Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Fatigue Crack Propagation in 2195-T8 Aluminium Alloy Plate

R. Doglione, M. Bartolone

Politecnico di Torino, c.so Duca degli Abruzzi 24, 10129 Torino, Italy, e-mail: roberto.doglione@polito.it

Keywords: 2195-T8 alloy, fatigue crack growth, fatigue threshold, stress ratio effect, crack closure.

Abstract

The paper deals with fatigue crack propagation in a 2195-T8 alloy plate. It is shown that fatigue resistance of this alloy is comparable to that of the classical 2xxx or 7xxx competitor alloys. This study highlights stress ratio effects on the fatigue behaviour at the threshold: the stress intensity factor range ΔK_{th} decreases as R increases. The crack growth path, very sensitive to the texture of the plate, occurs in a crystallographic way, giving rise to strong deflection and zig-zag advance. The crack path provokes a mixed mode I and II fatigue fracture, and makes active crack retardation by the crack closure mechanism.

1. Introduction

The 2195 alloy belongs to the Weldalite family, initially developed for use in aerospace launch vehicles, and now considered suitable for welded structural parts in commercial aircrafts. In both cases, an adequate damage tolerance is required. In this respect, the fatigue crack propagation resistance is a critical property. Published data on fatigue crack propagation for these alloys, in spite of their pratical importance, are scarce [1, 2]. Fatigue crack propagation results are reported in [1] for a 2095-T3 and T8 extruded bar and similar results are reported [2] for a 8 mm thick sheet 2195-T8 alloy.

2095 and 2195 are very similar alloys, the second one is less rich in copper; however, in the T8 temper both alloys are mainly strengthened by a fine and homogeneous dispersion of T_1 particles. The previously cited references [1,2] point out a typical feature of these alloys in the T8 temper, namely strong and complex crystallographic texture: predominant Brass, together with Copper and S components are present. In spite of this, in 2095 alloy [1] the crack path at low ΔK in the T8 temper was straight, following the nominal mode I, whereas in 2195 [2] the propagation was crystallographic in nature, i.e. the path was deviated, with deflection angle ranging from 5 to 30 degrees. In this last case a mixed mode crack growth arose. Moreover, in [2] a zig-zag crack path was reported on a microscopic scale. Then, in 2195 is present an important crack closure mechanism, related to the crack path tortuosity. This mechanism is suggested but not thoroughly discussed in [2], although is very important to explain stress ratio effects.

A further examination is requested, because crack closure may enhance fatigue crack propagation resistance at low stress ratio. Therefore, this paper reports further results of fatigue crack growth tests performed in air (60% relative humidity) at room temperature (20°C). A comparison with the previous results is carried out.

2. Experimental Procedures

After the determination of the tensile properties along the rolling (L) and long transverse direction (LT), fatigue crack propagation tests were performed according to the E647 ASTM Standard. Both LT and TL crack orientations were assessed, at different constant load ratio R=0.6, 0.4, 0.2 and 0.1. 50 mm wide CT samples were employed, machined from a commercial 6,35 mm thick plate. The tests were carried out by a MTS servohydraulic machine; the frequency was set to 40 Hz. The crack length was monitored by an optical travelling microscope (0.01 mm resolution) and by a stereomicroscope (0.02 mm resolution). The surface of the sample was previously polished. The crack propagation and closure was followed determining the elastic compliance of the CT sample by a crack mouth opening sensor.

Three different test procedure were followed. The K-decreasing procedure was adopted to explore the decreasing crack growth rate regime until the threshold. The load shedding was conducted as decreasing load steps (maximum 10%). Data were recorded for this alloy only after a minimum crack growth of six times the compression plastic zone; for shorter crack propagations, the rates were found affected by transient effects induced by the negative load step. The constant-load-amplitude was used from near-threshold crack growth rates to specimen fracture. A constant K_{max}=10 MPa√m test with increasing R was performed in order to obtain a threshold stress intensity range free of crack closure. The threshold stress intensity factor range was measured at a crack growth rate of 10^{-12} m/cycle**.** The microstructure of the material was characterized by optical metallography and fracture surfaces were analysed by SEM.

3. Results

The results of tension tests are reported in Table 1. The microstructure consisted of a typical pancake-shaped grain structure, with thickness of 10-15 µm, width of some hundred of µm and length of several mm.

Table 1: tensile properties of 2195-T8 alloy; n and k are the fitting parameters of the Hollomon law.

