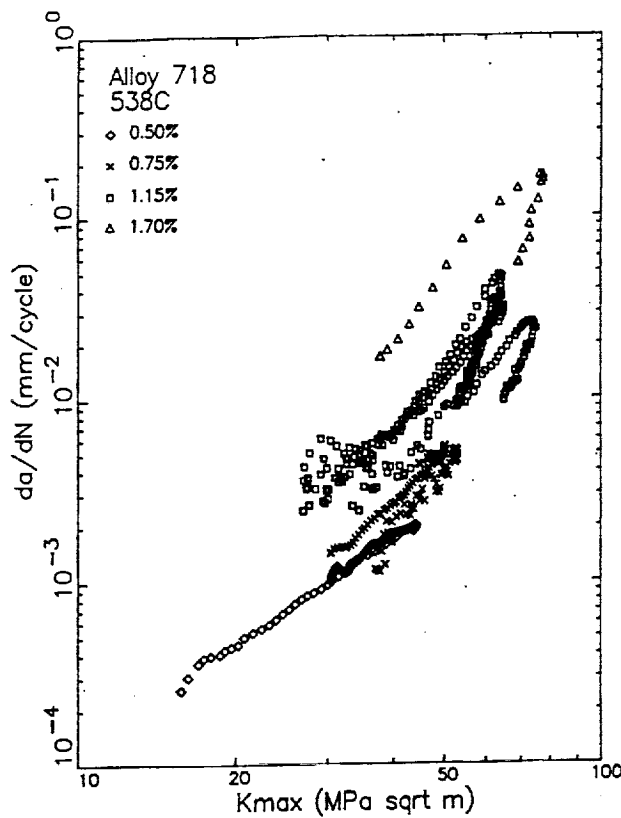


Fig. 9 - Isothermal crack growth rate as a function of ΔK_{max} .

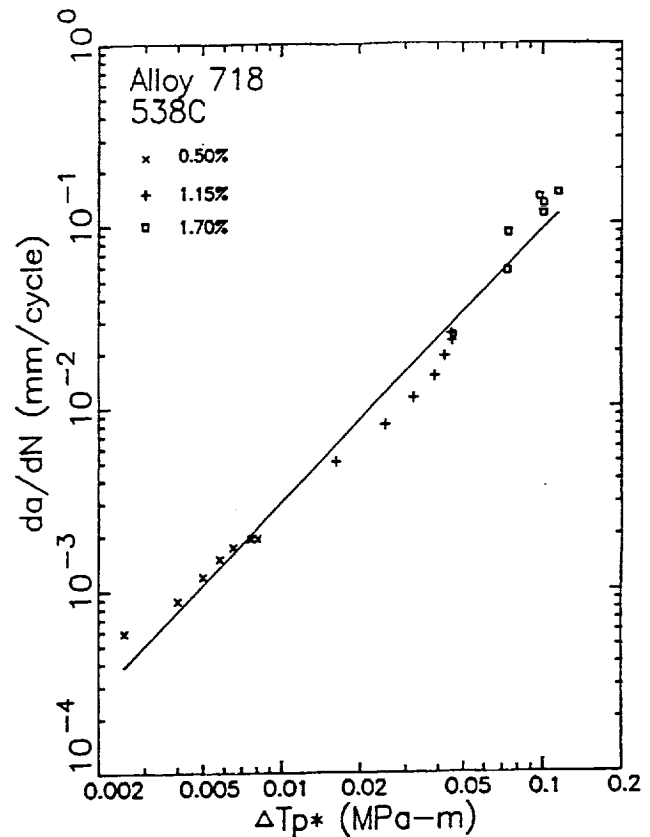


Fig. 10 - Isothermal crack growth rate as a function of ΔT_p^* .

