R RATIO INFLUENCE AND OVERLOAD EFFECTS ON FATIGUE CRACK MECHANISMS

J.D. Bertel, A. Clérivet, C. Bathias

Laboratoire de recherche sur l'étude et la prévention des défaillances mécanique et physico-chimique (ERA 910) - Université de technologie de Compiègne - France

ABSTRACT

CT specimens in 7175 T 651 aluminium alloy were tested with two R ratios in order to determine the function U = f(R) defined by ELBER. A relation was found which shows that the concept of effective stress intensity factor range ΔKeff explains only the R ratio influence where the crack propagates in plane stress and where the fatigue crack mechanism by striation is more important that the ductile decohesion mechanism. The overload effects were studied in terms of ΔKeff on CCT specimens in 2124 T 351 aluminium alloy. The obtained results show the ΔKeff concept explains only the overload phenomena in plane stress conditions of propagation.

KEYWORDS

Aluminium alloys ; effective stress intensity factor range ΔKeff ; fatigue crack mechanisms ; R ratio influence ; overload effects

INTRODUCTION

The purpose of these experiments is to investigate the influence of two important mechanical parameters on fatigue crack growth rate of two aluminium alloys which is not taken into account by the Paris' law, $da/dN = C\,\Delta K^m$. The investigations consist in determining the effective stress intensity factor range ΔKeff defined by ELBER, using notch clip gages and C.T.O.D. clip gages on CT and CCT specimens. Results show that in plane stress conditions, the ΔKeff explains R ratio influence and overload effect on fatigue crack propagation in aluminium alloys.

RECALLING ELBER'S MODEL

Elber (1971) showed that a fatigue crack in a aluminium sheet can close when the whole specimen is still submitted again to tension. As a result, compression stresses are induced around the crack when the load removes to zero (1967). ELBER concludes that a fatigue crack differs from an ideal mechanical crack in that it creates a region of residual strain during its growth. The **theoretical** crack tip opening displacement (C.T.O.D.) is consequently reduced.

Assuming that a fatigue crack cannot propagate when it is closed, he concludes that it is erroneous to take into account the total cycle amplitude to derive the Paris' relationship da/dN = f(ΔK) and he proposes to substitute the stress intensity factor range in this equation by an effective stress intensity factor $\Delta Keff = KM - Kop$, where KM is the maximum stress intensity factor and Kop the stress intensity factor required to fully open the crack tip.

In order to determine this ΔKeff, Elber (1971) plotted the displacement δ at the crack tip VS the stress S by means of a displacement gauge on thin sheets of 2024 T 3 aluminium alloy. Elber performed tests in which he varied parameters such as crack length, stress intensity factor and stress **ratio R** in order to determine their influence on ratio U defined as $U = \Delta Seff/\Delta S = \Delta Keff/\Delta K$. Only the stress ratio R appears to have a significant influence on the ratio U. Elber found a linear relationship between these two parameters expressed as $U = 0.5 + 0.4\ R$, with $- 0.1 < R < 0.7$ for aluminium alloy 2024 T 3, explaining in this way the influence of the ratio R on the fatigue crack growth rate in this alloy. Elber (1971) has also studied the overload influence on fatigue crack propagation. His conclusion is that under variable amplitude loading the crack closure phenemenon accounts for acceleration and retardation effects in crack propagation.

R RATIO INFLUENCE

Test Procedure

The material as received is an aluminium alloy type 7175, in T 351 state (quenched, prestretched and aged). Its chemical composition is given below :

Cu	Mg	Mn	Cr	Si	Fe	Ti	Zn
1.4	2.56	0.04	0.18	0.08	0.2	0.03	5.6

The material was annealed at 120°C for 24 h in order to obtain the T 651 state from the T 351 state.

Its mechanical properties in the longitudinal transverse direction in the T 651 state are the following :

σy (average) : 491 MPa
UTS (average) : 558 MPa
A% (average) : 8.7
E (average) : 68250 MPa

Compact specimens with W = 75 mm and a thickness of 10 mm where submitted to sine cyclic loading at two values of R (0.01 et 0.5) while maintaining the same ΔK or Kmax for the same crack length. In order to measure the changes in opening, we used both a double cantilever beam clip gauge allowing to plot notch displacement values (VG) and a surface gauge located at the crack tip allowing to plot crack tip opening values (δ). These plots were recorded at 0.2 Hz.

