JOURNAL OF MATERIALS SCIENCE 28 (1993) 1430 – 1434

Crack growth kinetics of 7050-T73651 aluminium alloy under constant load at 150 °C

F. SARIOĞLU, P. ABACHI, M. DORUK
Department of Metallurgical Engineering, Middle East Technical University, Ankara, Turkey

Crack growth tests at 150 °C under constant load conditions were performed on compact tension specimens of 7050-T73651 aluminium alloy. The d.c. potential drop method was employed to monitor crack lengths throughout the tests. Fracture mechanics parameters such as the stress intensity factor (K) and energy-rate line integral (C^*) were used to establish correlation with the crack propagation rates. As a result of experiments it was found that crack growth rates ($\mathrm{d}a/\mathrm{d}t$) versus K, over discrete ranges of rates, can be described as a power-law equation in the form $\mathrm{d}a/\mathrm{d}t = AK^n$. The parameter C^* appears to correlate well with the crack propagation rates through a single power law over a wide range of rates.

1. Introduction

Creep crack growth appears to be a major problem in components used in power generation and in various branches of process industries. Even some airframe components, especially leading edges, would be heated temporarily up to 150 °C during the flight of an aircraft. The aluminium alloys used in airframes lose strength rapidly at temperatures above 150 °C. The speed of civil supersonic transport is therefore limited to Mach 2.2, corresponding to a saturation skin temperature of about 125 °C. The airframe structures are required to give a service life of 20000–30000 h [1]. Accordingly, creep behaviour of aluminium alloys is expected to be one of the dominant factors even at temperatures as low as 125 °C.

The damage-tolerance based design of components and their lifing can only be employed when sufficient data are available concerning the crack growth kinetics of materials. Several parameters describing crack growth under creep conditions have been investigated over recent years. The general approach in these studies is that with these parameters, the crack tip stress and strain fields can be described under certain limiting conditions, and the crack growth rate can be correlated with them. Correlations in terms of stress intensity factor K [2], the net section stress or a reference stress in the uncracked ligament [3, 4] and non-linear fracture mechanics concepts like the C^* integral [5] have been found to be satisfactory under certain conditions.

The aim of this study was to assess the success of the stress intensity factor and C^* integral in describing the crack growth kinetics at 150 °C of the 7050-T73651 aluminium alloy used in airframe structures.

2. Experimental procedure

2.1. Test material and specimens

The test material was a cold-rolled plate of 7050-T73651 aluminium alloy. The chemical composition of the alloy is given in Table I. The T73651 temper applied to the plate by the manufacturer was solutionizing at 477 °C followed by double ageing at 121 °C for 24 h and at 163 °C for 24 h.

13 mm thick compact tension (CT) specimens were manufactured according to ASTM E 399 standard (Fig.1). They were cut in L–S orientation so that load was applied in the rolling direction while cracks propagated in the short transverse direction. The mechanical properties of the as-received material in different directions are given in Table II [6].

2.2. Testing procedure

All specimens were precracked at room temperature under sinusoidal tension load cycles with a frequency of 2 Hz using a closed-loop servo-controlled hydraulic machine. The fatigue loads were selected such that the stress ratios, R, were between 0.1 and 0.4 and the maximum load was less than one-fourth of the specimen limit load, as suggested in the related standards. Fatigue precracking was continued until the crack length to specimen width ratio, a/W, was about 0.5.

Creep crack growth tests were performed at 150 °C and under two different loads, 5.41 and 6.10 kN. The specimens were heated in a three-zone resistance furnace to provide uniform temperature distribution in the test section of the specimen. Temperature accuracy was ± 2 °C. Load-line displacements were recorded using a high-temperature extensometer equipped with a linear variable differential transformer (LVDT). The output voltage of the LVDT was recorded as a function of time on a strip chart recorded with a sensitivity of 0.04 mV mm^{-1}. The d.c. potential drop (DC PD) method was used to monitor crack lengths during creep testing with a constant-current supply of 10 A. The output voltage was measured with the help of a nanovoltmeter. The initial and final crack lengths

