DEVELOPMENTS IN CREEP-FATIGUE CRACK GROWTH TESTING AND DATA ANALYSIS

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Time-dependent creep-fatigue crack growth (CFCG) is a major design consideration and a factor in the estimation of remaining life for elevated temperature components. In-situ measurement of incremental changes in the load-line deflection during hold times is a key measurement in characterizing CFCG behavior. Such measurements during hold times of < 100 seconds were successfully accomplished in compact specimens for the first time. Trapezoidal waveforms with hold times of 10, 20, 50 seconds were used on 2.25Cr-1.0Mo steel specimens tested at 594°C(1100°F). A procedure for choosing a set of optimum conditions for generating CFCG data is proposed and a method for analysis is outlined.

INTRODUCTION

Improving the efficiency or achieving a longer life of new or existing energy conversion machinery is desirable. In the case of equipment such as steam headers, steam turbines, gas turbines, aircraft engines and nuclear reactors, this translates into an increase in their operating temperatures. Consideration of crack growth under creep-fatigue conditions can be the dominant factor in determining the allowable maximum stress and temperature, as well as the design and remaining lives of elevated temperature components [1]. The operation of these equipment involve start up, shutdown steps with continuous high temperature operation under sustained load being the intermediate step. Therefore, both creep and fatigue type processes influence the growth of cracks in the material. This loading history is most conveniently simulated in the laboratory by a trapezoidal loading waveshape applied to test specimens. Creep deformation occurs mainly during the sustained loading periods but it can also occur during the loading part of the cycle because the loading that occurs at high temperatures is often slow.

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To understand the effects of these loading variables on the crack growth rate, laboratory tests which can simulate these service conditions must be developed and their results modelled mathematically. Since long test times are prohibitive due to practical constraints, accelerated test methods are needed to predict service behavior with relatively short time tests. The most challenging step in developing an *accelerated test* for CFCG testing is the measurement of incremental deflection change (ΔV) during a single hold time (t_h) of the trapezoidal loading waveform. The advantages of measured deflection values over those obtained analytically are discussed in reference [2].

In this paper, an attempt has been made to establish testing conditions, including the choice of hold time and cyclic load levels during CFCG testing such that reliable deflection measurements can be made. Further, a technique for accurate measurement of deflection change during hold time is discussed. This technique is similar to the one used during J-resistance curve testing [3] for measuring crack extension by unloading compliance.

Prior studies [4-12] have shown C_t - parameter to be the most promising for characterizing experimental CCG and CFCG data. Thus, the average value of C_t, $(C_t)_{avg}$, was used to correlate the average crack growth rate during hold time, $(da/dt)_{avg}$.

EXPERIMENTAL PROCEDURE

Material and Specimens

The test material was a 2.25Cr-1.0Mo steel taken from the hot end of an ex-service header. The uniaxial version of the constitutive law chosen to represent the creep behavior of the material is given below.

$$\dot{\epsilon} = \frac{\dot{\sigma}}{E} + A_1 \epsilon^{-p} \sigma^{n_1(1+p)} + A\sigma^n \qquad (1)$$

where σ = stress and ϵ = strain. The dots denote their respective time derivatives. E is the elastic modulus. A, A_1 , n, n_1 and p are regression constants. The first term on the right hand side of Equation (1) represents the elastic strain rate and the other two represent the primary and secondary creep behaviors respectively. Most of the relevant tensile and creep properties of the material were obtained from prior studies [13]. These properties are listed in Table 1.

TABLE 1 - Material properties of 2.25Cr-1.0Mo steel at 594°C (1100°F)

Tensile Properties	Elastic Modulus × 10^{+3} *Mpa (ksi)*		Yield Stress *Mpa (ksi)*	
	161.92 (23.5)		172.25 (25)	
Plasticity Constants[#]	D		m	
	Mpa^{-m}	ksi^{-m}		
	1.39×10^{-13}	2.12×10^{-9}	4.99	
Secondary Creep Properties	A		n	
	$Mpa^{-n}hr^{-1}$	$ksi^{-n}hr^{-1}$		
	1.94×10^{-24}	5.41×10^{-16}	10.075	
Primary Creep Properties	A_1		n_1	p
	$Mpa^{-n\,(1+p)}hr^{-1}$	$ksi^{-n\,(1+p)}hr^{-1}$		
	8.26×10^{-28}	3.78×10^{-19}	4.92	1.1

[#] $\varepsilon_p = D\sigma^m$, where ε_p is the plastic strain. D and m are regression constants obtained from the true stress vs. true strain curve.

