CREEP CRACK GROWTH CHARACTERIZATION OF AUSTENITIC STAINLESS STEEL

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ABSTRACT

Creep crack growth tests were carried out on 304 stainless steel at 550°C in argon environment adopting compact tension specimens under controlled displacement-rate. Crack growth rates were correlated by the C*-integral obtained by single specimen methods directly applicable to test-records. The results are discussed and compared to data obtained for the same materials by other workers that adopted different methods or carried out constant-load tests. A good agreement is observed and it is suggested that C*-integral may characterize creep crack growth behaviour for 304 stainless steel.

KEYWORDS

Creep crack growth; C*-integral; 304 stainless steel; compact specimen; J-integral; elastic-plastic fracture mechanics.

INTRODUCTION

The behaviour of structural materials operating at high temperature is usually characterized by creep tests on smooth specimens. This approach, however, cannot predict and evaluate the structural integrity of cracked structural components operating under creep conditions. Then, the characterization of creep crack growth is requested for materials such as 304 stainless steel that are adopted in the severe conditions above mentioned. Various investigators (Landes and Begley, 1976; Ohji and co-workers, 1976; Turner and Webster, 1974) have proposed a parameter, C*-integral, - and different procedures to evaluate it - to study the crack growth phenomenon when extensive creep deformations are present in a specimen. Their results and further studies by other investigators (Ellison and Harper, 1978; Nikbin and others, 1976; Sadananda and Shahinian, 1978; Taira and co-workers, 1979) show for different materials and specimen configurations that C*-integral correlates fairly well - and in general better than other parameters - crack growth rate data.
Some studies have already been carried out on 304 stainless steels and they show that C*-integral is not significantly influenced by temperature (in the range of 540 to 700°C), heat treatment, and minor

chemistry differences, see Saxena (1978); testing environment, such as air or vacuum, see Taira and co-workers (1979); geometrical configuration, such as compact tension or center crack tension specimens in plane strain, see Saxena (1978), and center notched or double edge notched specimens in plane stress, see Koterazawa and co-workers (1977).
In the present investigation, creep crack growth tests were conducted on 304 stainless steel at 550°C in argon environment with compact tension specimens in plane strain condition. Approximate single specimen methods that have previously been applied to evaluate C*-integral directly from constant load test record have been applied to displacement-rate controlled tests. The results are discussed and compared to data obtained by more elaborate procedures to evaluate C*-integral or by constant load tests that have much longer duration.

C*-INTEGRAL

As suggested by Rice (1972), the J-integral (Rice, 1968), a path-independent energy line-integral, may be modified into the C*-integral a path independent energy-rate line-integral by replacing strain and displacement by their rates. The C*-integral is defined by

$$C^* = \int_\Gamma W^* \, dy - T_i \left(\frac{\partial \dot{u}_i}{\partial x} \right) ds$$

where

$$W^* = \int_0^{\dot{\epsilon}_{mn}} \sigma_{ij} \, d\dot{\epsilon}_{ij}$$

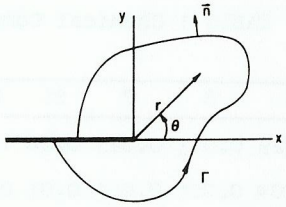

Fig.1 Coordinate system for C*-integral definition

as illustrated in Fig. 1, Γ is the line contour taken from the lower crack surface in a counterclockwise direction to the upper crack surface. W* is the strain energy rate density associated with the point stress σ_{ij} and strain rate $\dot{\epsilon}_{ij}$. T_i is the traction vector defined by the outward normal n_j along Γ, $T_i = \sigma_{ij} n_j$, $\dot{u}_i$ is the displacement-rate vector and s is the arc length along Γ.
When a material obeys a steady-state creep law (Hoff, 1954) the distribution of stress is independent of time and is the same as for nonlinear elastic material. Goldman and Hutchinson (1975) assumed a pure-power time-hardening relation between stress and strain-rate, so that in simple tension

