

FATIGUE CRACK PROPAGATION RATES OF THE ALUMINIUM ALLOY 6061-T651

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***Abstract**: This paper presents some results of a study for characterization of the fatigue behaviour of the aluminium alloy 6061-T651. The investigated material is a weldable aluminium alloy with high mechanical resistance used for structural applications. The frequent cyclic loads observed in structures requires the knowledge of the fatigue crack propagation curves for the base material (BM), welded material (WEL) and for the heat affected zone (HAZ) resulting from a typical welding process. With this purpose, fatigue crack propagation tests were performed in a servohydraulic machine, using normalized CT specimens, in order to derive the da/dN versus ΔK curves. Two stress ratios were investigated namely R=0.1 and R=0.5. The tests were carried out under load control, using a sinusoidal waveform with a frequency of 15Hz. It was observed that the base material was more sensitive to the stress ratio rather than the welded or HAZ materials. Tests carried out under R=0.1 showed that HAZ is the material with highest fatigue crack propagation rates. On the other side, the base material presents the lowest propagation rates. For R=0.5 no significant differences were observed in the crack propagation rates between the three investigated materials.*

***Keywords**: Fatigue crack propagation, Al 6061-T651, Base material, Welded material, Heat affected zone.*

1- Introduction

The evaluation of the fatigue crack growth propagation rates has been a subject of intense research. The Linear Elastic Fracture Mechanics (LEFM) has been the most appropriate methodology to describe the propagation period of fatigue cracks. The LEFM is based on the hypothesis that the stress intensity factor is the mechanical parameter that controls the stress range at the crack tip. For a geometry, where the stress intensity factor increases with the crack length, the curves that describe the crack length as a function of the stress application cycles has the shape represented in the Fig. 1. In this illustration two fatigue propagation curves are represented for two different stress values, σ_1 and σ_2. For both curves cracks start from the same initial defect, a_i, growing until reaching a critical dimension, a_c, responsible for the rupture. The applied stress is an important parameter in the propagation process. For the stress $\sigma_1>\sigma_2$ the propagation curves are similar, but $a_{c1} < a_{c2}$ and consequently $N_{r1}<N_{r2}$. This behaviour observed in the propagation of fatigue cracks led many authors to propose empiric laws with the following general form (Walton et al, 1967):

$$\frac{da}{dN} = \alpha\, f\left(\sigma,a\right) \tag{1}$$

These laws express the importance of stress and crack length in the crack propagation rates. Several authors have suggested, for the general law, Eq. (1), the following particular form:

$$\frac{da}{dN} = \alpha\sigma^m a^n \tag{2}$$

Liu (1964) suggested for the exponents *m* and *n* the values 2 and 1, respectively. Frost (1959) suggested values of 3 and 1, respectively.

The representation proposed in Eq. (2) to model fatigue crack propagation rates leads to a different curve, for each different stress values considered, not being a practical form. In alternative, several laws have been proposed to

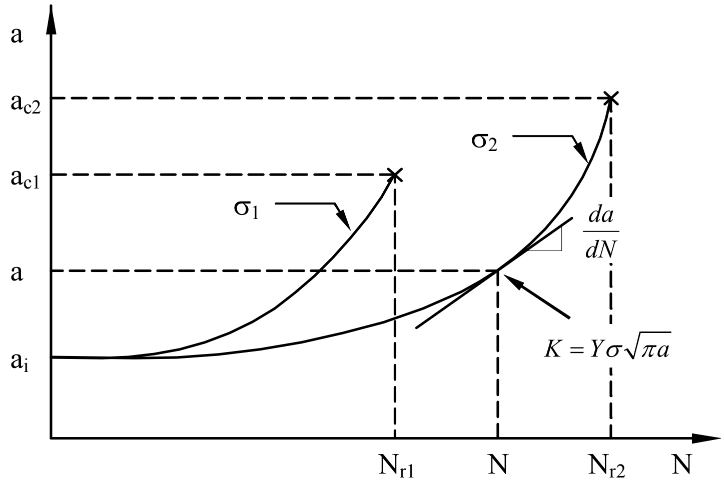

Figure 1. Schematic representation of fatigue crack growth curves for two different stress levels, σ_1 and σ_2.

characterize the fatigue crack propagation rates, combining the *da/dN* and *ΔK* parameters. A very known relation of this type was proposed by (Paris and Erdogan, 1963) and has the following form:

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{3}$$

where *da/dN* is the fatigue crack propagation rate, $\Delta K = K_{max} - K_{min}$ represents the range of the stress intensity factor and *C* and *m* are materials constants.