The CFCG tests were carried out using CT specimens which have become the preferred geometry in majority of fracture and crack growth test methods. These specimens offer the convenience of low test loads and the ease of instrumentation for load-line deflection measurements during hold times. The latter is because a clip-gage can be conveniently placed in the machined knife edges along the load-line and the whole assembly can be placed in a high temperature chamber. The specimens used had a width of 50.8 mm (2.0 in) and a thickness of 10.2 mm (0.4 in).

Test Conditions

All tests were carried out at 594°C (1100°F). Trapezoidal waveform was used for loading. The load levels, crack ratios, cycle times and K-levels are specified in Table 2. All these tests were carried out in air. It is noted that the rise time (t_r) and decay time (t_d), corresponding to the loading and unloading part of the cycle, respectively, were much smaller than the hold time (t_h).

Prior to the CFCG tests, a high temperature fatigue test with 1 Hz cycling frequency was also carried out at 594°C (1100°F) with the same load levels as the CFCG tests. The load levels, crack ratios and the K-levels for this test are also included in Table 2.

TABLE 2 - Description of the test conditions for the FCGR and CFCG experiments

Test Type	Hold Time	Hold Load *KN (kips)*	Crack Ratio		ΔK $Mpa\sqrt{m}(ksi\sqrt{in})$
		(R = 0.1)	*initial*	*final*	*final*
FCGR	0	5.86 (1.32)	0.3	0.4210	28.430(25.869)
CFCG	10 sec	5.86 (1.32)	0.4	0.5078	23.706(21.571)
CFCG	20 sec	5.86 (1.32)	0.4	0.4567	19.602(17.836)
CFCG	50 sec	5.86 (1.32)	0.4	0.4353	18.521(16.853)

Note:

initial value of ΔK for CFCG tests = 16.799 (15.286) $Mpa\sqrt{m}(ksi\sqrt{in})$
initial value of ΔK for FCGR test = 12.973 (11.804) $Mpa\sqrt{m}(ksi\sqrt{in})$

Test Equipment and Procedure

All the CFCG tests were carried out on servohydraulic machines. A high temperature stainless steel chamber was used to heat the specimen. Stainless steel leads were welded to the specimens in order to measure crack length using the 'potential drop method' [14]. The specimens were then mounted on the clevises in the chamber. The crack length, a, was calculated from the output voltages using Johnson's formula in accordance with the guidelines provided in reference [14].

A high temperature capacitance clip-gage was attached to the specimen to measure the load-line deflection. The working deflection range for the majority of the tests was 2.05 mm (0.1 in). The gage calibration was carried out at room temperature and applied to the high temperature because the calibration is not dependent on temperature in the range of 25°C to 600°C.

A strip chart recorder was used as the primary output device. It had three channels which were used for monitoring the (i) voltage change due to crack growth (ii) output voltage from the *summing amplifier* of the clip-gage for charting the load-line deflection changes during the hold times and (iii) load during the hold periods.

Use of the *unloading compliance box* was the key to the successful measurement of the incremental deflection changes during the hold time. This electronic circuit was used to subtract out the deflection change signal due to the loading part of the cycle so that the signal during the hold time could be further amplified by a factor of 10. This ensured precise measurement of deflection changes even for very short hold times (~ 10, 20 seconds). The speed of the strip-chart recorder was increased from 4 cm/hr to 4 cm/min., or in the same ratio, during the times when the output was being recorded to ensure visually clear plots of the deflection change during hold periods. Ten to twenty successive cycles were recorded each time and the average deflection change for these measurements was calculated. The crack growth during the recording of data was neglegible. The number of cycles recorded in each set was varied between 10 and 20 so that the optimum number could be decided on the basis of statistical accuracy and the time involved to record each set. This information forms a part of the proposed test procedure, discussed later.

Data Reduction

The load-line displacement changes during the hold times in each cycle were read from the strip chart recorder. The mathematical mean of all the measurements in a set (10 to 20 cycles) was calculated and the result was accepted as a load-line deflection change datum if the standard deviation for the set was low ($\leq 0.25 \times$ datum). A low standard deviation ensures high quality data. The median of the cycle numbers in the set was taken as the cycle count corresponding to the displacement datum. A crack length corresponding to the deflection measurement was calculated from the recorded potential drop as described before. The crack lengths and the corresponding hold time deflection values, the material properties and the specimen dimensions were input into computer programs [2] to calculate various fracture mechanics parameters (ΔK, C^*, $(C_t)_{avg}$) and crack growth rates. The final objective was to obtain plots of $(da/dt)_{avg}$ *vs.* $(C_t)_{avg}$ and da/dN *vs.* ΔK .