$$\dot{\epsilon} = A_N (\sigma)^N$$

and extended to steady-state-creep crack-problems the solutions of fully plastic crack problems that assume a pure-power strain-hardening relation between stress and strain, so that in simple tension

$$\epsilon = A_n (\sigma)^n .$$

Consequently, Goldman and Hutchinson (1974) proposed C*-integral as a single parameter characterizing the near-tip stress, strain-rate and displacement-rate fields, so that the product of stress and strain rate approach a 1/r singularity as r (distance to the crack tip) approaches to zero, that is,

$$\sigma_{ij} \cdot \epsilon_{ij} \; \alpha \; \frac{C^*}{r} .$$

Furthermore, Landes and Begley (1974) proposed to interpret C*-integral as the power difference between two identically loaded bodies having incrementally differing crack lengths.

METHODS OF EVALUATION OF C*-INTEGRAL

Several methods have been applied to evaluate C*-integral from the record - that is load, displacement at the point of load application and crack length against time - of creep crack propagation test for materials following a steady-state creep law. Two methods (Landes and Begley, 1976; Saxena, 1978) have been proposed in relation to tests performed under displacement-rate control ; the others were applied to constant-load tests. However, Harper and Ellison (1977) have shown that the C*-integral expression derived for constant load yields identically for constant displacement-rate. Furthermore, Musicco and Bernasconi (1980) have discussed that C*-integral is in general independent from the test condition that is dead load and prescribed displacement-rate as limiting cases.
Saxena (1978) has proposed to evaluate C*-integral by the fully-plastic solutions of crack problems given by Hutchinson and co-workers (1978) for pure tension and bending. For example, for a center-cracked strip of width 2 w and crack length 2 a, subjected to a uniform applied stress, σ_∞, in a direction perpendicular to the crack, assuming a pure power hardening relation between strain-rate and stress, C*-integral is

$$C^* = A_N \cdot a \cdot \left(\sigma_\infty / \sigma_o \right)^{N+1} \cdot \hat{J} \, (a/w, N) \qquad (1)$$

where $\hat{J}$ is a dimensionless function reported by Goldman and Hutchinson (1975) and σ_o is a reference stress.
This method requires only one specimen to evaluate C*-integral. On the other hand, it requires both constants of the steady-state creep law and its accuracy depends on the approximation of the dimensionless function J for the geometrical configuration and (a/w) values of the adopted specimen and the material hardening exponent, N
Landes and Begley (1976) proposed to evaluate C*-integral - that is defined in their interpretation as

$$C^* = - \frac{dU^*}{da} \qquad (2)$$

where U^* is the power per unit thickness defined for a load P and displacement rate u - by a graphical technique that generates different families of curves in various steps. This procedure requires a few specimens and it is quite laborious to be implemented. However, since it introduces only experimental approximation it may be proposed as reference method.
Ohji and co-workers (1976) observed that C*-integral may be expressed as

$$C^* = \int_0^P \left(\frac{\partial \dot{\Delta}}{\partial a} \right)_{P=\text{const}} dP$$

where P is the force per unit of thickness, B, and $\dot{\Delta}$ is the displacement-rate of the point of load application. Then, they derived a simple expression:

$$C^* = \mu \frac{P}{B\,(w-a)} \cdot \dot{\Delta} \qquad (3)$$

where μ is a function of the geometrical configuration and hardening exponent, N.
Harper and Ellison (1977) derived an expression of C*-integral

$$C^* = \xi \cdot \frac{P}{B \,.\, W} \cdot \dot{\Delta} \qquad (4)$$

where ξ is a function of the hardening exponent, N, and of m and its derivative with respect to (a/w), where m is the ratio of the tensile limit load of a cracked specimen to the limit load of an uncracked specimen. For a bend specimen configuration, P and $\dot{\Delta}$ are replaced by M, applied moment, and $\dot{\theta}$ rotation rate, respectively. Both equations (3) and (4) are weakly dependent on the hardening exponent and are directly applicable to the test record of a single specimen. On the other hand, they are strongly dependent on and their range of applicability has not been studied.
Haigh (1975) reported good correlation of crack growth rate data by the crack opening displacement rate, $\dot{\delta}_t$. This experimental evidence supported the proposal by Musicco and Bernasconi (1980) to relate C*-integral to $\dot{\delta}_t$:

$$C^* = \alpha \cdot \sigma_o \cdot \dot{\delta}_t \qquad (5)$$

where σ_o is a reference stress and α given by Shih (1979) is a strong function of N and $\dot{\delta}_t$ may be either measured experimentally or evaluated by functional expression as eq. (1).