Study of Crack Tip Opening Displacement

Starting from Elber's definitions, we have investigated the crack opening process on the surface of a compact specimen. Fig. 1 gives a typical plot of $P = f(\delta)$ on the surface of a specimen in 7175 alloy cracked under constant load with a stress ratio R of 0.01 for a crack length of 29 mm measured from the loading line. The intersection of the curved segment with the linear part allows to define Po, again according to Elber's model.

The values of Po for crack lengths (a) ranging from 23.75 mm to 43.75 mm allow to calculate the U values of with the formula $U = \Delta Peff/\Delta P = PM-Po/PM-Pm$. We find a mean U ratio of 0.4 for two specimens (1979).

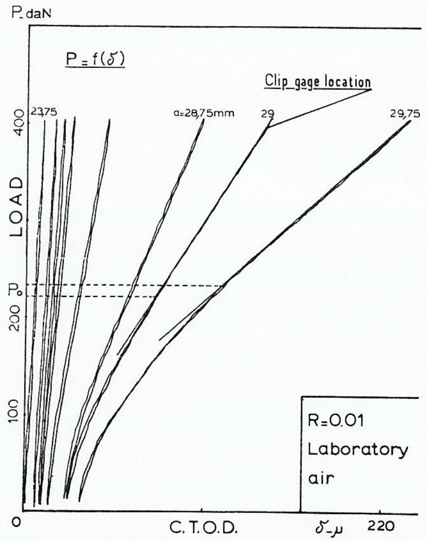

Fig. 1 : Load displacement diagram obtained with a crack tip clip gage

Similar curve of $P = f(\delta)$ has been **registered** for two specimens cracked with a R ratio of 0.5, one under a maximum load equal to that of the test performed with R = 0.01 and the other under a load amplitude equal to that of the test with R = 0.01. We find a mean U of 0.64 for a R ratio of 0.5 (1979). The function U = f(R) calculated from these values is given by the relationship $U = 0.4 + 0.4\ R$. Provided the Elber's definitions are verified, it can then be seen that for 7175 alloy, the function U on the specimen surface depends only on the stress ratio R.

Study of the Notch Displacement

Figure 2 shows typical plots of the notch displacement **versus** the load P for various crack lengths. In order to compare these displacements for two R ratios, we determined the maximum (VGM) and minimum (VGm) displacements as well as the displacements ranges $\Delta VG = VGM - VGm$ as a function of crack length (a).

On figure 3, the curves of VGM, VGm and ΔVG for R = 0.01 are average curves for all these tests performed in the same conditions. This figure shows that firstly when R varied from 0.01 to 0.5 with a constant ΔK for a single crack length the curve of minimum displacement corresponding to R = 0.5 coïncides with the curve of maximum displacement for R = 0.01. The curves of displacement range remain coïncident. Secondly, it can be seen that, when R varied from 0.01 to 0.5 with a same KM for a single crack length, the curves of maximum displacement remain coïncident. It is thus verified that the displacement range does not depend on the stress ratio R for a given ΔK.