Evaluation of ΔK . ΔK was evaluated as follows and was used to correlate the overall fatigue crack growth rate during a cycle, (da/dN), which is defined in equation (7).

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} F\left(\frac{a}{W}\right) \tag{2}$$

where ΔP is the applied load range, B is the specimen thickness and W is the specimen width. F is an empirical factor that accounts for the specimen geometry dependence of ΔK.

<u>Evaluation of $(C_t)_{avg}$</u>. $(C_t)_{avg}$ can be evaluated using the measured load-line deflection change rate during hold time as follows:

$$(C_t)_{avg} = \frac{\Delta P \, \Delta V_c}{B W t_h} \frac{F'}{F} - \left(\frac{F'}{F}\frac{1}{\eta} - 1\right) C^*(t) \tag{3}$$

ΔP is the applied load range, ΔV_c is the load-line deflection change due to creep during hold time t_h . F is the K-calibration factor, $F = (K/P)BW^{1/2}$. $F' = dF/d(a/W)$. B is the specimen thickness and W is the specimen width. η is a function of a/W, where a is the crack length, and n *and* n_1 i.e. the creep exponents in secondary and primary creep range respectively. For CT specimens η is given by equation (4) [15].

$$\eta = \frac{n}{n+1}\left(\frac{2}{1 - a/W} + 0.522\right) \tag{4}$$

$$\Delta V_c = \Delta V - \frac{B t_h}{P}\left(\frac{da}{dt}\right)_{avg}\left[\frac{2K_{eff}^2}{E} + (m+1)J_p\right] \tag{5}$$

where m is the plasticity exponent in the Ramberg-Osgood equation and P is the applied load level. K_{eff} is the value of K corresponding to the 'effective' crack length corrected for plasticity.

It is noted that the ΔV_c value which is obtained, using equation (5), from the total load-line deflection change, ΔV, by deflection partitioning approach [16] includes both primary and secondary creep contributions to the load-line deflection change. J_p is the fully plastic part of J and is obtained from expressions listed in Kumar et al [17]. $C^*(t)$ was determined using procedures outlined in previous research works [17] and must include the contributions of secondary and primary creep.

Determination of $(da/dt)_{avg}$. The average crack growth rate during hold time, $(da/dt)_{avg}$, was calculated as follows.

$$\left(\frac{da}{dt}\right)_{avg} = \frac{1}{t_h}\left[\left(\frac{da}{dN}\right) - \left(\frac{da}{dN}\right)_{cycle}\right] \tag{6}$$

$(da/dN)_{cycle}$ is the cyclic crack growth rate and was obtained from the 1 Hz FCGR test carried out prior to the CFCG tests. The overall crack growth rate during a fatigue cycle, (da/dN), is defined as

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_0 + \int_0^{\frac{1}{\nu}} \left(\frac{da}{dt}\right) dt \tag{7}$$

where $(da/dN)_0$ is the crack growth rate at a higher frequency ν. (da/dt) is the time-dependent crack growth rate.

RESULTS AND DISCUSSION

CFCG Behavior

The CFCG behavior of 2.25Cr-1.0Mo steel was characterized and a model has been proposed to estimate the crack growth rates for this material under trapezoidal loading waveshapes. ΔK and $(C_t)_{avg}$ have been used as the correlating parameters for the cycle dependent and time dependent crack growth rates respectively.

The 1 Hz frequency FCGR test data was used to calculate the cycle dependent crack growth rate, $(da/dN)_{cycle}$, and to obtain the Paris constants by regression analysis. Figure 1 is the graph of this data and the fatigue crack growth data obtained with various hold times. The linear regression line generated from this data is also shown.

The fatigue crack growth rate with various hold times plotted as a function of ΔK in Figure 1 is scattered, as expected, because ΔK is not suitable for characterizing the time-dependent crack growth rate during hold period. An increase in da/dN with increasing hold time for fixed ΔK is observed. This is due to the increasing contribution of time-dependent crack growth.

C_t was used as the correlating parameter for time dependent crack growth rate.