EXPERIMENTAL PROCEDURE

Material and Specimen Preparation

Testing was performed on AISI 304 L austenitic stainless steel supplied in as rolled 20 mm thick, 80 mm wide plate. The chemical composition (in weight percentage) based on six samples is given in Table 1. The metallographic analysis results in a quite coarse grain size (ASTM No 4) but little rolling texture, quite equi-axed grains after the annealing heat-treatment (30 min. at 1050°C water quenched, followed by 90 min. at 350°C, air cooled). The non-metallic inclusion content is normal and the distribution is homogeneous. The tensile properties at room temperatures and 500°C are shown in Table 2; six samples were used for each mean.

TABLE 1 Chemical Composition in Weight Percentage

Elem.	C	S	P	Si	Mn	Cr	Ni	Mo	Cu	Ti	N_2	Fe
Mean	0.029	0.013	0.023	0.64	1.12	18.84	10.05	0.17	0.13	< 0.001	522 ppm	rest
Var.	0.004	0.001	0.001	0.01	0.02	0.09	0.14	0.004	0.01	-	17 ppm	

TABLE 2 Tensile Properties (six samples for each mean)

Temp. [°C]	Specimen Orientation	Eng. Yield Stress $S_{0.2}$ [MPa]		Eng. Ult. Stress S_u [MPa]		Eng. Plastic Unif. Strain e_{pu} [%]		Eng. Plastic Strain at breaking point e_{pb} [%]	
		mean	var.	mean	var.	mean	var.	mean	var.
20°	longitudinal	252	8	606	8	68	2	80	2
20°	transversal	239	5	599	10	68	1	84	1
500°	longitudinal	125	6	378	4	34	1	41	1
500°	transversal	114	10	377	3	33	1	43	2

Figure 2 shows the schematic and the size of the compact tension (CT) specimens used in the present study. All the specimens were precracked by fatigue loading - imposing 15 MPa $\sqrt{m}$ as terminal value of ΔK

to ensure a sharp crack with minimum plastic deformation - at room temperature prior to testing. The initial nominal crack-length to width ratio, (a/w), obtained were in general 0.50 and for few specimens 0.70 or 0.80. The curvature of the crack front had a variation in length of about 1.3 mm from the mean value.

Creep Crack Growth Tests.

Specimen heating was by resistance furnace. Figure 3 shows a specimen in loading condition inside the furnace. Specimens were heated to 550°C in about two hours and left overnight to allow equilibrium thermal gradient to form. Temperature distributions were monitored by thermocouples placed near the crack plane. The thermal gradient was within ± 1°C along the crack-growth direction and negligible in the thickness direction; the stability with time was within 1°C.