0022-2461

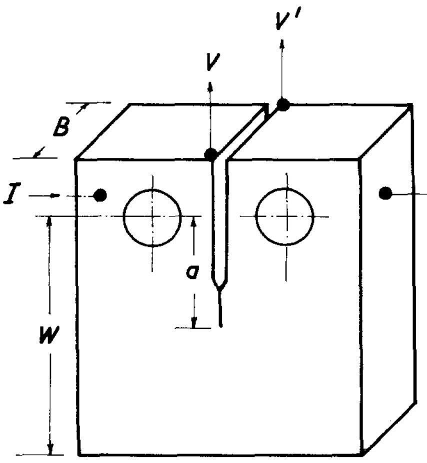

Figure 1 CT specimen with current (I) input-output leads, and potential pick-up (V) lead positions.

TABLE I Chemical composition of 7050-T73651 aluminium alloy (wt %)

Zn	Mg	Cu	Zr	Ti	Cr	Mn	Si	Fe	Al
6.20	2.25	2.30	0.12	0.06	0.04	0.10	0.12	0.15	Rest

TABLE II Mechanical properties of 7050-T73651 aluminium rolled plate in two directions

Direction	UTS ($N mm^{-2}$)	σ_Y ($N mm^{-2}$)	E ($N mm^{-2}$)	Elongation (%)
L	510	447	72200	10
ST	502	423	72800	7

were also measured optically and compared with that predicted by DC PD technique.

2.3. Determination of crack growth rates

The crack lengths were calculated using the calibration formula [7]

$$a/W = A + A_1\beta + A_2\beta^2 + A_3\beta^3 \qquad (1)$$

where $\beta = (V/V_0)/(V_{ref}/V_{ref0})$. Here, V and V_0 are voltage differences measured in the test specimen during the test period and at the beginning of the test, respectively, whereas V_{ref} and V_{ref0} are those measured in the reference specimen. The calibration constants were evaluated in the test piece as $A = -0.4507741, A_1 = 0.757523, A_2 = -3.412055 \times 10^{-2}$ and $A_3 = -2.571994 \times 10^{-2}$.

Crack growth rates were calculated by taking the first derivative of the third-order polynomial fitted to the available crack length–time data.

2.4. Determination of fracture mechanics parameters

The stress intensity factor K has been calculated from the expression recommended in ASTM E 399-83 standard. The path-independent energy-rate line integral, C^*, was evaluated using the formula given for CT specimens [8] :

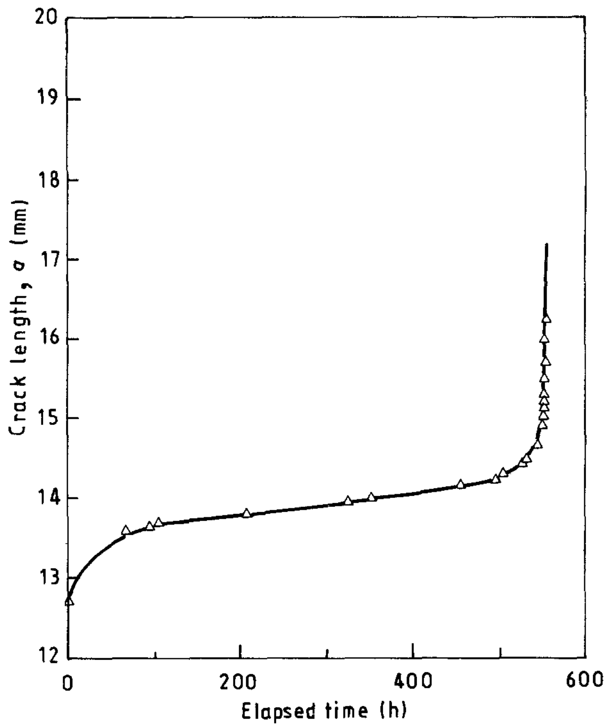

Figure 2 Crack length plotted against time ($P = 5.41$ kN, $T = 150\,°C$).

$$C^* = \frac{2(n-1)P\dot{\delta}}{(n+1)B(W-a)}$$

or

$$C^* = \frac{2P\dot{\delta}}{B(W-a)} \quad \text{for } n > 5 \qquad (2)$$

where P is the load, $\dot{\delta}$ is the load-line displacement rate, B is the specimen thickness, W is the specimen width, a is the crack length and n is the stress exponent in power-law creep.