2. Analysis of the da/dN *versus* ΔK curves

A typical experimental curve that relates *da/dN* with *ΔK*, for cyclic loads with constant stress amplitude and R=0, it is represented on Fig. 2 in a schematic way. The *da/dN versus ΔK* curves are usually derived, for the majority of high strength materials, for crack propagation rates ranging between 10^{-7} and 10^{-2} mm/cycle. The diagram illustrates three different propagation regions, usually designated by regions I, II and III. In the region I, the propagation rate depends essentially on the stress intensity factor. In this region there exists a *ΔK* value below which no propagation is verified, or if propagation exists the propagation rate is below 10^{-7} mm/cycle. This value of the stress intensity factor range is denominated propagation threshold and it is represented by ΔK_{lf}. In the region II a linear relation between *log(da/dN)* and *log (ΔK)* is observed. The Paris's law, Eq. (3),models this crack propagation region.

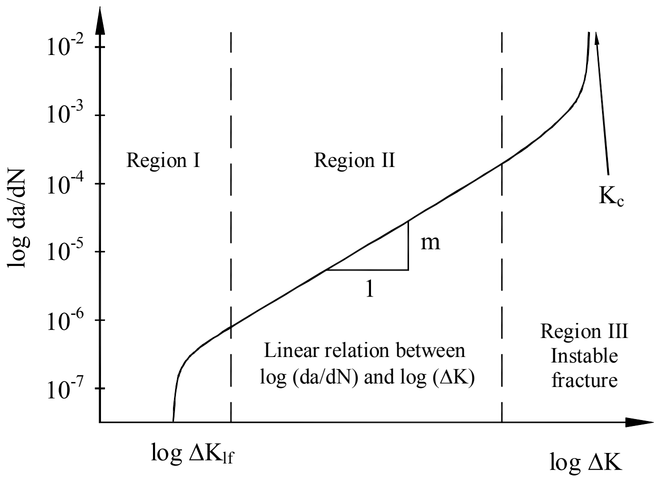

Figure 2. Schematic representation of the relation between *da/dN* and *ΔK*.

Region III appears when the maximum value of the stress intensity factor approaches the critical value, K_{Ic}. This region is characterized by an acceleration of the crack propagation rate that leads to an unstable propagation of the crack that consequently to the final rupture. The region III is not well defined for materials experiencing excessive ductility. For these materials is observed the development of gross plastic deformations in region III which invalidates the application of the MFLE since the basic hypothesis of the LEFM are violated.

3. Fundamental laws of fatigue crack propagation

The growth of fatigue cracks is a mechanical phenomenon that depends on the stress level and deformation localized at the crack tip, quantified by the stress intensity factor, *K*.
If we restrict our analysis for constant amplitude loading, the fatigue crack growth rate, *da/dN*, can be expressed as a function of several factors, as represented by the following relation:

$$\frac{da}{dN} = f\left(\Delta K, f, R, T, n\right) \tag{4}$$

where ΔK is the stress intensity factor range, f the frequency, R the stress ratio, T the temperature and n a constant dependent on the environment.

The first relation used to correlate the fatigue crack propagation rate with the stress intensity factor range was suggested by Paris (Paris and Erdogan, 1963). Although being an empiric relation, it has been generally accepted due to its mathematical simplicity and good correlation achieved for the region II of propagation. This relation presents, however, limitations because it does not allow the description of the propagation behaviour for the regions I and III:

$$\Delta K \rightarrow \Delta K_{lf} \qquad \frac{da}{dN} \rightarrow 0 \qquad \text{(Propagation threshold)}$$

$$K_{max} \rightarrow K_c \qquad \frac{da}{dN} \rightarrow \infty \qquad \text{(Instability condition)}$$

In order to overcome the limitation of the Paris's law, other equations with semi-empirical or analytical foundation were deduced. These alternative relations try to correlate the several regions of the curve *da/dN versus* ΔK.

