CREEP CRACK GROWTH AND CRACK PROPAGATION OF IN 800 H AT 830 °C

W. Oberparleiter* and P. Agatonovic**

Components of energy units e.g. the Gas Cooled Solar Tower in service are subjected to cyclic loading combined with dwell times and high temperatures. Also larger components welded together almost certainly contain defects from fabrication. Therefore fatigue life prediction methods have to account for crack propagation also but at the moment there is still a lack of data at high temperatures. Creep crack growth da/dt and fatigue crack growth da/dN using the "sloping line" method from (1) were determined for IN 800 H at 830° C. Both types of crack propagation may be described by the Paris type formula $da/dN = C \cdot (A)^n$ using C* for da/dt and J for fatigue crack growth da/dN as the gouverning parameter A.

INTRODUCTION

Up to date methods to design cyclic loaded components in the high temperature range are based on the fatigue life to crack initiation determined from smooth specimens. This, requires a component without defects. In larger components, however, which are welded together almost certainly defects occur, from fabrication. From these defects cracks may initiate under cyclic loading and cause the failure of the whole equipment. A typical example for this is the heat exchange unit of the Gascooled Solar Tower (GAST). The service conditions of this equipment (day- and cloud - cycles) lead to a significantly higher number of load cycles than in other energy units. Therefore an improved fatigue life prediction method is necessary for these components which also takes into account the crack propagation behaviour under creep and cyclic loading conditions. Such types of problems and their solutions are known from linear elastic fracture mechanics at ambient temperatures.

* Industrieanlagen Betriebsgesellschaft mbH, Ottobrunn, FRG
** MAN - Technologie GmbH, Munich, FRG

But in the high temperature range there is also a lack of sufficient experience and material data, because failure at high temperatures is accompanied by extensive inelastic deformation. At temperatures of 800 to 900 °C which are predominant in tubes of the heat exchanger of the GAST after a short time, these inelastic deformations reach conditions for which linear elastic fracture mechanics is not applicable.

FUNDAMENTAL PRINCIPLES

Fatigue crack growth

In the linear elastic case the stress distibution at the crack tip is described by the stress intensity factor K. The fatigue crack growth rate da/dN is described by

$$da/dN = C \cdot (\Delta K)^n \tag{1}$$

Load controlled tests in a prior phase of the IN 800 H programme has shown that crack growth rate versus ΔK at 830 °C depends on the maximum load Fo, figure 1, that means because of the large plastic deformations at this temperature the K-concept is no longer applicable. ΔK has to be replaced by the elastic plastic parameter ΔJ. Also load controlled tests to determine crack propagation at 830 °C were not suitable. Inelastic deformations in the ligament of the CT-specimen cause an instable increase of the displacement v and creep of the material. This instable deformation behaviour in load controlled tests leads to a large increase of da/dN and a quick failure of the specimen.

Opposite to the load control, displacement controlled tests lead to a decrease of the load F with increasing crack length. This causes a decrease of da/dN and in the extreme case to a crack stop. A way out of this dilemma is a displacement controlled test using the "sloping line" control proposed by Dowling and Begley (1). In this case the upper load is controlled by a monotonic decreasing line

$$F_R = F_{max} - m \cdot v \tag{2}$$

while the minimum deformation is kept at zero. So the decrease of the ligament W-a due to crack growth Δa is balanced out by the decreasing load F. The "sloping line" control was done using a microprocessor. The desired load line is fixed by the load F_0 and the displacement v_0 at the beginning of the test and the slope m defining load change over the displacement. In the following cycles the displacement v is increased in digital steps; the resulting load F_G is measured and compared with the load F_R from (2). If $F_R - F_G = 0$ the displacement is decreased to zero again, see figure 2.

To determine ΔJ the hysteresis loops F versus load line displacement v were recorded.