3. Results and discussion

Both crack length versus time and crack propagation rate versus time curves represent the well-known characteristics of a creep curve (Figs 2 and 3). The same type of typical curve was also observed in load-line displacement versus time records. Log(da/dt)–log$K$ plots consist of three discrete regions (Figs 4 and 5). The data in these regions were fitted to the relation $\log(da/dt) = a + b \log K$ by the least-squares method. The b values obtained are shown on the plots. In contrast to the three discrete regions in (da/dt)–K relations, single linear correlation was obtained for logarithmic plots of (da/dt)–C^* (Figs 6 and 7).

These results show that for stress intensities lower than 44% of K_{IC}, no significant time-dependent crack growth has taken place at 150 °C in 7050-T73651 during 150 h. From the data given in Figs 2 and 3, it is evident that for higher loads, the general trend is the increase in crack growth rates with time during the tests. However, there was an apparent decrease in growth rates in the preliminary stages of the tests. This

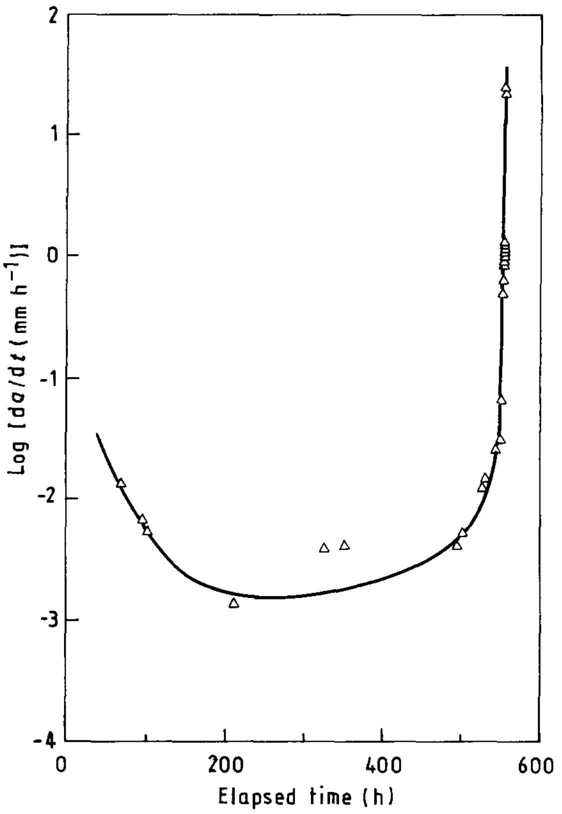

Figure 3 Crack growth rate as a function of time ($P = 5.41$ kN, $T = 150\,°C$).

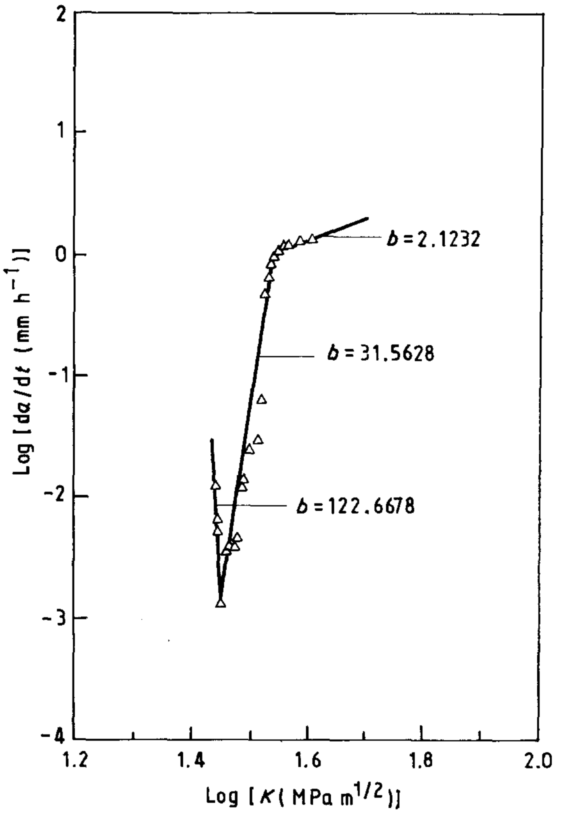

Figure 4 Crack propagation rate as a function of the stress intensity factor ($P = 5.41$ kN, initial $K = 24.76$ MPa m$^{1/2}$, $T = 150\,°C$).