Figures 2 is the graph of *da/dt* vs. C_t for the CCG data [18] and $(da/dt)_{avg}$ vs. $(C_t)_{avg}$ for the CFCG data. The loading and unloading parts of the trapezoidal waveform used in the CFCG tests were the same as those for the triangular waveform employed in the FCGR test while the hold times varied from 10 seconds to 50 seconds. Crack growth behavior was considered completely cycle dependent for the loading and unloading portions of the trapezoidal waveform while the crack growth during the hold time was considered as being only time dependent. The *measured* $(C_t)_{avg}$ values are plotted against $(da/dt)_{avg}$ in Figure 2. An excellent correlation between all CCG and CFCG data is observed and all data fall on a single trend when *da/dt* is characterized in terms of C_t and $(da/dt)_{avg}$ in terms of $(C_t)_{avg}$. This has the important implication that life prediction procedures for this material would be considerably simplified because CCG data could be used to predict the life of components under CFCG conditions and vice-versa. The time dependence of the model was obtained by generating a regression line through the data in Figure 2.

Combining the cycle and time dependent crack growth rates, we express below the model for total fatigue crack growth rate per cycle under trapezoidal waveshapes.

$$\frac{da}{dN} = 1.08\times10^{-6}\ \Delta K^{1.94} + 1.46\times10^{-2}\left[(C_t)_{avg}\right]^{0.722} t_h \qquad \mathbf{(8)}$$

The above equation can be effectively used to predict the service life of high temperature components made of 2.25Cr-1.0Mo steel under, both, CCG and CFCG conditions at 594°C (1100°F). This model has been established under the assumption that the crack growth during hold time is only due to creep deformation. Any other time-dependent effects like oxidation at the crack tip have not been incorporated. Neither have any synergistic effects due to any complicated interactions of the creep and fatigue mechanisms of crack growth during unloading/reloading been incorporated. Despite these simplifying assumptions, the CCG and CFCG data at various hold times collapses into a single trend.

Recommended Method for CFCG Testing

Outline of the Steps in Conducting a CFCG Test .

(1) Material properties needed:
- (i) Elastic properties - Young's Modulus (E)
- (ii) Yield strength (σ_{ys}^{c})
- (iii) Plastic properties - D, m
- (iv) Primary creep properties - A_1, n_1, p
- (v) Secondary creep properties - A, n

The creep properties are the regression constants in the constitutive creep law that the material obeys (equation 1 in this study). It is important to note that fairly accurate estimates of $(C_t)_{avg}$ can be made using Equation 3 even when accurate values of creep constants are not available because for CT specimens $(F'/F)/\eta \approx 1$.

(2) Selecting the specimen geometry and size:

The following factors should be considered in selecting the specimen size and geometry:-

(i) CT specimens have an advantage over CCT specimens because the transition time for extensive creep conditions to develop is longer for the same K and a/W. Due to the longer transition times in the CT specimens, the condition that $t_c/t_l \ll 1$ is more easily satisfied and ΔK is a meaningful characterizing parameter for longer hold times and crack sizes, provided the time independent plasticity is negligible and small scale yielding (SSY) conditions prevail [19]. t_c is the cycle time and t_l is the transition cycle time defined for extensive creep conditions to develop. Another advantage of the CT specimen is that a clip-gage to measure deflection can be placed conveniently at the load-line.

(ii) Constraints pertaining to the amount of material available can also be instrumental in deciding the specimen dimensions especially if the orientation of the specimen is dependent on the location of cracks in the material.

(iii)The size/shape of the furnaces and load capacity of the test machines can also affect the choice of specimen size.

(3) Selecting the waveshape for loading:

The loading waveshape should simulate the actual loading conditions. For power-plant components, this is very often a trapezoidal waveform. The rise/decay and hold times should be decided for a trapezoidal waveshape with a hold at maximum load. Other waveforms, with hold times at minimum load or negative load ratios may be employed, if needed.

(4) Choosing the K-levels/load-levels:

This choice depends on the crack growth rates required during the test. Ideally, crack growth rates should be approximately those encountered by the material during service. However, quite often the time available for generating creep-fatigue data dictates the selection of the crack growth rates. For example, if the test data are desired within one month, an average crack-growth rate can be obtained by dividing the expected crack extension by the total number of cycles that can be applied in one month. Since the number of fatigue cycles enter into the equation, the K-levels for the test can be selected only in conjunction with the hold time, which is discussed next.

(5) Selecting the hold times:

In addition to simulating the service conditions, other factors enter into selecting the length of the hold time as follows:-

(i)The hold time should be selected in conjunction with the K-level such that crack extensions on the order of 5 mm (0.2 inches) are obtained during the planned duration of the test. When testing a new material, trial and error is often necessary to select the appropriate K-level/hold-time conditions.