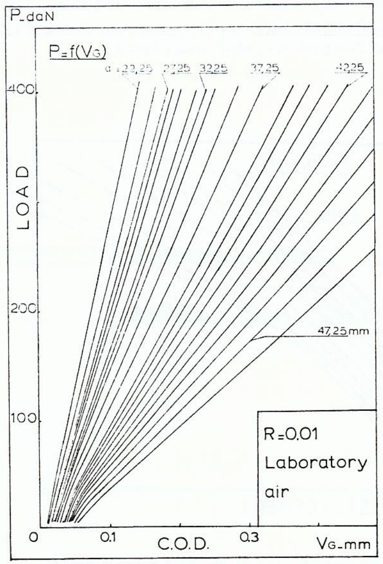

Fig. 2 : Load displacement diagram obtain with a notch clip gage

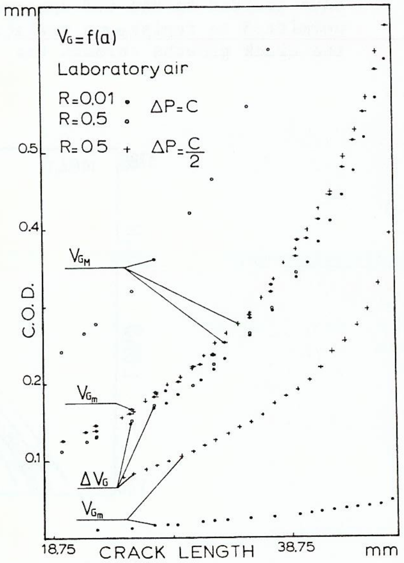

Fig. 3 : Effect of R ratio on the notch displacement

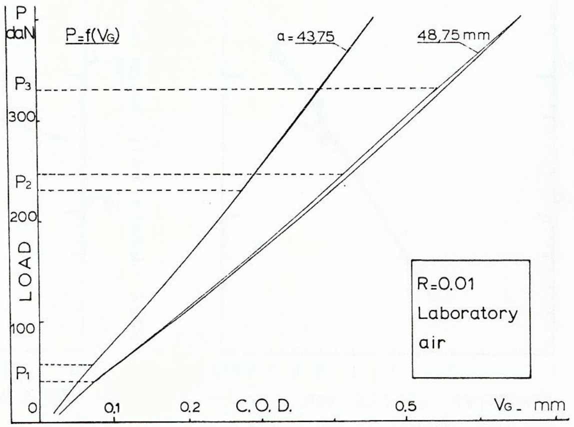

Fig. 4 : Crack opening determination with the notch displacement

Figure 4 shows a typical plot of VG = f(P) for a test conducted at R = 0.01. On this curve, we can define three points. Sometimes, the point P3 cannot be identified and the increase occurs then in the same way as the decrease. The stress intensity factors corresponding to the loads P1 has been found unchanged for any KM. On the otherhand the values of P2 are independant of crack length and consequently, K2 depends on KM (1979) (1978).

We can define a new ratio X = (PM - P2)/(PM - Pm) which remains constant as does the ratio U. The comparison of the results obtained with the displacement gauge and the C.T.O.D. gage located on the surface allows to infer that the point corresponding to the crack opening as understood by Elber is the point P2. The point P1 then corresponds to the start of the crack tip opening inside the specimen. In the tests with R = 0.5, it is impossible to determine P1 as Pm assumes a value higher then the latter. However, the point P2 remains and the various measured values allow to calculate the ratio X defined above (1979) (1978). Finally the function X = f(R) calculated from these values is given by X = 0.38 + 0.45 R.

Discussion

From the results gained during the tests on crack opening displacement, we can infer that the increase of the macroscopic growth rate with R does not depend on the displacement range since, for a given ΔK, this range is not affected by a change in R.

The tests on surface opening at crack tip show that the opening point to be taken into account to calculate ΔKeff as defined by Elber is not the first point P1, determined from the displacement curves, but a second point P2, which corresponds to the point Po determined from the surface plots. This remark gives the reason of the discrepancies previously noted.

The equation of U and X derived through the two methods are slightly different due to the different determination of P0 and P2 : global or local measurement.

A comparison of the two curves P = f(VG) and P = f(δ) shows that the point P2 corresponds to the surface opening (PO) and P1 corresponds to inside opening. It appears then the curve P1 - P2 is a plot of both the crack opening displacement from the inside to the surface and the configuration change due to the remaining cross section which decreases as the crack opening comes nearer to the surface (1979) (1978).

We succeeded in establishing a relationship to obtain ΔKeff vs R which is very close to that proposed by Elber. However, our results show a change in the exponent m of the Paris' relation (fig. 5) when R varies from 0.01 to 0.5 for crack growth rates ranging from 10^{-4} to 10^{-2} mm/cycle).

The concept of ΔKeff does not explain the variation of the exponent m. Elber's assumptions are applicable without difficulty only to the case of thin sheet cracked under plane stress conditions for alloys such as the 2024 in which the cracking mechanism by formation of striations is predominant even with a high R ratio. In the case of alloy 7175 cracked under plane strain conditions, the influence of R on ΔKeff is compounded by the effect of thickness and the inception of ductile mechanisms with dimples when R increases.