Direction	E [GPa]	$R_{0.2}$ [MPa]	R [MPa]	A%	n	k	B [mm]
L	73	549	579	8	0.022	668	6.35
LT	73	580	602	9	0.036	677	6.35

Complete crack growth curves are shown in Figure 1 for R=0.1, in terms of nominal mode I stress intensity range ΔK_I, together with competitor Al alloys. It is clear that the long crack propagation behaviour of the 2195-T8 alloy is equivalent to the high strength 2xxx or 7xxx series alloys. At higher R values, the curves for 2195-T8 alloy differ each other substantially only in the threshold region, showing typical stress ratio effect. In Figure 2 the results of the stress intensity range at threshold versus stress ratio is resumed. The nominal ΔK_{th} in mode I is plotted: in reality crack deflection gives rise to a mixed I and II crack propagation. A behaviour characterized by negative slope in the curve is shown [4].

The crack path was never perpendicular to the load direction, in pure mode I: the global deviation angle varied mostly in the range 4°-17° and sometimes reached 30°. Moreover, the angle was non reproducible from a sample to another at the same R and orientation, in contrast to the results reported in [2]. A clear dependence of the deviation angle on the testing direction and stress ratio was not detected. The stress intensity range at threshold ΔK_{th} shows no dependence on the global deflection angle.

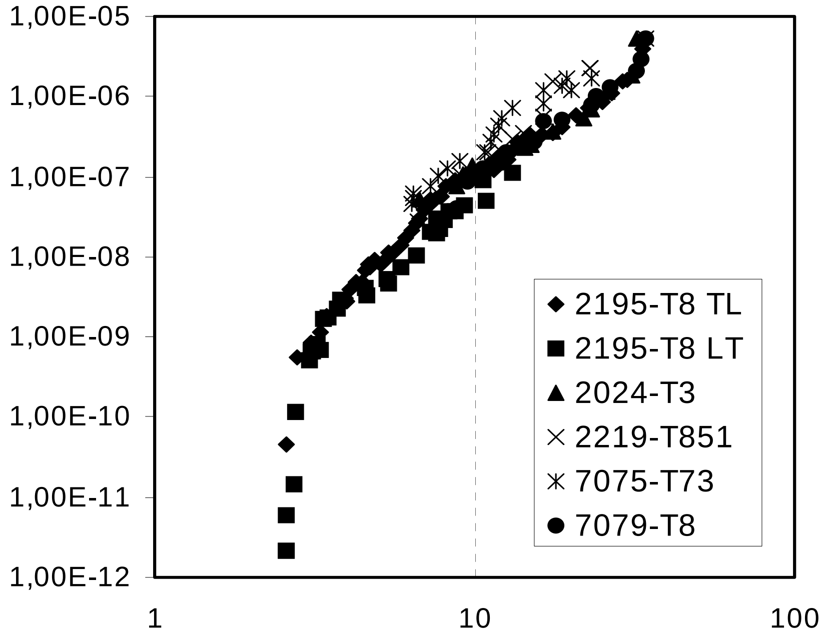

Figure 1: fatigue crack growth curves for high strength Al alloys and 2195-T8 alloy. The data are valid for R=0.1.

At local level, a zig-zag crystallographic crack growth path occurs, as reported in [2], but the scatter of the deviation angle here was much stronger. Crack branching was also detected. In [2] a constant local deflection angle was assumed from surface observation; in our samples SEM analyses showed that the local angle varied widely along the crack front, Figure 3. The crack followed different angles in different grains or even in the same grain (Figure 3). The length of the kink varied between 0.1 to a few μm (Figure 3). Thus, is not possible to assume a representative kink angle for local stress intensity evaluations, and the application of Linear Elastic Fracture Mechanics at kinked crack is itself doubtful, since the size of the plastic zone is of the order of the kink length. Therefore, the analyses carried out in [2] on deflected cracks are not proposed here; further experimental work is necessary to clarify the situation. Crack closure results are reported in Figure 4 expressed as K_{cl}/K_{max} versus ΔK_I. The scatter in such kind of measurement is important. The trend is quite insensitive to the stress ratio R, and in the threshold region K_{cl} is nearly $0.5 \cdot K_{max}$, irrespective of R. At the highest stress ratio, R=0.6, the closure stress intensity K_{cl} is always below the minimun stress intensity K_{min}: in this case crack growth occurred nearly in absence of closure effects.

This fact suggests the constancy of ΔK_{th} at stress ratio higher than 0.6. On the contrary, the fatigue threshold obtained at constant K_{max}=10 MPa√m with increasing R is 0.99 MPa√m at a stress ratio of 0.9.

