DAMAGE TOLERANCE STUDY OF AN ASTM 148-90-60 STEEL CAST RAILWAY COMPONENT

ESTUDO DA TOLERÂNCIA AO DANO DE UM COMPONENTE FERROVIÁRIO EM AÇO ASTM 148-90-60

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ABSTRACT

In this paper, fatigue life extension results of a cast steel ASTM A148 90-60 of railway couplings, used in service in Portugal for coal transportation, resorting to two crack growth relationships, Paris equation and modified Paris equation, are presented and discussed. Fatigue lives were obtained in terms of the threshold value and it was possible determined for both crack growth relationships significant crack extension lives. Therefore for these components and in this application damage tolerant procedure can be used with safety and this component can be kept in service provided appropriate inspection procedures are applied to detect and measure fatigue cracks. This proceeding will avoid early retirement from service of these components, since extension life can be assumed with safety.

RESUMO

Neste artigo, são apresentados e discutidos resultados de extensão de vida à fadiga para um componente ferroviário de aço vazado ASTM A148 90-60, usado no acoplamento da locomotiva à primeira carruagem recorrendo a dois modelos de propagação de fissuração, equação de Paris e a equação de Paris modificada. A vida à fadiga é obtida em termos de valor limiar de propagação e é possível determinar extensões de vida significativa. Portanto para estes componentes a tolerância de dano pode ser usada com segurança e consequentemente estes componentes podem ser mantidos em serviço providenciando procedimentos de inspeção para deteção e medição de fissura. Este procedimento evitará que os componentes sejam retirados prematuramente de serviço, economizando recursos.

1. INTRODUCTION

In 1961, Paris, Gomez and Anderson (1961) suggested the relation between the crack extension per cycle (da/dN) with the maximum stress intensity factor K_{max}. Subsequently, Liu (1963) work implied that the crack growth was a function of the stress intensity factor range $\Delta K = K_{max} - K_{min}$. Also, Paris and Erdogan (1963) proposed a similar relationship known as Paris equation, Eq. (1).

$$\frac{da}{dN} = C\left(\Delta K\right)^m \qquad (1)$$

where a, is the crack size, N is the number of cycles, ΔK is the stress intensity factor range, and C and m are coefficients related to material property experimentally determinate.

The relationship between crack growth per cycle and ΔK has three distinct regions: region I where the crack growth is slow and several authors have introduced the concept of a fatigue threshold stress intensity factor range, ΔK_{th}; region II is the region of Paris equation and its variants, is thought to hold; and region III, associated with rapid crack growth, tearing or static modes. For stage II, Paris' law in Eq. (1) works correctly, up to deviations in region III, which in turn depend strongly on the R-ratio since the fracture mode becomes essentially static and governed by the maximum value of the stress intensity factor. The curve exhibits a rapidly increasing growth towards ductile tearing and/or brittle fracture, and a possible transition curve was proposed first by Foreman et al. (1967).

The coefficients C and m are both random variables. In 1987, Ichikawa has reported that m and logC are normally distributed and there is a strong negative correlation between them, (Ichikawa, 1987).

A review of the controversial views on the correlation between coefficient and exponent in the power law equation of fatigue crack growth was studied by Bergner (2000). It is shown that the correlation is an algebraic one that can be suppressed by choosing a particular scaling factor characteristic of the set of materials under investigation. The approach allows the variability of the power law coefficient to be quantified more clearly and the responsible influence factors to be identified.

Crack growth rate has become an important material property for characterizing fatigue crack propagation. From the viewpoint of probabilistic fracture mechanics, the scatter of crack growth rate should be taken into account in it statistic.

Over the years the relationship, Eq. (1), has continued to be modified to account for a variety of observations, including R ratio, K_{max} effects and crack closure, (Schijve, 2003).

The objective of the current work is to analyse the two crack growth rate relationships: the Paris equation and a modified Paris equation with the appropriate value of the threshold for crack propagation ΔK_{th}. To this end, an improved direct current potential drop (DCPD) technique is employed to measure fatigue crack initiation and propagation. The material analysed in the present research is ASTM 148 90-60 cast steel, used in railway couplings. To characterize the fractography over the whole range ΔK, fracture surfaces were prepared for examination, using scanning electron microscopy (SEM).