In figure 3 the change of the hysteresis loop due to crack length is shown. ΔJ was determined from the area U under the F- v - curve using the simple form for CT-specimens

$$J = \frac{2 \cdot U}{B\ (W-a)}$$

According to Begley and Landes (5) the total area under the F- v - curve was used minus a small part for crack closure, figure 3.

Creep crack growth

Similar to fatigue crack growth da/dN creep crack growth da/dt may be described by

$$da/dt = B \cdot A^{n}$$

where A can be replaced by the linear elastic stress intensity factor K, the net section stress or C*. As pointed out before crack growth at 830 °C is not a linear elastic phenomenon, therefore (3) and (4) propose C* in the high temperature range to describe the stress distribution at the crack tip. C* initially was proposed by Rice as the independent line integral of the energy release rate. C* therefore is a simple modification of the J-Integral where the displacement v is replaced by the displacement rate $\dot{v} = f(t)$

$$C^{*} = \frac{1}{B} \int_{0}^{F} \left[\frac{\delta \dot{v}}{\delta a}\right]_{F} \cdot \delta F \quad = \quad \frac{1}{B} \frac{\delta U^{*}}{\delta a} \tag{3}$$

or simple for CT-specimens

$$C^{*} = \frac{2 \cdot U}{B\ (W-a)} \cdot \frac{\delta v}{\delta t} \tag{4}$$

To determine da/dt versus C* Landes and Begley (5) proposed tests under different (constant) displacement rates $\dot{v}$. The basis for the data reduction is a plot crack length versus time t and a plot load F versus displacement v , figure 4.

TEST PROGRAMME

At temperatures > 800 °C two types of crack propagation occur:

- creep crack growth da/dt under static loading depending on the loading time or displacement rate $\dot{v}$

- fatigue crack growth da/dN under cyclic loading depending on the maximum load and the number of cycles

Crack propagation under cyclic loading including dwell times is thought to be a combination of both crack growth types.

For crack growth predictions material data as

- creep crack growth da/dt vs C*
- fatigue crack growth da/dN vs ΔJ

are necessary at 830 °C.

Creep crack growth da/dt was determined using different displacement rates $\dot{v}$ in the range 0.04 mm/h $> v <$ 1.5 mm/h. As described before the fatigue crack growth was determined using the "sloping line" controll according to Begley and Landes (5). Additional test parameters were

- the slope m in the "sloping line" control
- the test frequency
- additional dwell times of 1 and 2 minutes.

MATERIAL; SPECIMEN GEOMETRY; TEST EQUIPMENT

CT-specimens according to ASTM E 399 with a thickness $s = 14$ mm and a width of $W = 50$ m were used for the tests. The specimens were machined from a 16 mm thick plate. Mechanical properties are given in table 1.

The tests were carried out in a 60 KN servohydraulic testing machine fitted with a radiant heater to produce the temperature of 830 ° C. The deviation of temperature during the test was less than 5 ° C.

All the tests were displacement controlled. For this purpose the load line displacement was measured using a MTS-extensometer. The extensometer was fitted outside the heater additionally cooled with water and only the quartz beams were inside the heater.

The hysteresis loops load F versus displacement v, figure 5, and F versus displacement rate v, figure 4, were drawn by a x-y-plotter, or a x-t-plotter respectively.

RESULTS AND DISCUSSION

The creep crack growth rate da/dt plotted against C* fit to a straight line in a log-log plot. Therefore da/dt can be described by

$$da/dt = 0.043 \cdot (C^*)^{0.98}$$

The scatter is quite small, see figure 6. The slope n = 0.98 agrees reasonably with results from (6) where n = 0.88 was found for IN 800 at 800 °C. Some more tests , especially at

lower displacement rates , are necessary to improve this relation and reduce the scatter.