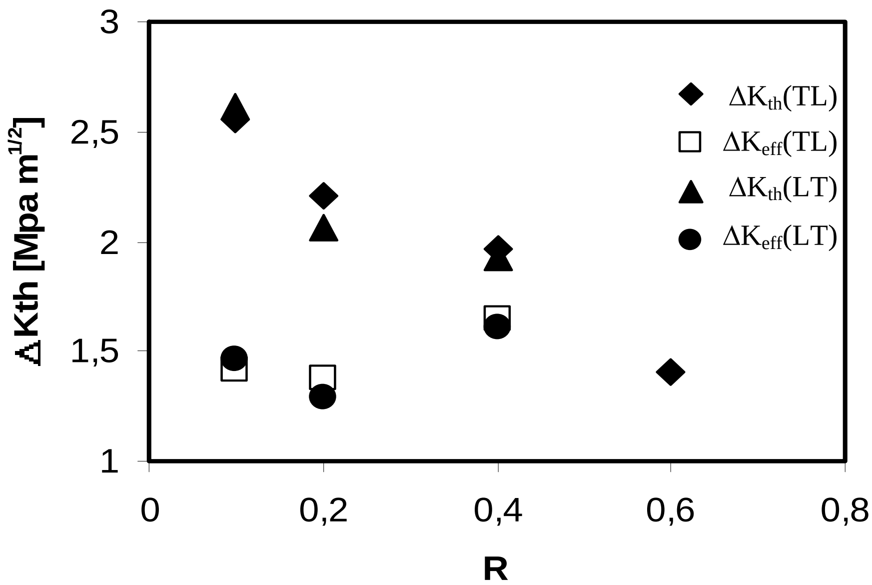

Figure 2: nominal and effective (crack closure corrected) fatigue threshold versus stress ratio for 2195-T8 alloy.

4. Discussion

2195 alloy was claimed to be more isotropic than earlier commercial Al-Li alloys, mainly 2090 and 8090 and the target was quite reached, since tensile characteristics are very similar in the rolling (L) and long-transverse (LT) directions. Fatigue crack propagations thresholds show the same tendency, Figure 2. No noticeable difference can be detected between ΔK_{th} in the TL and LT directions. In literature, a minimum value in the tensile and fatigue properties is reported at 45° to the rolling direction [2]: the minimum is not very marked and it is possible to conclude that 2195 alloy has improved isotropy in comparison with other Al-Li alloys.

As reported in the previous paragraph, ΔK_{th} is quite insensitive to loading direction and macroscopic deflection angle. But also values for the local kink angle are not clearly identifiable. Is not possible to assume a representative kink angle at the threshold for local stress intensity evaluations, and the application of Linear Elastic Fracture Mechanics at kinked crack is itself doubtful, since the size of the plastic zone is of the order of the kink length [5]. Therefore, the analyses carried out in [2] on deflected cracks are not proposed here; further experimental work is necessary to better clarify the situation, and for the moment a semplified analysis of the threshold behaviour is proposed.

For sake of semplicity, here the approach of mixed mode is disregraded. Irrespective of the testing direction, it is possible to interpret stress ratio effects in the threshold region and low R regime in terms of crack closure.

We can consider the effective stress intensity factor range at threshold, i.e. $\Delta K_{eff,th}(R)= K_{max}-K_{cl}$. The ratio K_{cl}/K_{max} versus ΔK is quite insensitive to loading direction and stress ratio (Figure 4) ; at the threshold, this ratio holds constantly α, here 0.5 ca.

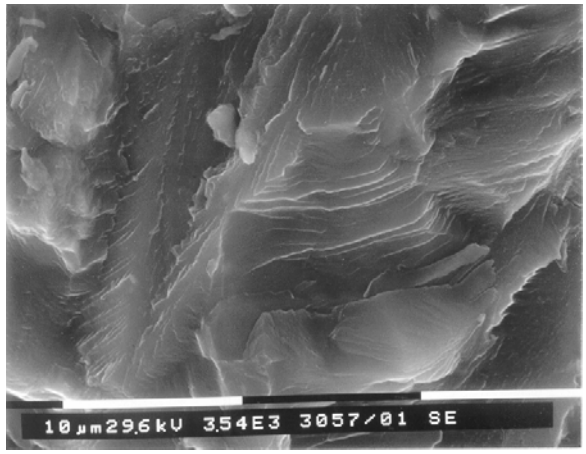

Figure 3: Crystallographic crack growth.