Note in Fig. 11 that the temperature-gradient data for the two strain ranges align well with one another but not with the rest of the data. The gradient crack propagation data was taken in the constant-temperature (650°C) portion of the specimen (the integration path, however, did contain the gradients). Unfortunately the 650°C isothermal data were not

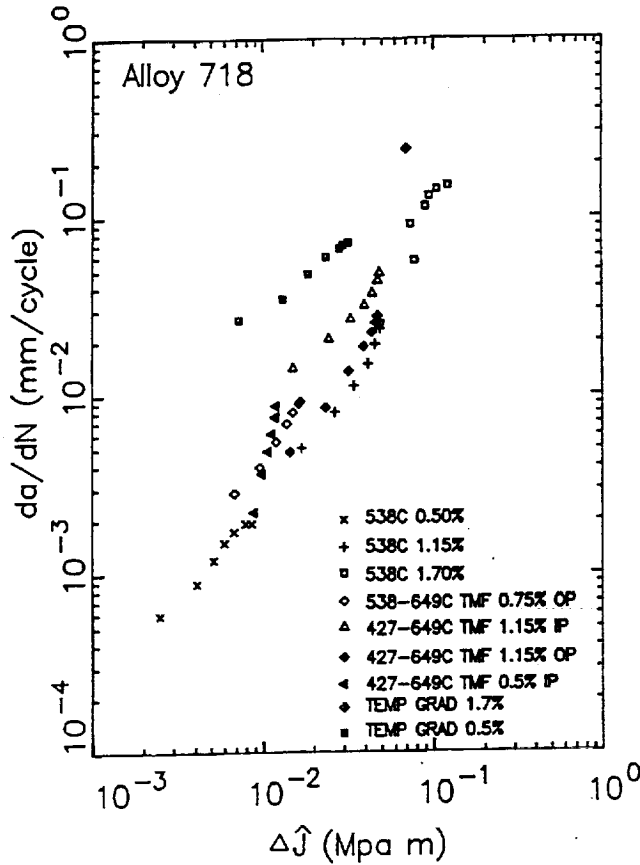


Fig. 11 - Isothermal, TMF, and temp. gradient crack growth rate as a function of ΔJ .

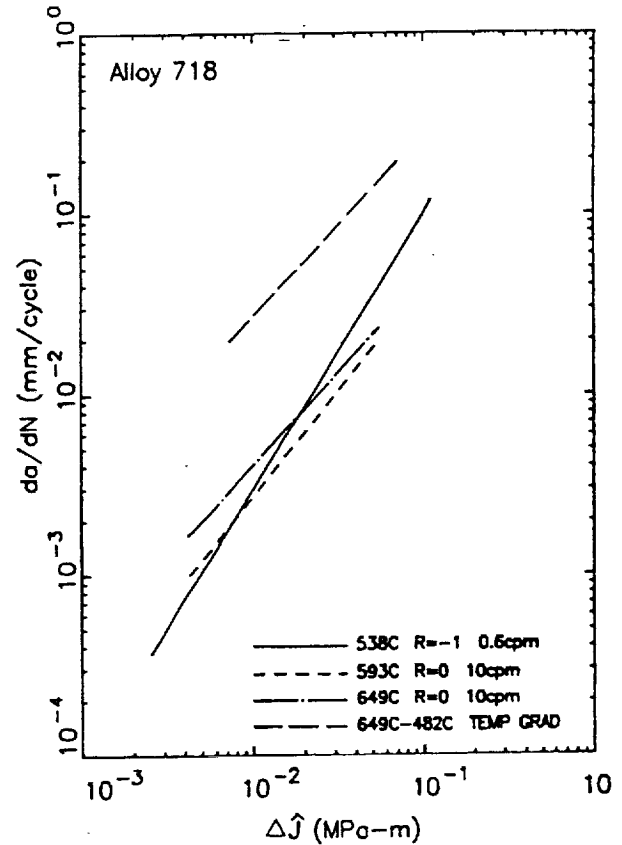


Fig. 12 - Crack growth rate trend lines as a function of ΔJ^* for isothermal and temp. gradient tests.

analyzed. But in Fig. 12 the trend line for the 650-480°C gradient tests can be compared with 650°C isothermal data from the hold-time series (zero hold time), which were run at a much faster rate. The lines are nearly parallel. The difference may be due to time-dependent crack growth occurring during the slower gradient tests.

SECOND CONTRACT. OPTION PROGRAM

Approach

The Principal Investigator for the option program was R.H. Van Stone. This program extended the previous studies to time-dependent behavior using similar procedures. First, the rate versions of four integrals were evaluated from a theoretical standpoint. These were the C^* integral and the rate versions of J^* (Blackburn, 1972), $\hat{J}$ (Kishimoto et al., 1980), and ΔT_p^* (Atluri et al., 1983). For the theoretical evaluation, the J^* and $\hat{J}$ integrals (which were not originally proposed as rate integrals) were converted to such by replacing strain and displacements by their time rates. C^* is the rate version of the J integral, as formulated by

Goldman and Hutchinson (1975) and so named by Landes and Begley (1976).