One important alternative to the Paris's law is the Forman's law (Forman *et al.* 1967) that is able of describing the crack propagation behaviour for regions II and III:

$$\frac{da}{dN} = \frac{A(\Delta K)^m}{\left(1 - R\right)K_c - \Delta K} \tag{5}$$

where A and m are material constants. This equation takes in account the effect of the mean stress through the inclusion of the stress ratio, R, as well as the effect of the fracture toughness through the inclusion of K_c. Maddox mentions (Maddox, 1975) that Illg-McEvilly and Hudson-Scardina, obtained satisfactory results with the application of this equation.

Erdogan and Ratwani (Erdogan et al. 1970)] modified the Forman's law in order to predict the propagation behaviour in region I, through the substitution of ΔK by $(\Delta K - \Delta K_{lf})$, where ΔK_{lf}, represent the propagation threshold. This modification predicts no propagation for ΔK values such that $\Delta K = \Delta K_{lf}$:

$$\Delta K = \Delta K_{lf} \rightarrow \frac{da}{dN} = 0 \tag{6}$$

These authors also suggested the parameter $\beta = \dfrac{K_{max} + K_{min}}{K_{max} - K_{min}}$ instead of R obtaining the following propagation law:

$$\frac{da}{dN} = \frac{A\left(1+\beta\right)^q \left(\Delta K - \Delta K_{lf}\right)^p}{K_c\left(1+\beta\right)\Delta K} \tag{7}$$

where A, p and q are material constants. Erdogan and Ratwani (Erdogan *et al.* 1970) applied Eq. (7) for several values of β and obtained satisfactory results for the propagation period of the aluminium alloy 6061-T4.
Another equation which includes the effect of the mean stress and models the propagation behaviour for regions I, II and III, was proposed by C. M. Branco (Branco *et al.* 1976) with the following form:

$$\frac{da}{dN} = A\Phi^{\alpha} \tag{8}$$

where A and α are constants of the material and Φ is a parameter for the three propagation regions.

Equations (5), (7) and (8) have some important advantages over the Paris's law because they predicted the effect of the mean stress, essentially for cycles where the stress ratio is greater or equal to zero. Since Eq. (7) and (8) make use of normalized parameters they have also the advantage of using a single equation to obtain all the values of propagation rates, independently of the stress ratio. The Paris's law requires a different curve for each value of the mean stress. Although the mentioned disadvantages, the Paris's law still is the equation more used to model the propagation of fatigue cracks due to its mathematical simplicity as well as to the safety of the results obtained. Also, the Paris's law requires a small number of experimental parameters to be identified.

4. Experimental procedure

In order to determine the fatigue crack propagation curves (*da/dN versus ΔK* curves) CT ("Compact Tension") specimens were used. This specimen geometry presents, in relation to the alternative CCT geometry ("Center Crack Tension"), the advantage of obtaining a larger number of readings with a smaller material volume. The specimens were cut from a plate of aluminium 6061-T651 with 24 mm of thickness, containing butt welded joint made from both sides using the MIG welding process. The filler material used in the welding process was the AlMg-5356. Due to material limitations, specimens with thickness B=10 mm, and nominal width, W=50 mm were used. These dimensions are according to the recommendations of the ASTM E647 standard (ASME, 1982). Figure 3 illustrates the locations in the aluminium plate where the specimens were extracted.