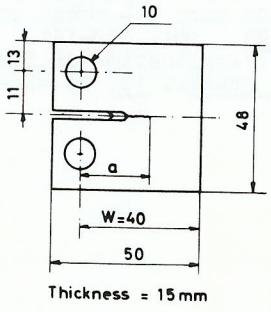

Fig. 2. CT specimen

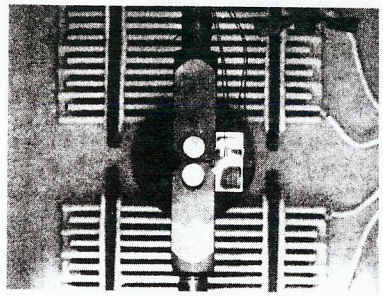

Fig. 3. Test equipment

Testing was performed on a servohydraulic test system INSTRON 1272. The load was continuously monitored by a load-cell transducer. The displacement was continuously monitored by a linear variable differential transducer placed in the load line and verified by a mechanical comparator. The crack-length was measured at 0.5 mm intervals by a Zeiss telemicroscope of about 100 μm accuracy through a glass window on one side of the furnace. Bench-marking procedure was periodically conducted during testing to determine proper post-test tunnelling corrections to the optical crack length measurements on one side of the specimen. Curvature of the crack front caused a maximum variation in crack length of about 2 mm from the mean value obtained by the nine points method and planimetric measurements on macro-fractographies. Uncertainty was found in the measurements of the initiation of creep crack growth and the data related to this first stage were not considered herein.
Creep crack-growth tests were performed in displacement-rate control The displacement-rate was varied at about constant crack-extension intervals of about 1 mm within 10 and $50 \cdot 10^{-6}$ m/hr. Three different displacement-rates were imposed during each test. Tests were run up

to a 300 hr duration. Only the deeply pre-cracked specimens were tested under constant displacement-rates varying in the range from 120 to $240 \cdot 10^{-6}$ m/hr and they lasted about 80 hr.

RESULTS AND DISCUSSION

C* integral was evaluated by using eqs. (1), (3), (4) and (5) that have been adapted to the specific specimen-geometry under consideration assuming the hardening exponent $N = 7$ and $A_N = 2 \cdot 10^{-18}$ for the steady-state creep law where stress is expressed in MPa and strain-rate in strain/hr. The crack opening displacement rate was estimated by simple calculations of the position of the plastic hinge point as suggested by Haigh (1975). C*-integral and crack growth rate $\dot{a}$ were correlated with the expression:

$$C^* = A_\eta \, (\dot{a})^\eta . \qquad (6)$$

The data obtained by eqs. (3), (4) and (5) are plotted using different symbols in a log-log diagram in Fig. 4. These data were reduced for crack length to width ratios ranging from (a/w) = 0.60 to 0.80 at 5 mm intervals. They show a good correlation and the hardening coefficients, η, obtained by these three methods are quite close. Furthermore, the scatter in C*-integral for these three different types of data is about a factor of two. Equation (1) was applied for the cases of (a/w) = 0.70, 0.75 and 0.80 and the hardening coefficient was η = 1.3 with good correlation. The data related to (a/w) greater than 0.80 and to the deeply pre-cracked specimens give $\eta = 2$ and the correlation is quite reduced. This fact could be explained in terms of minimum size requirement for remaining ligament as discussed by Saxena (1978).
The two lines in Fig. 4 indicate the data obtained from Saxena (1978) that used the methods based on eqs. (1) and (2) for an AISI type 304 stainless steel on 25 mm thick, compact tension specimen in displacement-rate controlled tests. If the method by Landes and Begley (1976) referred as equ. (1) - is considered as reference method the present study data show a good agreement in terms of hardening coefficient, η, with Saxena's data (see Fig. 4). Further values of η for 304 stainless steels may be obtained from

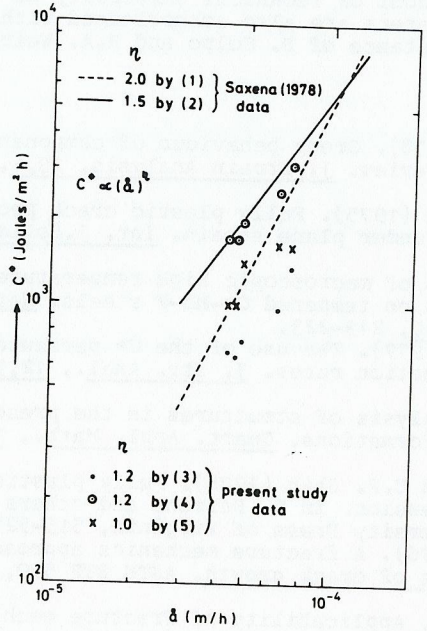

Fig. 4. Summary of C*-integral vs. a data for 304 stainless steels.

data by Koterazawa and co-workers (1977) and Taira and co-workers (1979). Their results show hardening coefficients η varying from (approximately) 0.85 to 1.0 for center notched and double edge notched, 1.5 mm thick specimens and for center notched, 2.3 mm thick specimens respectively, over an extended (from 10^{-6} to 10^{-2}m/hr) range of crack growth rate.