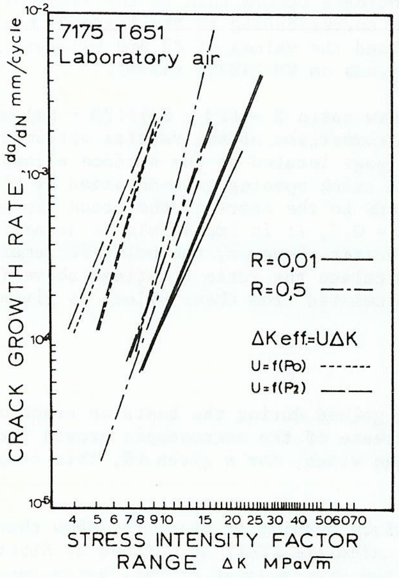

Fig. 5 : Fatigue crack growth rate VS the effective stress intensity factor range

OVERLOAD EFFECTS

Test Procedure

The material tested is an aluminium alloy, 2124 T 351. Its chemical composition is given below :

Si	Fe	Cu	Mn	Mg	Cr	Zr	Ti
0.11	0.23	4.35	0.6	1.45	0.01	0.04	0.02

Its mechanical properties in the longitudinal transverse direction are the following : $\sigma y = 274$ MPa ; UTS = 440 MPa ; A% = 18

Compact specimens (W = 75 mm, B = 12 mm) and CCT specimens (W = 200 mm, H = 600 mm, B = 1,6 mm) were submitted to sine or triangular cyclic loading with a basic ΔKo, just before overload of 12 MPa$\sqrt{m}$. In order to study the opening mechanisms more practically we have registered C.O.D. and C.T.O.D. on CCT specimen with an overload ratio $T = \Delta Kpeak/\Delta KO = 2$. Three clip gages were used : one straddling the center notch and two others located at the tips of the two cracks.

Study of Crack Tip Opening Displacement

Because an overload ratio of 1.5 on a CT specimen is not sufficient to register variations on the curves $P = f(\delta)$ due to the small retardation (≃ 4000 cycles), we have decided to use CCT specimens. The application of an overload ratio of 2 has permitted to register a variation of P opening, as it can be seen figure 6, when the crack growths through the zone affected by the overload.

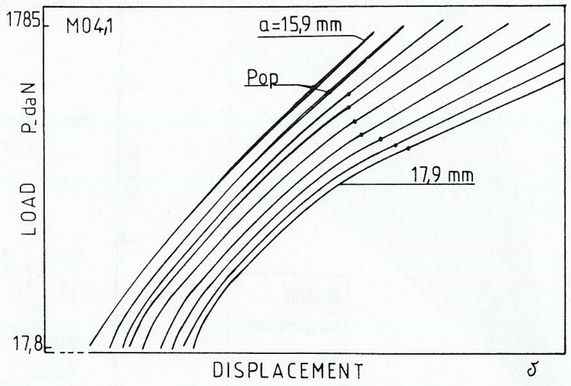

Fig. 6 : Load displacement diagram obtained with a crack tip clip gage

For each value of Pop we have calculated corresponding values of $U = \Delta Peff/\Delta P$ to determine $\Delta Keff$.

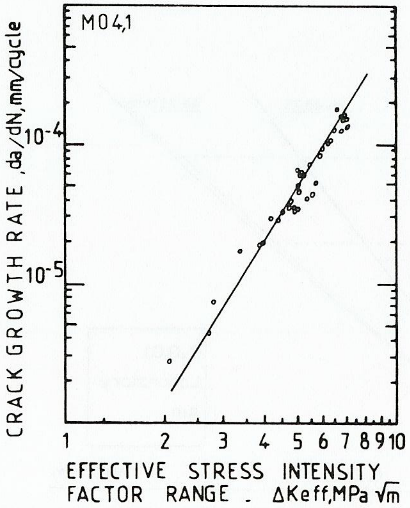

Fig. 7 : Fatigue crack growth rate VS the effective stress intensity factor range - R = 0.01

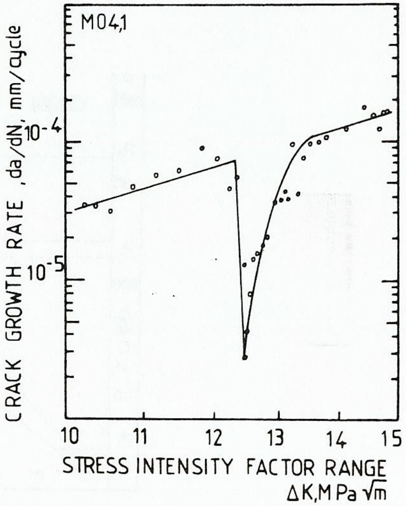

Fig. 8 : Fatigue crack growth rate VS the stress intensity factor range - R = 0.01