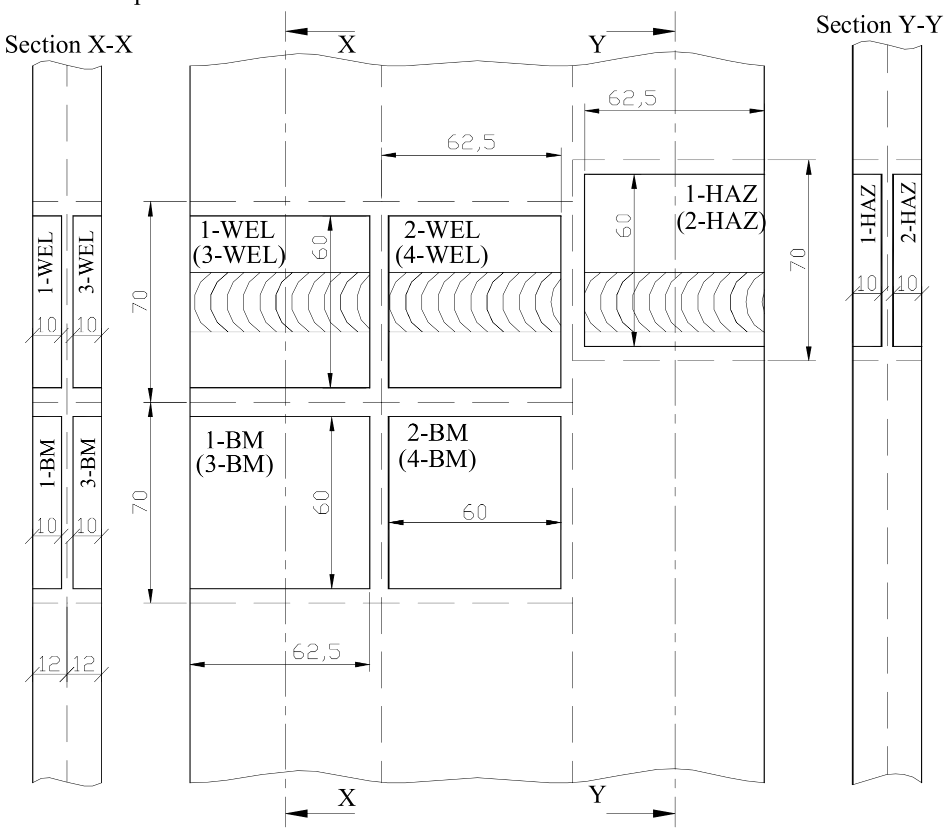

Figure 3. Location of the specimens on the aluminium plate.

Specimens containing base material, HAZ and welded materials were cut from the plate. This extraction process was planned in agreement with the recommendations included in the standard. The specimens were tested in a servohydraulic machine, rated to 100 kN, applying a sinusoidal waveform with 15 Hz. The crack length was measured on both faces of the specimen, using to two magnifying glasses. The resolution of the measuring device was 0.01 mm.

In order to obtain the curves *da/dN versus ΔK* it is necessary to find an appropriate expression to evaluate *ΔK*. The ASTM E647 standard propose the following formulation of *ΔK*, for the CT geometry (Srawley, 1976):

$$\Delta K = \Delta\sigma\, f\left(\frac{a}{W}\right) \tag{9}$$

where *f(a/W)* is the compliance function, that is specified in the standard, and $\Delta\sigma$ is the applied stress range. For the CT geometry $\Delta\sigma$ assumes the following form:

$$\Delta\sigma = \frac{\Delta P}{BW^{1/2}} \tag{10}$$

where ΔP is the applied load range, B and W define, respectively, the thickness and the nominal width of the specimen.

5. Results and discussion

Table 1 summarizes the experimental program carried out in order to derive the *da/dN versus* ΔK for the base material, heat affected zone, and welded material. The stress ratios tested were R=0.1 and R=0.5. It was verified that for some tests, namely for tests performed with welded material, the crack deviates from the ideal shape, namely it was observed a divergence between the crack on the two faces of the specimen. This phenomenon can be explained by the following factors: misalignments, asymmetrical disposition of the welding or existence of inclusions, oxides or porosities in the welding.

Table 1. Experimental program (S.Ribeiro, 1994).

Material	**Specimen Nº.**	**R**	**Frequency [Hz]**	**Maximum load [N]**	**Minimum load [N]**	**Number of cycles**
Material Base	2 - BM	0.1	15	3676.8	367.6	603500
	3 - BM	0.5	15	8372.7	4186.3	68000
Welded Material	1 - WEL	0.1	15	3231.0	323.1	1800400
	3 - WEL	0.1	15	3600.0	360.0	1028700
	2 - WEL	0.5	15	6205.5	3102.7	296300
HAZ	1 - HAZ	0.1	15	29652	296.52	129840
	2 - HAZ	0.5	15	4688.2	2344.1	117200