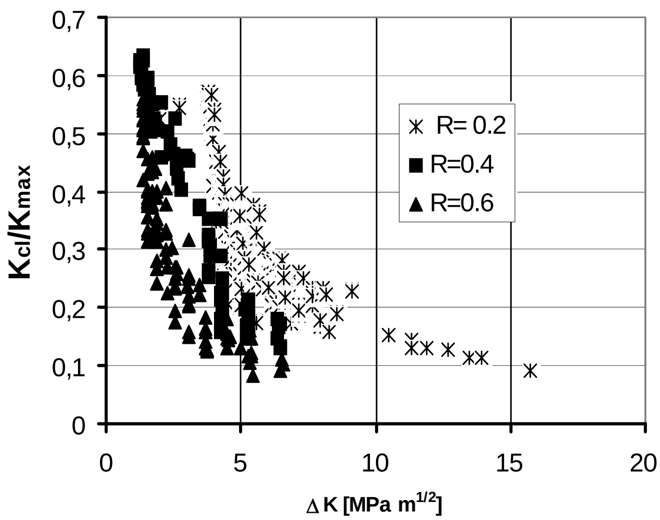

Figure 4: Crack Closure versus stress intensity factor range for TL sample.

Introducing α and R in the definition of the nominal and effective stress intensity range:

$$\Delta K_{eff,th} = (1-\alpha)\cdot K_{\max} \ , \tag{1}$$

$$\Delta K_{th} = (1-R)\cdot K_{\max} \ , \tag{2}$$

and, only if $K_{min}<K_{cl}$ (here R=0.1, 0.2 and 0.4), for the low R regime we obtain:

$$\Delta K_{eff,th} = \frac{1-\alpha}{1-R}\Delta K_{th} \ . \tag{3}$$

The above assumptions give the results reported in Figure 2. It is shown that $\Delta K_{eff,th}(R)$ value are leveled on the threshold value at R=0.6, where crack closure is absent. It may be concluded that a simple model based on crack closure works satisfactory, in the case of the 2195-T8 alloy, to account for stress ratio effects on ΔK_{th} at medium-low stress ratio ($R \leq 0.6$).

The previous model cannot explain the further decrease of ΔK_{th} at high R. In the last years, a strong criticism has been advanced on the crack closure concept [4,6]. It was concluded that the closure effect on ΔK was overestimated. The present data show that closure indeed exists at least till R=0.6. An additional decrease of ΔK_{th} may be explained in two ways. The first might be lack of sensitivity in closure measurement at the mouth of the sample. Since alternative measurements are not jet available, it is not possible to judge. The second might be a K_{max} effect on ΔK_{th}. The applied K_{max} at threshold was around 3 MPa√m ca until R=0.6, whereas at R=0.9 was 10 MPa√m ca. The similitude in fatigue is violated. In the last case the crack tip is subjected to threefold stress intensity factor and ninefold plastic zone size: the damaged volume is wider and crack growth might occurs more easily, explaining a lower ΔK_{th}. This is a suggestion, but more work is necessary to clarify the whole question.

5. Conclusions

The experimental determination of the fatigue crack growth curves in a 2195-T8 alloy plate led to the following points:

- crack growth resistance of the present alloy is comparable to that of the classical competitors Al alloys (2xxx and 7xxx series);
- crack growth occurs crystallographically in mixed mode I and II, with very tortuous path;
- important stress ratio effects appear in the threshold region, ΔK_{th} decrease as R increase;
- crack closure is the main cause of stress ratio effects until R=0.6;
- further decreasing in ΔK_{th} occurs beyond R=0.6 apparently without crack closure.

Acknowledgement

This work has been supported by the authors because of the structural lack of italian funds for the scientifical research. The availability of a MTS testing system for the tests is acknowledged to the Politecnico di Torino.

References

[1] C. P. Blankenship Jr and E. A. Starke Jr, Fatigue Fract. Engn. Mater. Struct., 14 No. 1, 103-114, 1991
[2] D. L. Chen and M. C. Chaturvedi, Metallurgical and Material Transations A, 31A, 1531-1541, 2000.
[3] Metals Handbook Vol. 19, Fatigue and Fracture, ASM International, Metals Park, OH, 785, 1996.
[4] A. K. Vasudevan and K. Sadananda, Metallurgical and Material Transations A, 26A, 1221-1234, 1995.
[5] S. Suresh and C. F. Shih, Int. J. of Fracture, 30, 237-259, 1986.
[6] D. Kujawski, Int. J. of Fatigue, 25, 793-800, 2003.