Crack propagation rate da/dN under cyclic loading is shown in figure 7. Using ΔJ instead of the linear elastic stress intensity ΔK da/dN is independent from crack length and maximum load. Also the results for different slopes m in the "sloping line" control fit to a straight line in a log-log plot with very small scatter. Similar to da/dt also da/dN can be described by the same type of power law

$$da/dN = 2.4 \cdot 10^{-5} \cdot (\Delta J)^{1,61}$$

The exponent n of this relation agrees quite well with values of n = 1.4 to 2.3 from literature (7).
This good agreement postulates too that the graphical determination of ΔJ used was successful.

A reduction in the test frequency from f = 0.52 Hz to f = 0.1 Hz causes a slight increase of da/dN for a constant ΔJ, figure 8. This is probably caused by additional creep crack growth at lower test frequencies at 830 °C. The same trend is confirmened by the tests including dwell times of 1 or 2 minutes at maximum displacement,figure 9. Including 1 minute dwell time da/dN is about 7 - times higher than without dwell time at constant ΔJ. Figure 9 also shows that there is no measurable difference between 1 and 2 minutes dwell time. This result is based on only 3 tests and should be improved with additional tests . The large creep deformations in tests at 830 °C with dwell times cause a quick relaxation at the crack tip independent of the long way to crack closure, figure 10, which the great scale displacements at the loading line show.

CONCLUSIONS

- Due to the intensive inelastic deformations in the high temperature range the use of linear elastic fracture mechanics to assess crack growth is not possible any longer
- The results have shown that there is a good correlation between creep crack growth da/dt and C* as well as fatigue crack growth da/dN and ΔJ for IN 800H at 830 °C.
- The relation da/dN = f (ΔJ) depends on the test frequency and dwell time. The trend to higher da/dN at dwell times may be described by a superposition of

$$da/dt = f\ (C^*) \text{ and } da/dN = f\ (\Delta J).$$

- These results are only a small part of the problems which have to be solved to find a method for crack growth prediction in the high temperature range under cyclicloading including dwell times.

REFERENCES

(1) Dowling, N.E. and I.A. Begley, "Mechanics of Crack Growth," STP 590, 1976, pp. 82 - 103

(2) Oberparleiter, W., R. Heidenreich, IABG-report TF-1333,1982

(3) Krompholz, K. et al, Engineering Fracture Mechanics, Vol. 16, No 6, 1982, pp. 809 - 819

(4) Koterazawa, R. and T. Mori, Trans. ASME, I. Eng. Mater. Techn. 99, 1977.

(5) Begley, I. A. and I. D. Landes "Mechanics of Crack Growth", STP 590, 1976, pp. 128 - 149.

(6) Hollstein, T., Z. f. Werkstofftechnik 16, 1985, pp. 223 - 228.

(7) Tanaka, K. et al, Eng. Fract. Mechanics, Vol. 19, Nr. 5, 1984, pp. 805 - 825.

(8) Agatonovic, P. and Oberparleiter W. "Vorträge der 17. Sitzung des Arbeitskreises Bruchvorgänge," 1985, pp. 115 - 126.

TABLE 1 - Mechanical Properties of IN 800 H.

Temperature °C	Rm MPa	$R_{p\ 0,2}$ MPa	Young´s modulus MPa
760	236	90	145 000
870			138 000
980			129 000