The evaluation of the fatigue crack propagation rates was made through the polynomial method that is referred in the ASTM E647-82 standard. Figures 4 to 6 represent the *da/dN versus* ΔK curves for the base material, welded material and heat affected zone and for stress ratios R=0.1 and R=0.5, respectively. The results correspond to the region II, region of validity of the Paris's law. Figures 7 and 8 compare the propagation curves for the three tested materials. It can be concluded that the propagation rates increase with the increase of R. This influence is more significant for low values of ΔK. R influences the crack propagation curves for the three materials but its influence is more significant for the base material. The HAZ shows low sensitivity to the stress ratio. It can be observed that HAZ presents the greatest propagation rates for R=0.1. The propagation rates of the welded material present intermediate values between HAZ and the base material. Tests conducted with R=0.5 do not show significant differences in the propagation rates for the three materials. The factors that justify these results are several. Among them it can be referred the elevated levels of residual stresses at the crack tip, the effect of the stress ratio, the yield stress and the grain size that is distinct for three materials. Finally, the Fig. 9 represents all the curves obtained for the several materials and stress ratios.

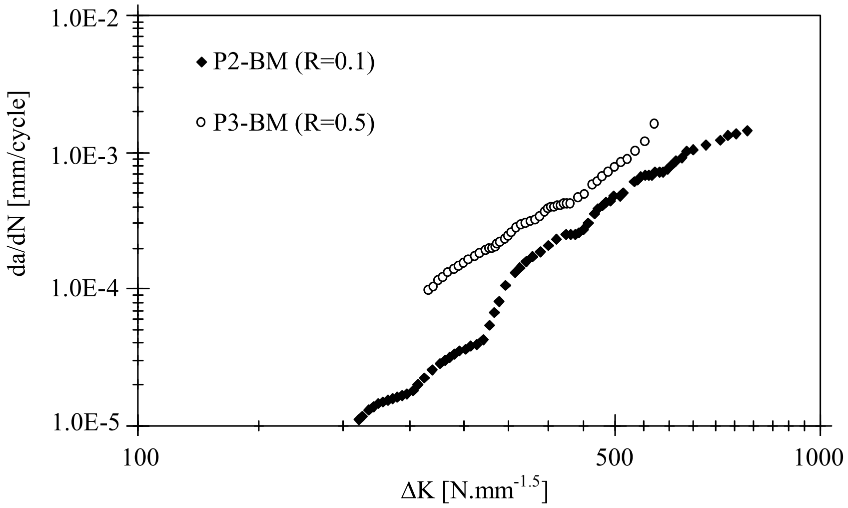

Figure 4. Fatigue crack propagation rates of the base material for R=0.1 and R=0.5.

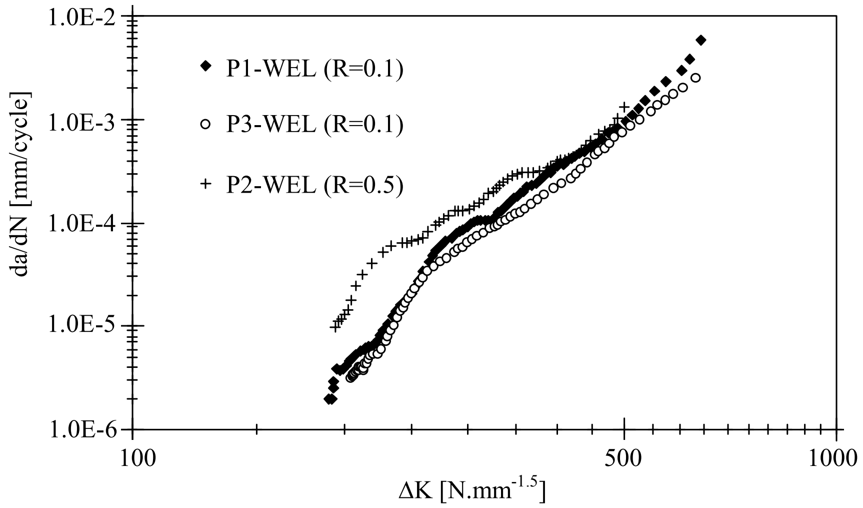

Figure 5. Fatigue crack propagation rates of the welded material for R=0.1 and R=0.5.