initial decrease is attributed to the decay of deformation rate as observed in primary creep in smooth specimens. As the test progresses, the creep cracking phenomenon prevails.

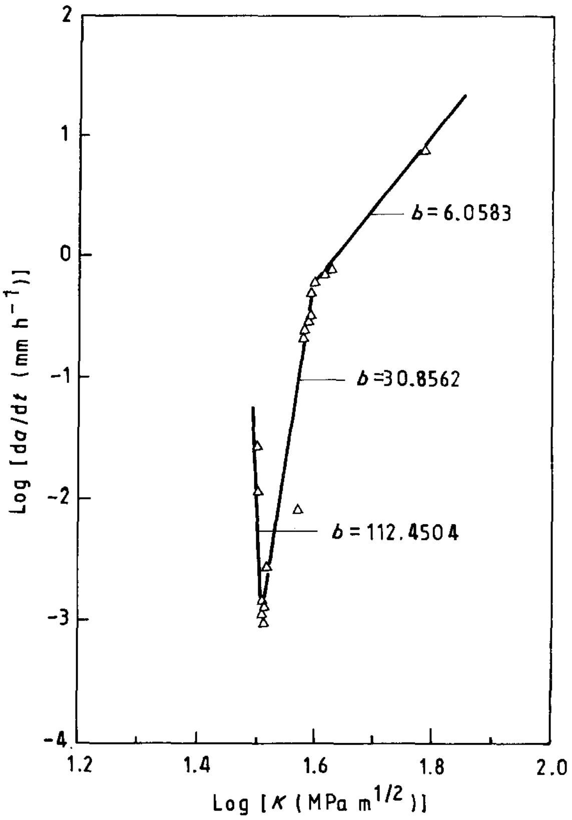

Figure 5 Crack growth rate as a function of the stress intensity factor ($P = 6.10$ kN, initial $K = 30.53$ MPa m$^{1/2}$, $T = 150\,°C$).

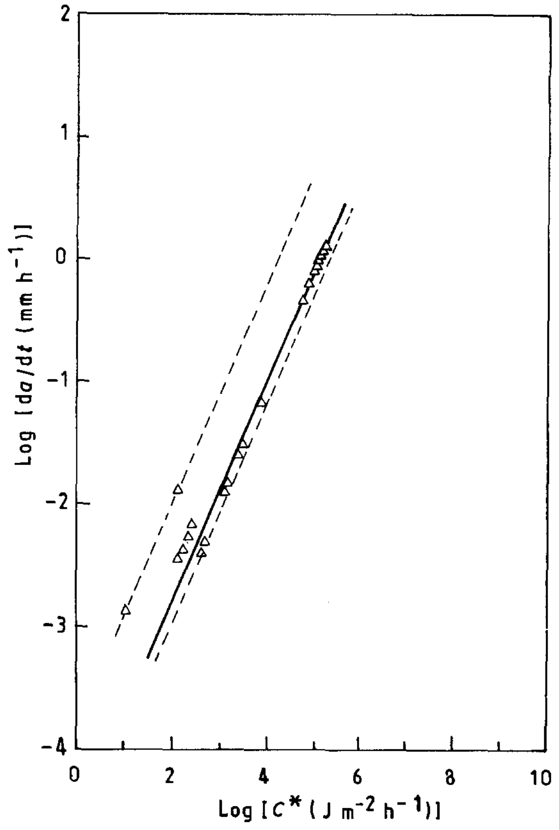

Figure 6 (△) Crack growth rate as a function of the energy-rate line integral, C^* ($P = 5.41$ kN, $T = 150\,°C$). (——) $\log(\mathrm{d}a/\mathrm{d}t) = -4.8539 + 0.955 \log C^*$ or $\mathrm{d}a/\mathrm{d}t = (1.3999 \times 10^{-5})(C^*)^{0.995}$.