CONCLUSION

C*-integral evaluation methods that are simple and directly applicable to test-records have been applied for displacement-rate control tests and they have shown to yield good agreement - for the limited range of crack growth rate explored - with literature data for AISI 304 stainless steel. The comparative analysis of the results from this study and previous investigations suggests that creep crack growth behaviour for 304 stainless steels may be characterized by equ. (6) where the hardening coefficient η is weakly influenced by whether the specimen is in plane stress or plane strain condition.

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REFERENCES

Ellison, E.G., and M.P. Harper (1978). Creep behaviour of components containing cracks - A critical review. J. Strain Analysis, 13,1, 35-51.

Goldman, N.L., and J.W. Hutchinson (1975). Fully plastic crack problems: the center-cracked strip under plane strain. Int. J.Solids Structures, 11, 575-591.

Haigh, J.R. (1975). The mechanisms of macroscopic high temperature crack growth part I: experiments on tempered Cr-Mo-V steels. Materials Science and Engineering, 20, 213-223.

Harper, M.P., and Ellison, E.G. (1977). The use of the C* parameter in predicting creep crack propagation rates. J. Str. Anal., 12,3, 167-179.

Hoff, N.J. (1954). Approximate analysis of structures in the presence of moderately large creep deformations. Quart. Appl. Math., 12, 49-55.

Hutchinson, J.W., A. Needleman and C.F. Shih (1978). Fully plastic crack problems in bending and tension. In N. Perrone and others (Eds.), Fracture Mechanics, University Press of Virginia, 515-527.

Landes, J.D. and Begley, J.A. (1976). A fracture mechanics approach to creep crack growth. Mechanics of crack growth, ASTM STP 590, 128-148.

Koterazawa, R. and Mori T. (1977). Applicability of fracture mechanics parameters to crack propagation under creep condition. Trans. ASME. J. Eng. Mat. Techn., 99, 4, 298-305.

Musicco, G.G. and Bernasconi G. (1980). Application of elastic-plastic fracture mechanics to creep crack growth, (in Italian). Proceedings of the VIII AIAS National Symposium, to be published

Nikbin, K.M., Webster, G.A. and Turner, C.E. (1976). Relevance of nonlinear fracture mechanics to creep cracking. Cracks and Fracture, ASTM STP 601, 47-62.

Ohji, K., Ogura, K. and Kubo S. (1976). Fracture mechanics approach to mainly mode III creep crack growth (in Japanese). Trans. Japan Society of Mech. Eng., 42, 354, 350-358.

Rice, J.R. (1968). Mathematical analysis in the mechanics of fracture. In H. Liebowitz (Ed.), Fracture, Vol. 2, Academic Press, 191-311.

Rice, J.R. (1972). As quoted by Landes and Begley (1976).

Sadananda, K. and Shahinian P. (1978). Application of fracture mechanics techniques to high temperature crack growth. In N. Perrone and others (Eds.), Fracture Mechanics, University Press of Virginia. 685-703.

Saxena, H. (1978). Evaluation of C* for the characterization of creep crack growth behaviour in 304 stainless steel. Westinghouse R & C., 78-ID3-MOMAR-PI.

Shih, C.F. (1979). Relationship between the J-integral and the crack opening displacement for stationary and extending cracks. In Hutchinson, J.W. (Ed.), Nonlinear Fracture Mechanics, Technical University of Denmark.

Taira, S., Ohtani R. and Kitamura T. (1979). Application of J-integral to high-temperature crack propagation part I - creep crack propagation. Trans. ASME, J. Eng. Mat. Techn., 101, 154-161.

Turner, C.E. and Webster, G.A. (1974). Application of fracture mechanics to creep crack growth. Int. J. Fract., 10, 3, 455-459.