The rate integrals were first evaluated from a theoretical standpoint. Next the computational path-independence was studied using the edge-cracked strip model from the Basic Program. The cases considered were uniform end displacement, uniform stress, and uniform stress with a temperature gradient (decreasing in the direction of crack advance). For these and subsequent rate calculations, the rate integrals were calculated by dividing the differences between the integrals by the creep time between two relevant load cases. The postprocessor developed in the Basic Program was revised to accommodate subroutines for computing the rate integrals.

Static loading tests were run at 590°C and 650°C with strain levels of 0.4, 0.75, and 1.15%. Two tests with a constant load of 700 MPa were also run at the same temperatures. Cyclic load tests (with hold time) were chosen to represent a simple combination of time-independent and time-dependent loading. The test matrix for these tests is shown in Table 2. TMF tests (with hold time) were chosen to represent a more complicated combination. Strain levels were 0.40% IP and both IP and OP at 1.15%. For all three conditions, tests were run with no hold time, with 300 s hold at maximum load, and with 300 s hold at zero load. The instrumentation and method of calculating the integrals from test measurements were the same as in the Basic Program.

Table 2. - Test Matrix for Cyclic Load with Hold Time

Temp., °C	Strain (%) at Hold Time		
	0 s	30 s	300 s
540			0.4, 1.15
590	0.4, 1.15	0.4, 1.15	0.4, 1.15
650		0.4, 1.00	0.4, 1.15

In addition, the experimental results from the first contract (Meyers, 1982) were re-analyzed to see if the path-independent integrals would help consolidate these data. The Hastelloy-X tubular specimen was modelled as a center-crack flat plate with uniform end displacements. Bending of the specimen due to the presence of the crack was assumed negligible. Finite element analyses required only minor modifications to the mesh used for the single edge-crack specimen. Additional Hastelloy-X data required for the analyses were obtained from published sources.

Results

The results of the option program were reported by Kim and Van Stone (1992). The evaluation of the path-independent rate integrals is summarized in Table 3. The C* integral, as expected, is not suitable but the other three hold promise.

Table 3. - Evaluation of Path-Independent Rate Integrals

Integral	Capable of handling:			
	Non-Proportional Cyclic Loading	Creep Deformation	Temperature Gradient	Elastic-Plastic Strains
J^*	Yes	Yes	Yes	Yes
$\hat{J}$	Yes	Yes	Yes	Yes
ΔT_p^*	Yes	Yes	Yes	Yes
C^*	No	Steady State Only	No	No

The rate versions of both the J^* and the $\hat{J}$ integrals collapsed the static loading tests (constant load as well as constant strain) equally well. An example, for the rate version of the $\hat{J}$ integral at 650°C, is shown in Fig. 13. The rate version of Atluri's ΔT_p^* resulted in a poor correlation.

The cyclic load with hold time was first analyzed with a simple superposition method,

$$(da/dn)_{\text{hold time}} = (da/dn)_{\text{cyclic}} + t_h \cdot (da/dt)$$

where t_h is the hold time. The results for the J^* integral and its rate version (Fig. 14) show fairly good correlation for two strain ranges. Better correlation was obtained using a modified superposition model,

$$(da/dn)_{\text{hold time}} = (da/dn)_{\text{cyclic}} + \beta \cdot t_h \cdot (da/dt)$$

where $0 \leq \beta \leq 1$ and β is a function of maximum strain, hold time, and temperature. When β was determined to minimize the standard deviation between the predicted and experimental crack growth data for individual specimens, a much better correlation resulted (Fig. 15). The parameter β is a function of maximum strain, hold time, and temperature, but more tests would be required to define it fully.