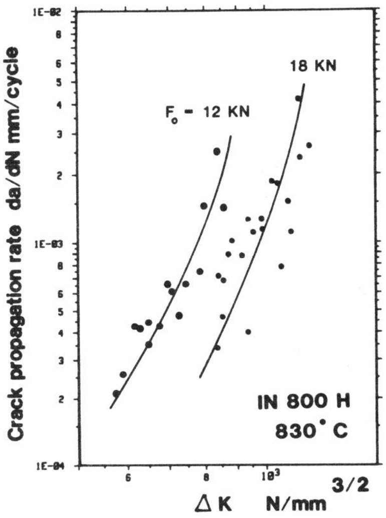

Figure 1 Fatigue crack growth
da/dN vs Δ K

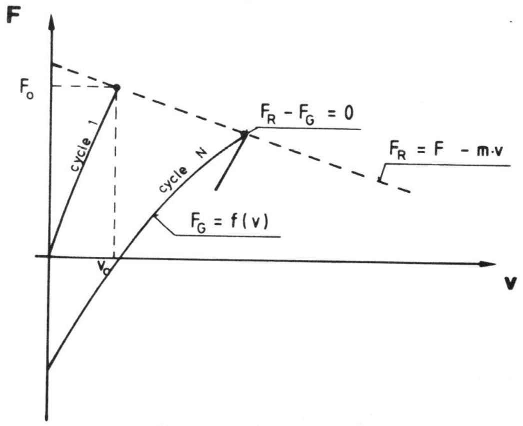

Figure 2 Principles of sloping line control (schematic)