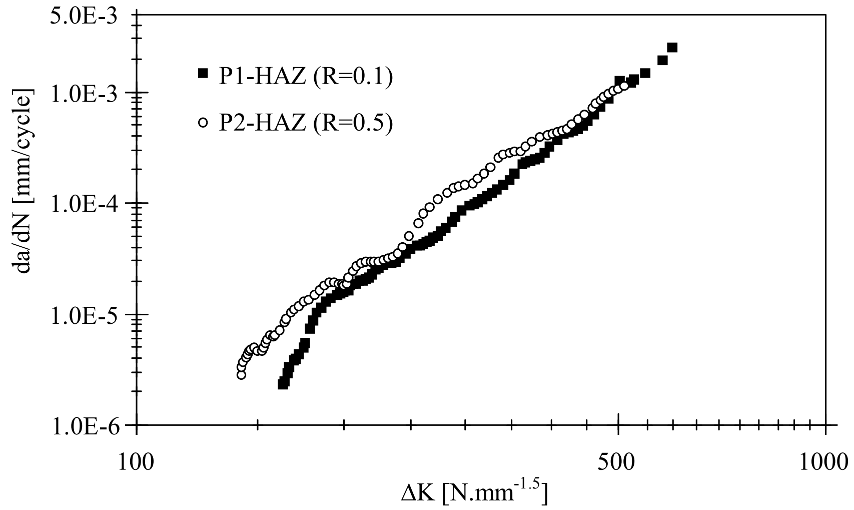

Figure 6. Fatigue crack propagation rates of the heat affected zone for R=0.1 and R=0.5.

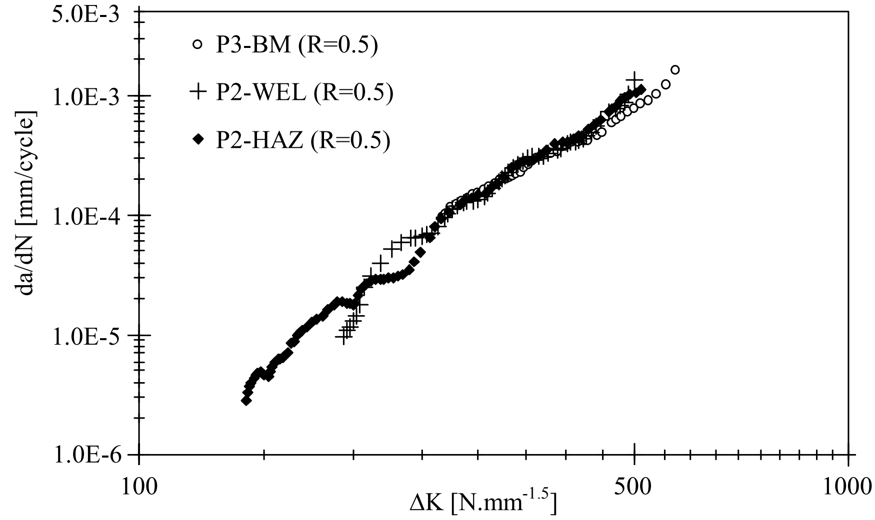

Figure 7. Fatigue crack propagation rates of the base material, welded material and heat affected zone for R=0.5.

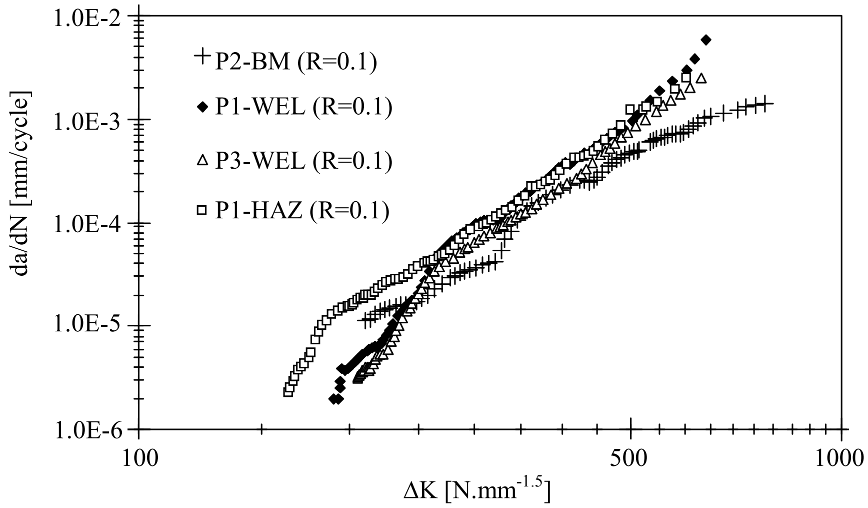

Figure 8. Fatigue crack propagation rates of the base material, welded material and heat affected zone for R=0.1.