The TMF with hold time data were not analyzed using path-independent integrals. However, the results were qualitatively similar to those obtained separately for

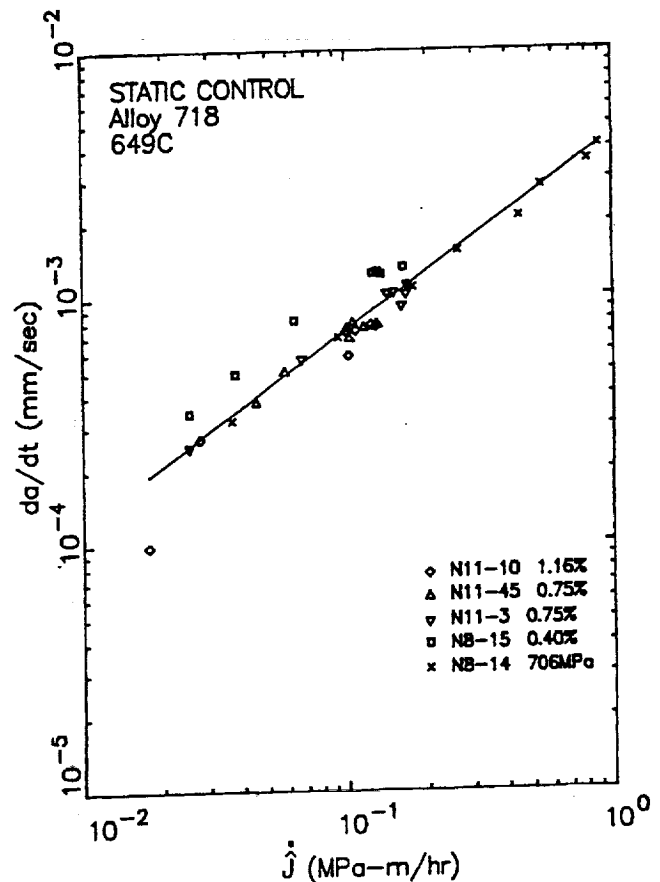


Fig. 13 - Time rate of isothermal crack growth as a function of $\hat{J}$.

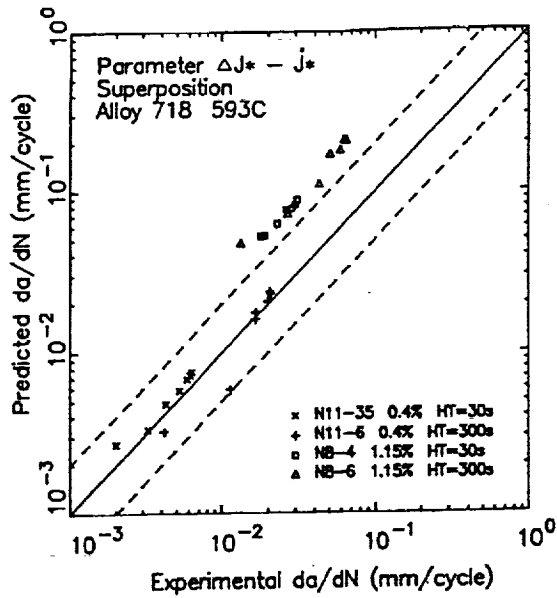


Fig. 14 - Cyclic loading with hold time; crack growth rate prediction by simple superposition using ΔJ^* .

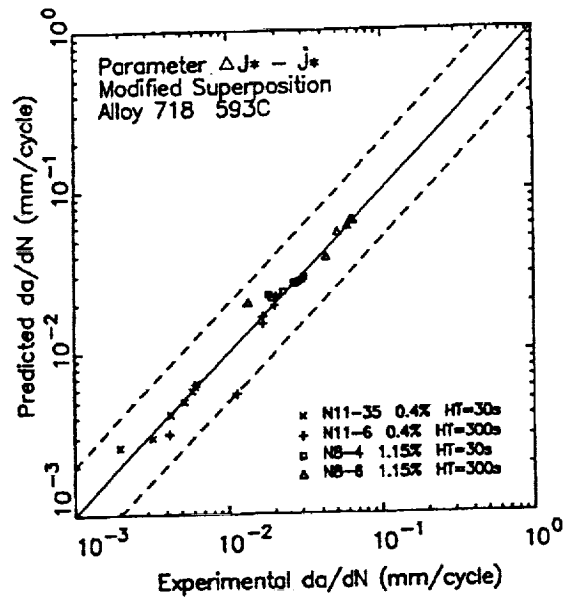


Fig. 15 - Cyclic loading with hold time; crack growth rate prediction by modified superposition using ΔJ^* .