Methodology of statistic data treatments are discussed in detail. At the end are presents the results of a damage tolerance analysis of these components. A comparative analysis of the results is presented using experimental values obtained for the same material in service for the reliability value of 95% in similar conditions.

2. EXPERIMENTAL DETAILS

2.1. Material and test specimen

As was said before, an ASTM 148 90-60 cast steel, used in railway couplings of freight is used in this study (Morgado et al., 2007). Conventional mechanical proprieties are reported in Table 1, together with the parameters of the cyclic curve (Infante et al., 2003).

The specimens were of a single edge notched bend type, with dimensions of 20 mm of width, 10 mm of thickness, 100 mm of length and 1 mm of pre-crack (BS 5447:1977 (1987)). The six specimens (Fig. 1) used in experimental procedure were taken from one of the supplied couplings (Fig 2).

Table 1 - Conventional and cyclic mechanical properties for ASTM 148 90-60 cast steel

Ultimate stress, UTS [MPa]	651.03
Monotonic yield stress, $\sigma_{p0.2}$ [MPa]	463.95
Elastic modulus, E [GPa]	207
Elongation at failure, A [%]	28.5
Reduction area, q[%]	47.9%
Cyclic yield stress, σp0.2cyc [MPa]	348
Hardening exponent, n	0.177
Hardening coefficient, k′ [MPa]	1089

2.2. Experimental procedure

Fatigue crack growth tests were performed general according with ASTM standard E647-05. The bending in three points tests

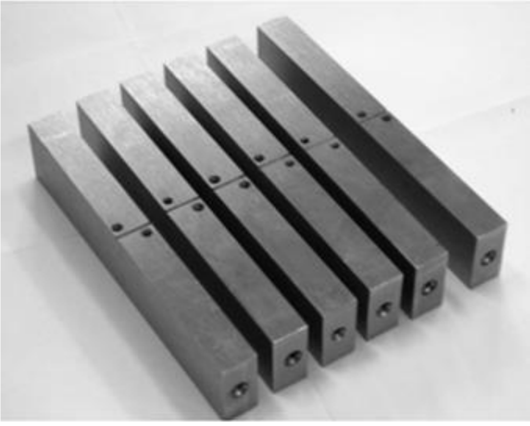

Fig. 1 - Six test specimens.

Fig. 2 – Cut zone in the railway coupling.

were carried out for a stress ratio of R=0.1, with test temperature and relative humidity recorded but not controlled beyond the room laboratory condition. The cyclic test frequency varied between 10-20 Hz, and the load wave was sinusoidal.

A potential drop technique was used for crack propagation monitoring purposes using a direct current potential drop (DCPD) pulsed system (Morgado, 2009) coupled with the controller of the servo hydraulic Dartec M1000/RK testing machine with a capacity of ±100 kN. In Fig. 3 is presented the tests rig.

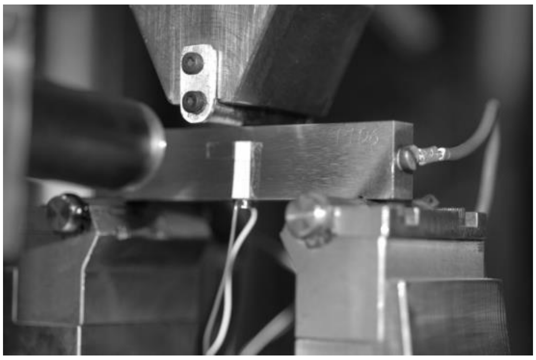

Fig. 3 - Test rig

During the tests the loading frequency conditions were changed to produce visible marks on the fracture surface which enable the identification of crack shapes (Fig. 4). For data treatment, 7 points were used along the thickness direction (10 mm), whose position was obtained with the MAXTSCAN coordinate table.

Fig. 4 – Marks on fracture surface.