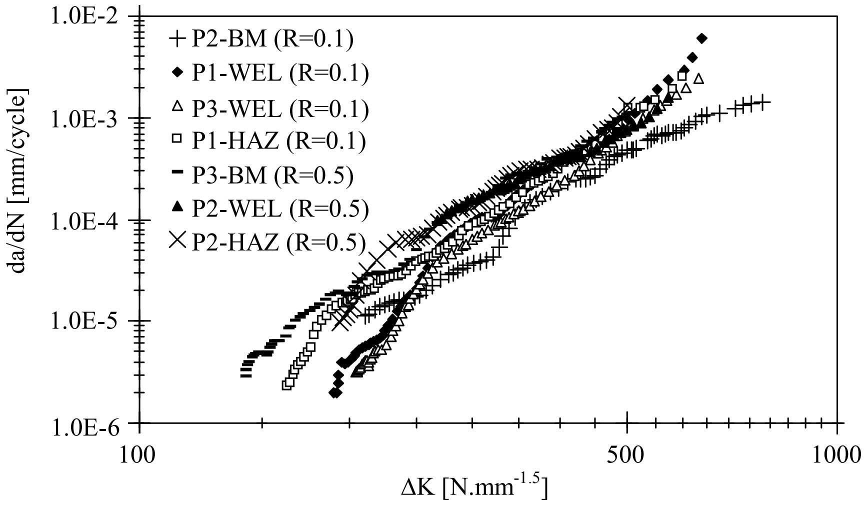

Figure 9. Fatigue crack propagation rates of the base material, welded material and heat affected zone for R=0.1 and R=0.5.

The values of the coefficient of the Paris's law are listed in the Tab. 2 for the three materials and for the two stress ratios, R=0.1 and R=0.5. The correlation factors for the adjusted curves are considerably high.

Table 2-Constants of Paris's law of the tested materials.

Material	R=(min/max)	da/dN = C.(ΔK)^m			R^2
		C *	C * *	m	
BM	0.1	1.9199E-15	3.7086E-12	4.1908	0.9822
BM	0.5	1.2863E-12	9.8151E-11	3.2547	0.9912
WEL	0.1	6.5017E-20	6.7761E-14	6.0120	0.9731
WEL	0.5	1.9094E-15	6.7566E-12	4.3657	0.9639
HAZ	0.1	1.1363E-16	1.7580E-12	4.7932	0.9863
HAZ	0.5	8.7433E-16	4.8669E-12	4.4972	0.9930
BM	0.1;0.5	1.3790E-14	1.0619E-11	3.9242	0.8592
WEL	0.1;0.5	4.5939E-19	1.6769E-13	5.7082	0.9249
HAZ	0.1;0.5	5.4406E-16	3.6208E-12	4.5489	0.9770
BM; WEL; HAZ	0.1	3.2668E-17	8.3120E-13	4.9371	0.9314
BM; WEL; HAZ	0.5	2.0587E-15	6.7596E-12	4.3444	0.9835
BM; WEL; HAZ	0.1; 0.5	2.6567E-16	2.2733E-12	4.6217	0.9039

* da/dN (mm/cycle) and (K (N.mm-1.5)

* * da/dN (m/cycle) and (K (MPa.m0.5)

6. Conclusions

The described experimental program consisted on the evaluation of the fatigue crack propagation behaviour for aluminium alloy 6061-T651. The tests were made for three conditions of the material: base material, welded material and heat affected zone. Two stress ratios, namely R=0.1 and R=0.5, were considered on the experimental program. Based on the present study the following conclusions can be drawn:

1 - The influence of R was more significant for the base material than for the other two materials. Tests made at HAZ showed lower influence of the stress ratio on the propagation rates. The influence of R increases when ΔK decreases.

2 - Tests made in HAZ, for R=0.1, presented the highest propagation rates. The base material presented the lowest propagation rates. For R=0.5 no significant differences were observed in the fatigue cracks propagation rates between the three materials.

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