(ii) Sensitivity of the displacement-gage available for measuring the load-line deflection change is also a factor in selecting the hold time. Since this measurement is the key to a successful CFCG test, the hold time should be selected such that the deflection which accumulates during the hold time is approximately three to five times the sensitivity of the displacement-gage/amplifier system used. Again, trial tests may be necessary when testing a new material to establish that this is in fact the case.

(iii) The hold time chosen should be no more than, approximately, fifty percent of the calculated transition time for the expected final crack size in the test.

(6) Selecting the test temperature:

Test temperature should be the same as the service temperature. Higher temperatures may be used to decrease the test duration, however, caution must be exercised in selecting the test temperature. It is essential to ensure that the deformation and cracking mechanisms do not change substantially when higher temperatures are employed.

(7) Type of test to be conducted:

Either load control or displacement control tests can be conducted. However, while conducting a load control test, SSY conditions should be ensured.

(8) Required Measurements from the test:

The measurements to be made during the test are the deflection change during hold time, total load-line deflection and the crack length corresponding to different stages of the test i.e. the a vs. N data, where N = number of cycles. It is advisable to monitor the load during the hold time to ensure that the deflection changes are not due to any random variations in the load. The load-line deflection data can be obtained using a high temperature clip-gage, calibrated at room temperature and placed along the load-line of the CT specimen. In order to increase the sensitivity of the deflection change output, the deflection signal during the loading portion of the cycle should be electronically subtracted out and the signal during the hold time should be amplified. It is important to point out that this also amplifies the noise which may need to be filtered from the signal. A strip-chart recorder is very useful in recording the output deflection traces which can be visually examined to assess the quality of the data obtained. It is the authors' view that good and bad data may be easier to recognize on a strip-chart record than in one obtained from a computerized data acquisition system. Since, only a strip-chart recorder was used in this study, a fair evaluation of the efficacy of a computerized data acquisition system as an output device for this application is not possible. However, it is suggested that a strip-chart recorder be used at least as a backup device for recording the output. The crack length data must be obtained by 'non-visual techniques'. Electric potential drop method (DC and AC) have been widely used. In this study, DC potential drop was used with satisfactory results. The details of this technique were discussed earlier in [2] and are also described in Reference [20].

(9) Presentation of the Test Results:

Whenever CFCG testing is carried out for a material, it is suggested that the $(da/dt)_{avg}$ vs. $(C_t)_{avg}$ data be compared with the da/dt vs. C_t data from CCG tests on the same material because if they show the same trend, life estimation procedures for the material can be simplified, as discussed earlier.

Along with the explanation of the test conditions used, the results from the development of the test procedure should include information on the characterization of the crack growth behavior of the material. Comprehensive analytical schemes for the prediction of crack growth rates under any given set of loading conditions and hold times are preferable.

Additional Suggestions for Collecting Data . In this study all the CFCG tests were carried out as per the outline presented above. Figure 3 shows a set of good data. However, during the course of testing and analysis of the results, certain interesting observations were made which should be kept in mind while carrying out CFCG tests according to the proposed test methodology.

(1) Racheting - The clip-gage which was calibrated for an opening of 2.54 mm (0.1 inch) corresponding to 10 volts saturated earlier (fewer cycles and crack extension) during the 50 second hold time test as compared to the 20 second hold time test. Therefore, racheting is more a concern with longer hold times. It was observed that towards the end of the 10 second hold time test (ie. the end of the gage's range), the crack growth rates were very high. Thus, greater care and recording a greater number of measurements towards the end of the test is suggested.

(2) On the basis of observations made while collecting and analyzing the

data, it is proposed that corresponding to each set of deflection change measurements there should be two crack length measurements and total deflection measurements made, preferably during the first and last cycles of the set. The average of the two crack lengths should be used as the crack length for the average deflection change obtained from the set of measurements. This would account for any erratic behavior in the crack growth, which could be the case as shown in Figure 4. This is a photograph of the actual test data from the 20 second hold time test.

(3) On several occasions deflection change data had to be discarded due to high noise to signal ratio in the output. Figures 5 and 6 are examples of this situation. This noise could be due to the fluctuations in the electrical/electronic circuitry associated with the gage or the gage itself not being perfectly aligned. This was more prevalent during the 10 seconds hold time test. This was probably because during this short hold time the gage did not get sufficient time to stabilize before displacement direction got reversed due to unloading. This explains why in case of the 2.25Cr-1.0Mo steel the 50 second hold time data was the 'cleanest', virtually noise free as shown in Figure 3.