2.3. Fracture surface examination

Fracture surfaces were prepared for examination using scanning electron microscopy (SEM S-2400 Hitachi), to characterize the fractography over the whole range of ΔK. This permitted direct comparison of the fracture surface features at values of da/dN and ΔK in the near threshold, intermediate ΔK, and high ΔK/overload regions for each specimen tested.

Figures 5 to 7 shows SEM fractographs for the fracture surface morphology of the cast steel ASTM148 90-60 at different values of ΔK.

The analysis allowed identifying fatigue striation direction of the crack growth (Fig. 5).

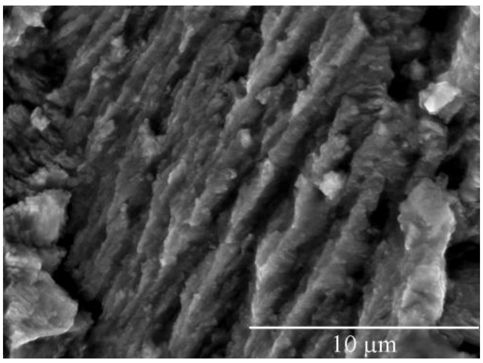

Fig. 5 - SEM fractography; near threshold, ΔK=18.43 MPa$\sqrt{m}$

It is possible also observe portions of the composed surface for alveolar cavities with origin in the cleavage of well visible micro cavities on Fig. 6; deep secondary cracks called intergranular crack propagation and transgranular cleavages in the zone of crack progression can also be observed in this figure.

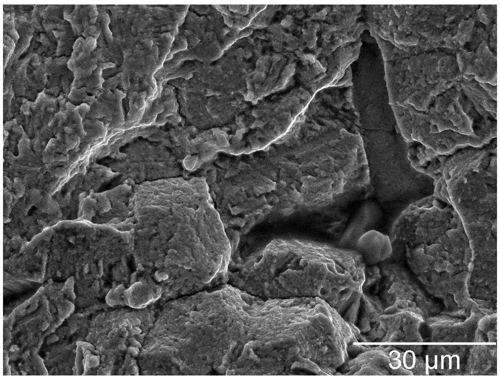

Fig. 6 - SEM fractography; Paris law regime $\Delta K = 21.31\ MPa\sqrt{m}$

On progressing from the threshold region up through the Paris Law regime and into the overload regime, there was a consistent increase in the amount of cleavage fracture on the fracture surface, as shown in Fig. 5 to 7, respectively. These morphological characteristics are typical of fatigue fracture surfaces (Hertzberg, 1989; ASM Handbook).

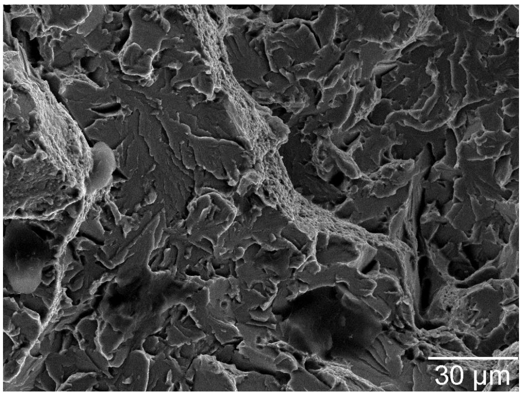

Fig. 7 - SEM fractography; high $\Delta K = 49.5\ MPa\sqrt{m}$

2.4. Presentation and analysis of experimental results

The calibration curves relate crack size with PD measurements taken near the crack (Morgado, 2009). From calibration curves determined experimentally for each specimen, the propagation curves were obtained (a versus N). After that, for different crack lengths, values of ΔK were obtained.

The stress intensity factor range, ΔK, was calculated according to following Eq. (2).

$$\Delta K = f\left(\frac{a}{w}\right) \times \Delta\sigma\sqrt{\pi a} \qquad (2)$$

$f\left(\frac{a}{w}\right)$ is the geometric factor (Branco, 2006), and $\Delta\sigma = \sigma_{max} - \sigma_{min}$ is the stress range.