Figure 7 shows that when crack growth rate is plotted VS ΔKeff, all the experimental points obtained in the affected zone are located on a straigth line which corresponds to the relation $da/dN = C\,\Delta Keff^m$ determined before overload and after overload outside the affected zone. We can see figure 8 that the relation between da/dN and ΔK is not linear and hence that the Paris'law is not verified in the curve part corresponding to the overload.

Influence of R ratio

A CCT specimen was tested with a R ratio of 0.5 conserving the same basic ΔKo and the same overload ratio (T = 2) as in the tests conducted with R = 0.01.

Similar curves P = f(δ) was obtained permitting to calculate ΔKeff. Figure 9 shows that the relation is linear, when we consider ΔKeff in state of ΔK (fig. 10) in the same manner that the tests conducted with a R ratio of 0.01.

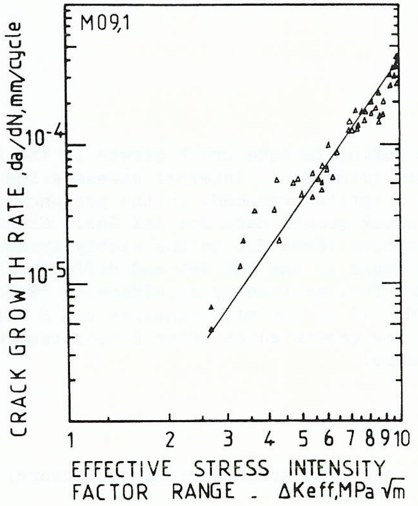

Fig. 9 : Fatigue crack growth rate VS the effective stress intensity factor range R = 0.5

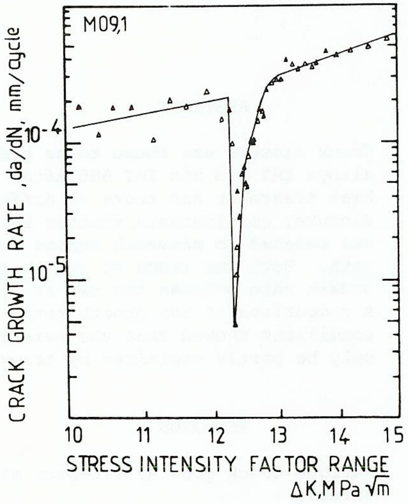

Fig. 10 : Fatigue crack growth rate VS the stress intensity factor range R = 0.5

Discussion

It is interesting to note that any variation of Pop was obtained with the central notch clip gage during cracks growth through the affected zone. Explanation is that these variations are due to more residual deformations created by the overload which affect only the tips of the two cracks. So, the variations of Pop were obtained only with clip gages located at the crack tips.

These local variations have permitted to calculate a new relation, in terms of ΔKeff, which is linear explaining the effect of overloads on thin sheets for different R ratios. These results are in good agreement with Schijve results (1977).

A second point is that the straight lines obtained with two different R ratios are similar confirming the relation obtained by Elber for 2024 T 3 :
U = 0.5 + 0.4 R.

The ΔKeff appears to be a good criteria to explain the crack growth mechanisms for 2124 T 351 aluminium alloy tested under variable amplitude loading with different R ratios, at least for thin sheets.

CONCLUSION

1. The crack opening phenomena observed in our tests depends on the applied method (overall measurements or local measurement) which accounts for the differences in ΔKeff found in the litterature. The systematic use of the two methods allowed us to bring to light common features permitting the calculation of ΔKeff according to Elber's criteria.

2. For a given ΔK, the displacement range is the same for any stress ratio R.

3. The concept of ΔKeff does not fully explain the influence of the ratio R. Strictly speaking, the change in the fracture mechanism in crack tip when KM varies should be taken into account.

4. The concept of ΔKeff appears to be a good criteria to explain the overload phenomena in aluminium alloys, at least in the case of thin sheets where the crack propagates, in plane stress state.

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