(4) It is suggested that, if possible, the same calibration be used on the strip-chart recorder throughout the test in order to minimize any errors during visual inspection of data for measuring the deflection change. However, the calibration chosen should be such that significant deflection change is visible in each cycle so that the accuracy of measurement from the strip-chart is not compromised.

CONCLUSIONS

An accelerated test procedure for creep-fatigue crack growth (CFCG) testing has been developed and the various steps in conducting tests and analyzing data are outlined and discussed. The CFCG behavior of 2.25Cr-1.0Mo steel at 594°C (1100°F) has been characterized following the proposed test procedure. A model has been presented which can be used for assessing the residual life and/or safe inspection intervals for 2.25Cr-1.0Mo steel components under trapezoidal waveshape loading at 594°C (1100°F). The following conclusions can been drawn from this study:

(1) The accelerated test procedure that has been developed shows promise for use for CFCG testing, as demonstrated by the successful testing carried out on 2.25Cr-1.0Mo steel for characterizing its behavior at 594°C (1100°F) under trapezoidal waveshape loading conditions. Detailed methods have been developed that allow one to utilize the existing extensometry on CT specimens for obtaining reliable load-line displacement changes during the hold-time. This is the keystone in the development of a successful test methodology. However, a more extensive

study on different materials is recommended to further develop this technique.

(2) Ideal conditions for the CFCG testing of 2.25Cr-1.0Mo steel at 594°C (1100°F) have been presented. It is suggested that a hold time of 50 seconds and a rise and decay time of 0.5 seconds represent ideal conditions for CFCG testing.

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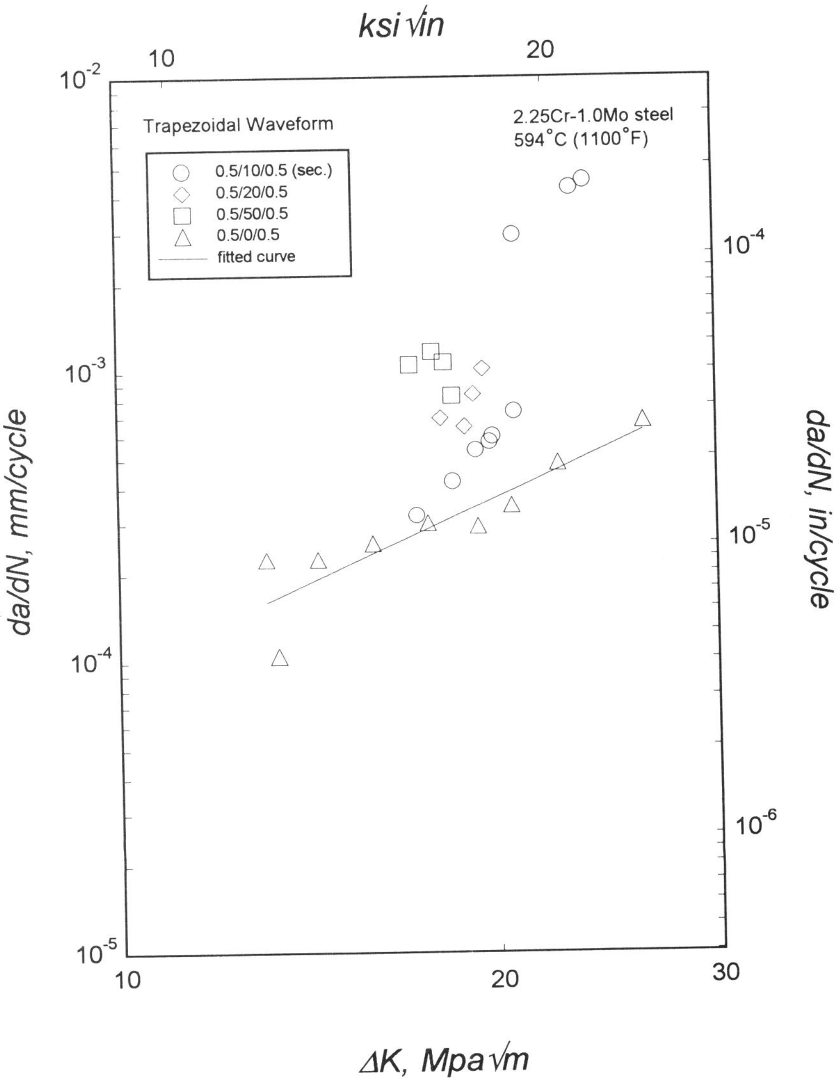


Figure 1 Fatigue crack growth data with various hold times and without hold time.