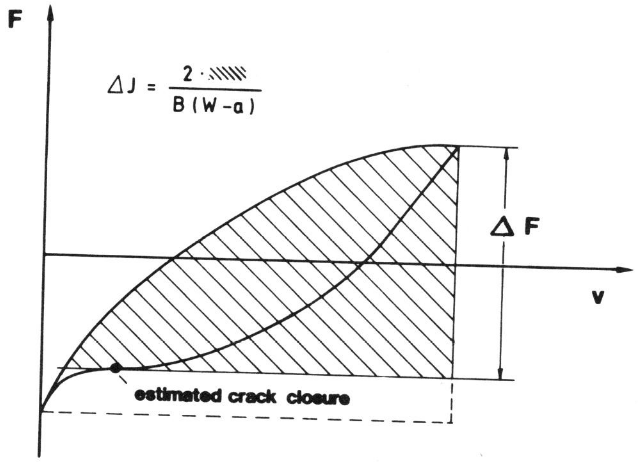

Figure 3 Definition of J under cyclic loading

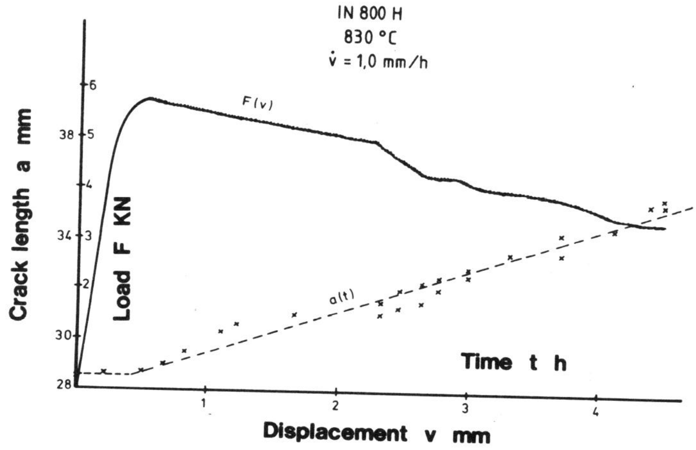

Figure 4 F - v (a - t)-plot for a constant displacement rate $\dot{v}$

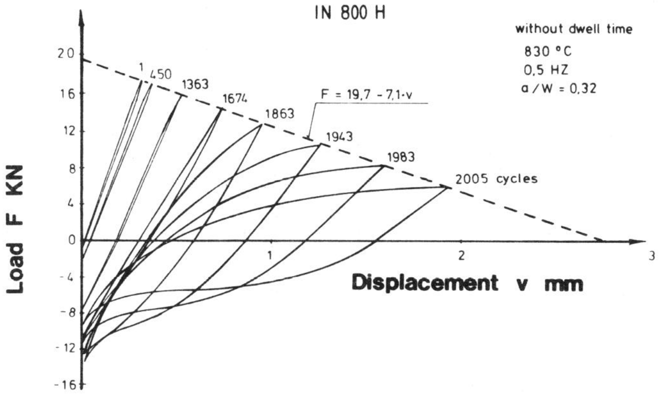

Figure 5 "Sloping line" controlled test without dwell time

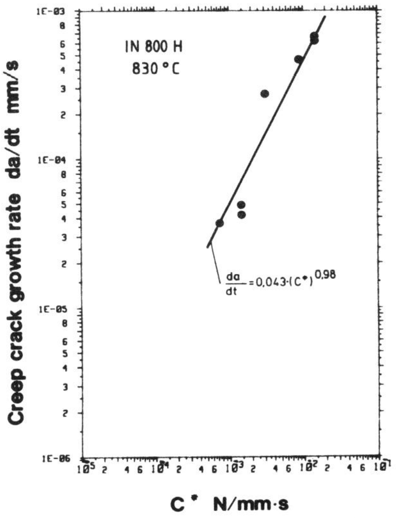

Figure 6 Creep crack growth da/dt versus C*

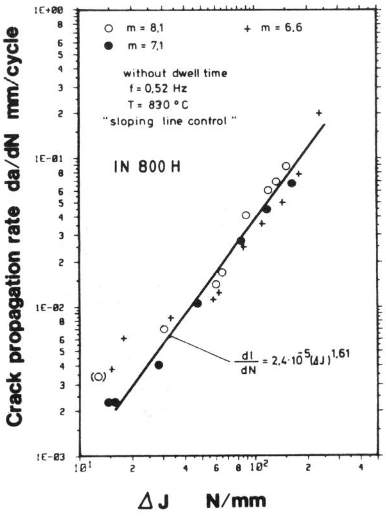

Figure 7 Fatigue crack growth da/dN versus J

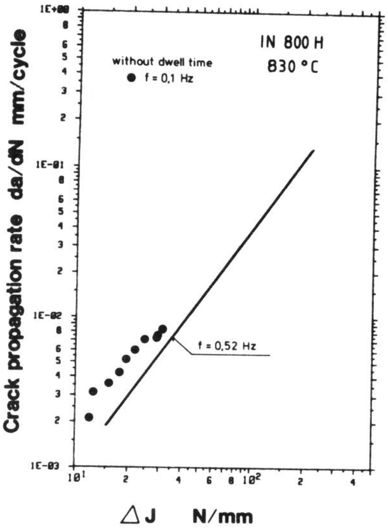

Figure 8 Influence of test frequency on da/dN

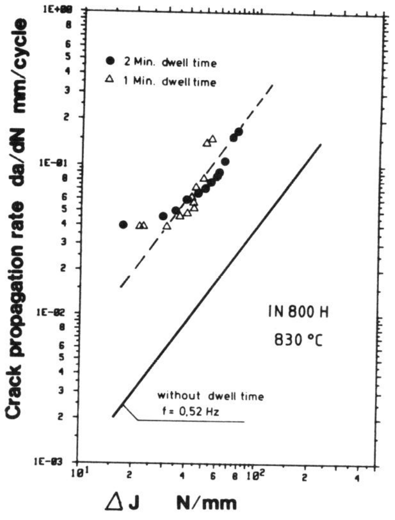

Figure 9 Influence of dwell time on da/dN

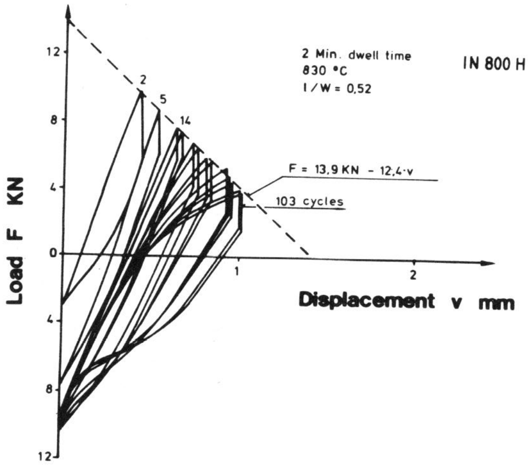

Figure 10 "Sloping line" controlled test with 2 min. dwell time