Comparison of Figs 4 to 7 indicates that the correlation of da/dt with C^* is much better than with K. When correlated with C^*, the ratio of rates at the top of the scatter band to that at the bottom of the band is

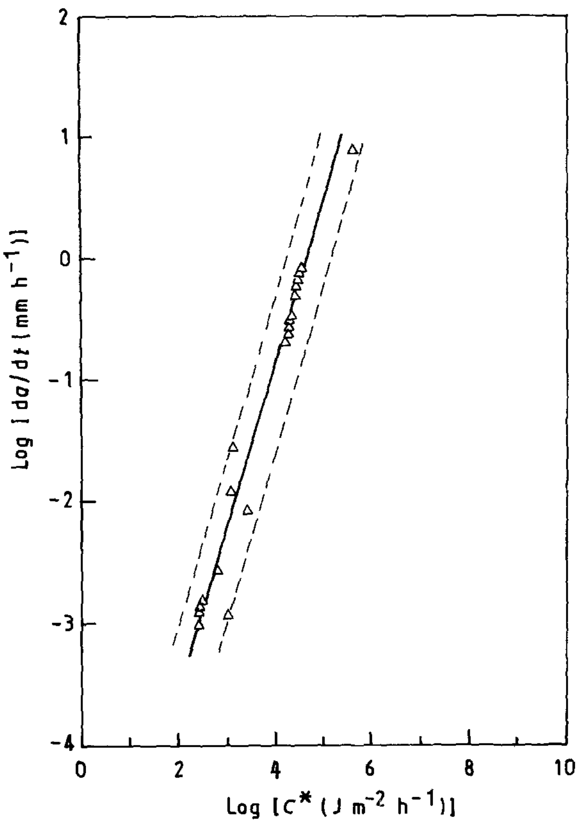

Figure 7 (△) Crack growth rate as a function of the C^* integral ($P = 6.10$ kN, $T = 150\,°\mathrm{C}$). (——) $\mathrm{Log}(\mathrm{d}a/\mathrm{d}t) = -6.0917 + 1.2906 \log C^*$ or $\mathrm{d}a/\mathrm{d}t = (8.096 \times 10^{-7})\,(C^*)^{1.2906}$.

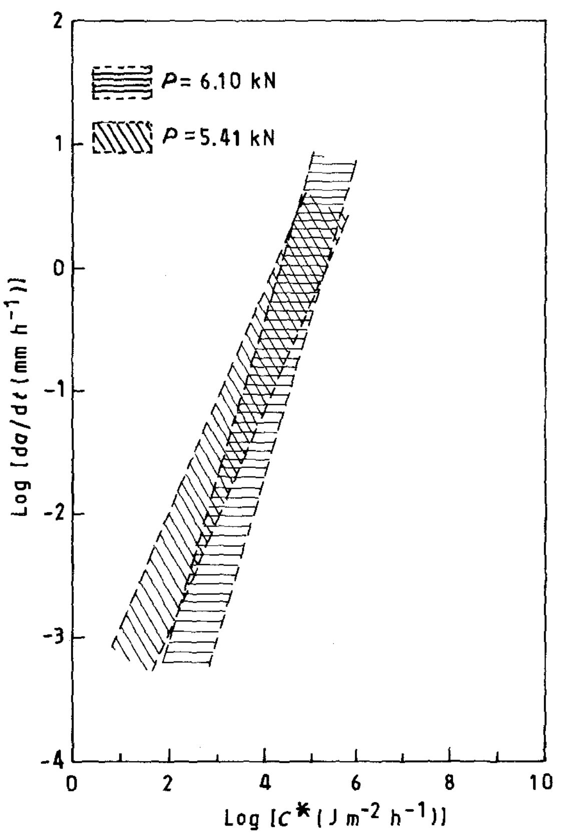

Figure 8 Scatter bands for crack growth rate–C^* relationships obtained under two different loads ($T = 150\,°\mathrm{C}$).

less than 15 (Fig. 8), but the same ratio in the case of K is more than a factor of 75. The poor correlation of creep crack growth rate with K has to be expected also because of the large-scale yielding observed in test pieces.