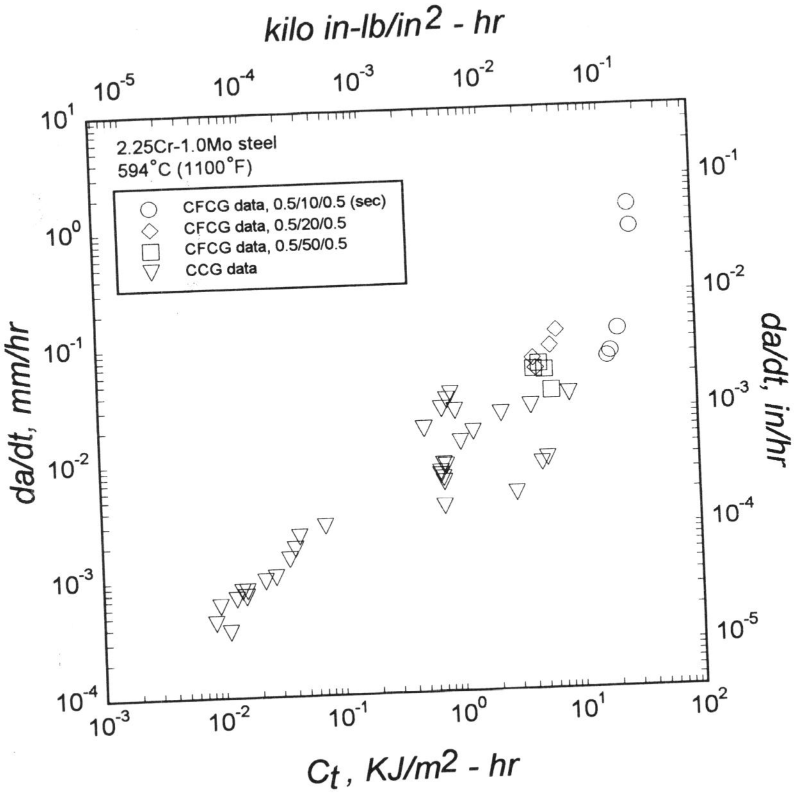
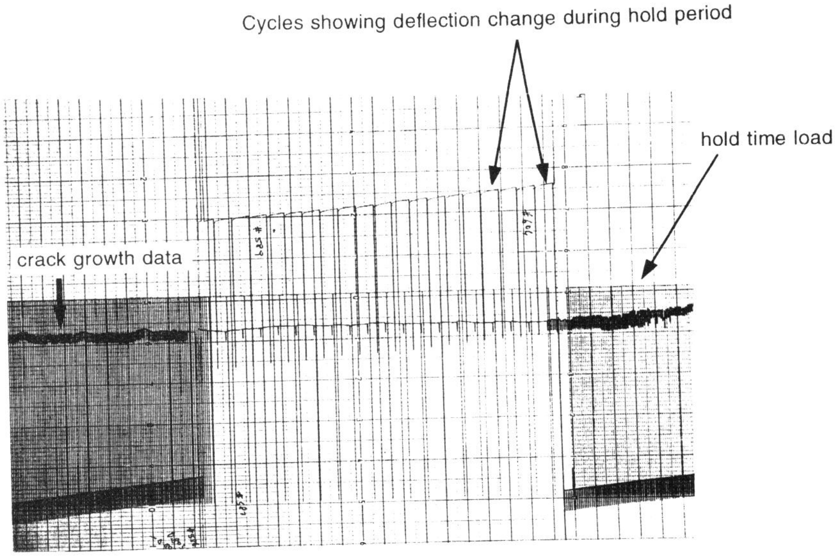


Figure 2 Correlation of the crack growth rates with the measured values of C_t. (The average values of *da/dt* and C_t are plotted for CFCG data)


Cycles showing deflection change during hold period

hold time load

crack growth data

Figure 3 Good deflection change data from the strip chart.