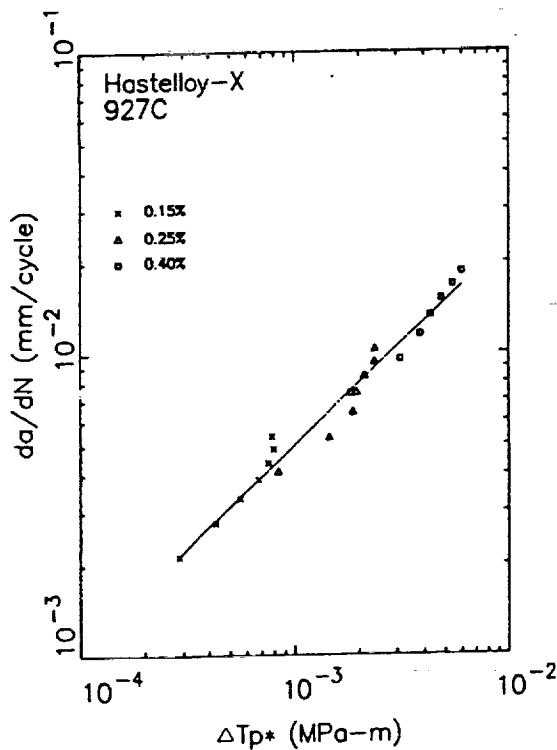


Fig. 16 - Hastelloy-X isothermal crack growth rate as a function of ΔT_p^* .

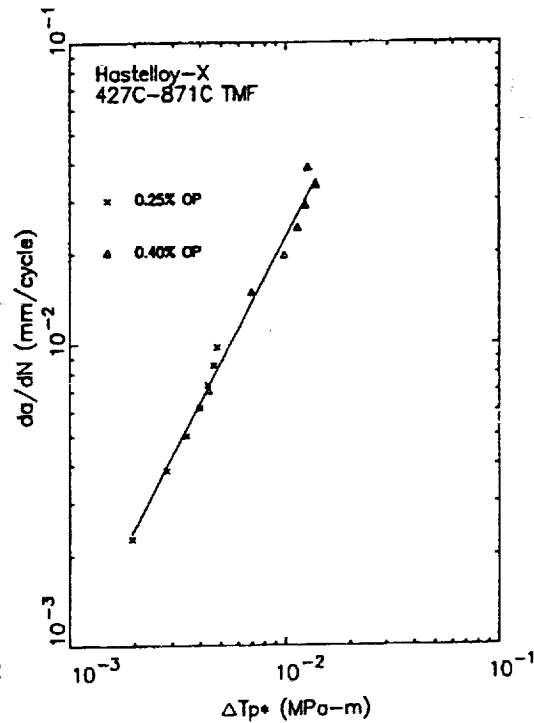


Fig. 17 - Hastelloy-X TMF crack growth rate as a function of ΔT_p^* .

TMF and for static loading. Thus the TMF with hold time data could probably be modeled successfully with path-independent integrals.

The re-analysis of the Hastelloy-X data from the first contract was fairly successful. The J^* , $\hat{J}$, and ΔT_p^* integrals correlated the isothermal data well. The ΔT_p integral was not as successful and seemed to worsen with increasing temperature. An example of the correlation for the ΔT_p^* integral at 930°C is given in Fig. 16. The same three integrals (J^* , $\hat{J}$, and ΔT_p^*) also correlated the 430-870°C out-of-phase (OP) TMF data well, and an example (for the ΔT_p^* integral) is shown in Fig. 17. However, the correlation for all three integrals worsened as the maximum cycle temperature increased. This is probably due to creep crack propagation, which increases with temperature and was not accounted for in the analyses.

SUMMARY AND CONCLUSIONS

The first contract showed the need for methods for correlating fatigue crack growth in turbine engine hot sections. It also showed that linear elastic fracture mechanics methods are not adequate and that simple nonlinear methods are but a slight improvement.

The greatest success of the second program was the performance of the path-independent integrals. Four integrals (Atluri's ΔT_p and ΔT_p^* , Blackburn's J^* , and Kishimoto's $\hat{J}$) were all able to correlate the isothermal data. Three (ΔT_p^* , J^* , and $\hat{J}$) were able to correlate the TMF data. Two (J^* and $\hat{J}$) were able to correlate the time-dependent tests. Three integrals (ΔT_p^* , J^* , and $\hat{J}$) were able to correlate the data for Hastelloy-X from the first contract under isothermal and OP TMF loading reasonably well. Also, the buttonhead single edge crack specimen proved an excellent choice for the second contract.

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