In addition, one can follow the suggestion of Riedel and Rice [9] to determine the characteristic time for the transition from a small-scale creep to extensive creep of the whole specimen which is given as

$$t_i = \frac{K_I^2(1 - \nu^2)}{E(n + 1)C^*} \tag{3}$$

where ν is Poisson's ratio, E is the elastic modulus and n is the exponent in Norton's creep law.

The transition time t_i can be used as a first approximation to determine whether K or C^* is a valid parameter to characterize creep crack growth. If the time needed for a crack length increment, for instance by 1 mm, comes out to be shorter than t_i, then K may be a valid parameter to describe crack growth kinetics. Otherwise, C^* will give a more satisfactory result.

Values of t_i have been evaluated from data obtained for two load values used. For example, in the test done under 5.41 kN, K has increased from 27.668 to 40.081 MPa m$^{1/2}$ whereas C^* has increased from 261.779 to 179 187.201 J m^{-2} h^{-1}. The corresponding t_i values have dropped from the initial value of 2.3701 to 0.0072 h. Therefore the time required for the crack to grow by 1 mm has decreased from 147.956 to 0.725 h. The ratios of these times to the transition times are calculated to be between 62.43 and 100.7, respectively. According to these data, values of t_i are much smaller than times needed for an increase in crack length by 1 mm. This means that extensive creep occurs ahead of the crack tip before any significant crack advance takes place. It can therefore be concluded that the C^* integral is more appropriate than K for correlation with the crack propagation rate for the aluminium alloy tested in this work.

Finally, it is worth mentioning that selection of the time for an increment of 1 mm in crack length for comparison is somewhat arbitrary. Thus, the usefulness of the characteristic time is only in terms of providing initial guidance in the choice of K or C^* rather than as an absolute criterion for validity of the particular parameter.

4. Conclusions

The following conclusions can be drawn from the results of this study.

1. Under creep conditions, the energy-rate line integral satisfactorily describes crack growth kinetics. This has been proved in 7050-T73651 high-strength aluminium alloy tested at 150 °C.
2. Evaluation of data according to the transition time concept introduced by Riedel and Rice proves that extensive creep occurred ahead of the crack tip. This again shows the suitability of the C^* integral in

characterizing the crack growth behaviour of a test alloy.

References

1. F. A. A. CRANE and J. A. CHARLES, in "Selection and Use of Engineering Materials" (Butterworths, Herts, 1987) p. 229.
2. G. J. NEATE and M. J. SIVERNS, in Proceedings of International Conference on Creep and Fatigue in Elevated Temperature Applications, Sheffield, 1974 (Institution of Mechanical Engineers 1975).
3. B. L. FREEMAN and G. J. NEATE, *Mater. Sci. Engng* **36** (1978) 241.
4. D. J. SMITH and G. A. WEBSTER, *J. Strain. Anal.* **16** (1981) 137.
5. J. D. LANDES and J. A. BEGLEY, ASTM STP 590 (American Society for Materials and Testing, Philadelphia, 1976) p. 128.
6. "Materials Research on Specific Components; Studies on Fracture Toughness and Fatigue Behaviour of 7050-T73651 Semi-Product", Report No. TF- 621.3 (Industrieanlagen Betriebgesellschaft mbH, Ottobrun, Germany, 1976).
7. M. A. HICKS and A. C. PICKARD, *Int. J. Fracture* **20** (1982) 91.
8. R. KOTERAZAWA and T. MORI, *J. Engng. Mater. Tech.* **99** (1977) 298.
9. H. RIEDEL and J. R. RICE, in "Fracture Mechanics, Twelfth Conference ASTM STP 700" edited by P. C. Paris, (American Society for Testing and Materials, 1980) p. 112.

Received 28 January
and accepted 11 August 1992