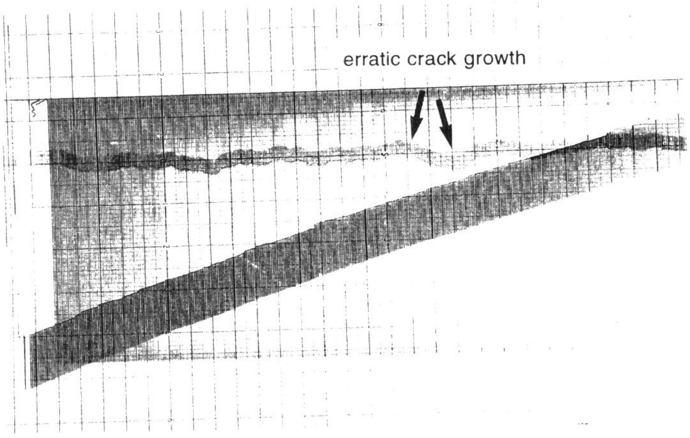

erratic crack growth

Figure 4 Erratic behavior in crack growth (from the 20 seconds hold time data).

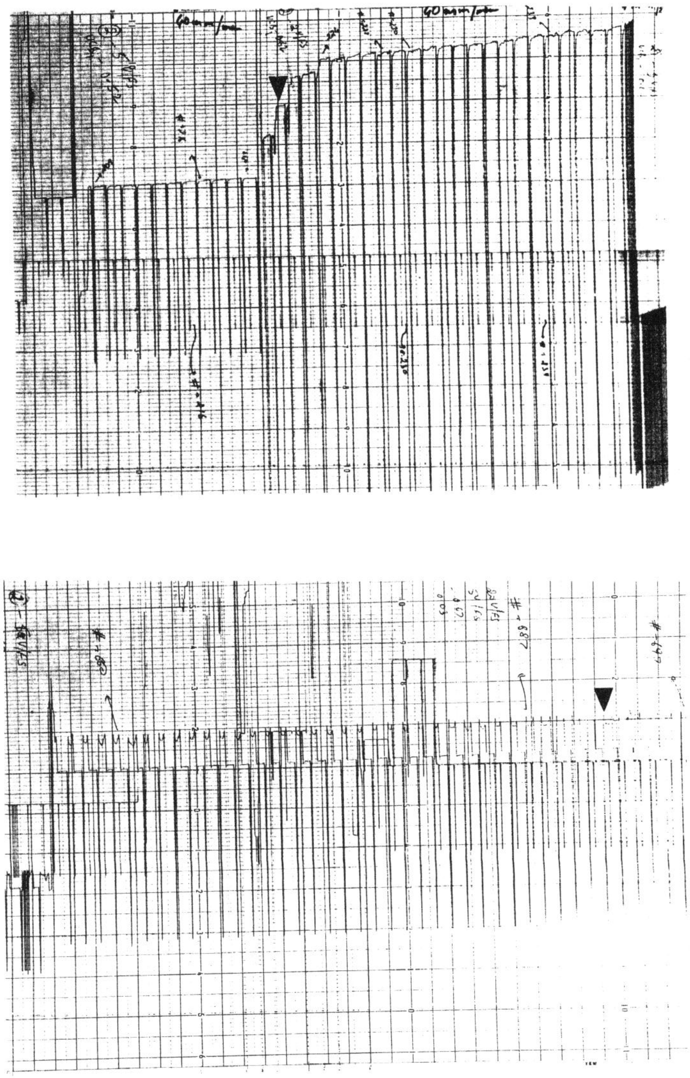


Figure 5 Examples of noise in the data (10 seconds hold time test).

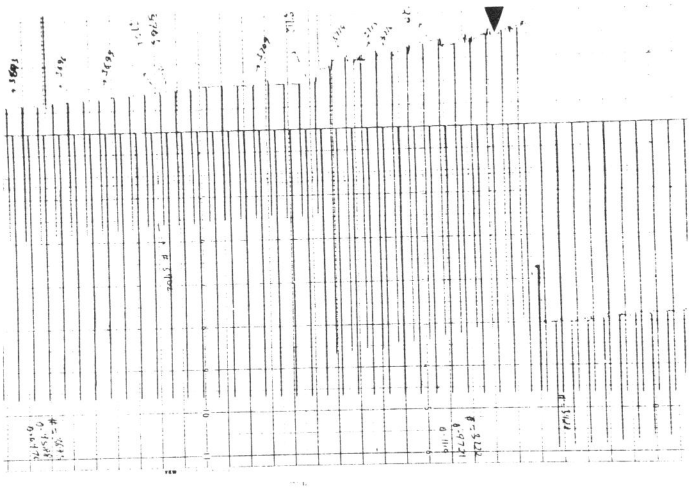


Figure 6 Another example of noise in the data (20 seconds hold time data).