The da/dN curves were obtained for all the specimens tested. Secant method was used to calculated da/dN. The number of points used to calculate da/dN using the secant method depended in the quality of the DCPD data, number of points collected and crack propagation speed. The maximum number of points used to calculate da/dN was 13 (Morgado, 2009).

From the viewpoint of probabilistic fracture mechanics, the scatter of crack growth rate should be taken into account. In Fig. 8 the propagation curve (regimes I and II) of an individual specimen can be observed.

3. PROBABILISTIC MODELS OF EXPERIMENTAL DATA

3.1. Paris Law Parameters

Tests when there is scatter in the results

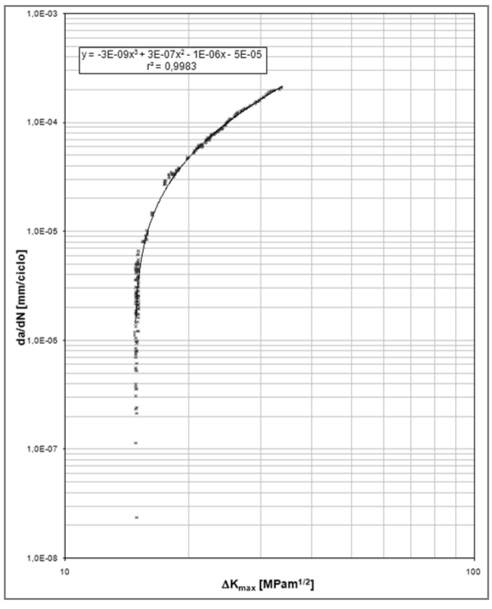

Fig. 8 - PT06 specimen propagation curve

require a proper statistical treatment. For the purpose of abbreviation the following notation is introduced: X=log (ΔK) and Y=log (da/dN). The geometric represent-tation of the Paris equation is a straight line, given by the expression, Eq. (3), where a= log(C) and b=m must be estimated from the data points $((da/dN)_i, (\Delta K)_i)$, i=1,2,….,n.

$$Y=a+bX \tag{3}$$

Log-normal life distribution can be used to determine any probability of failure, P_f. The probability of survival, is defined by Eq. (4)

$$P_s = 1 - P_f \tag{4}$$

Figure 9 represents the Paris Law for reliabilities of 95%, 90%, %50%, 10% and 5%. The slope of the propagation curve was obtained for the $\Delta K = 23MPa\sqrt{m}$ and $\Delta K = 32MPa\sqrt{m}$.

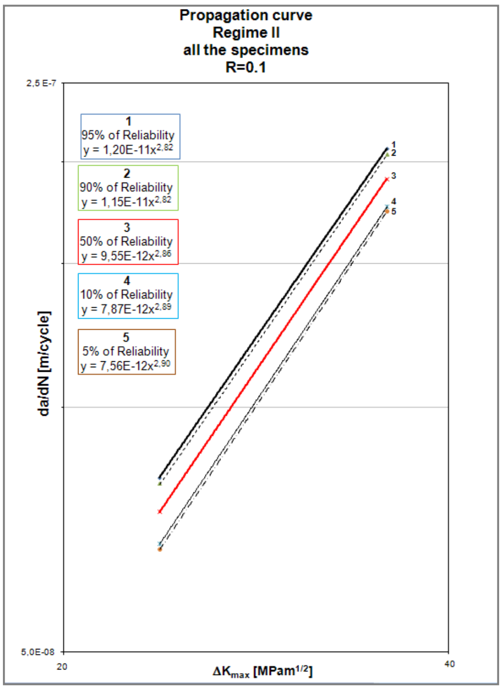

Fig. 9 - Present the da/dN vs ΔK curve (Paris Law), obtained from a set of raw data given for treatment of different reliability

3.2. Paris Law Modified Parameters

Reliability fatigue analysis in these couplings railway, has been conducted Morgado (2009), where strain gauge data were analysed and from those data fatigue cycles were derived. The data acquisition was carried out in the most severe predefined journeys in terms of load levels. Continuous acquisition of strain gauges rosettes measurements was carried out over 48 km in two journeys (loaded and empty wagons), Morgado (2007). The coupling between the locomotive and the first wagon was selected where higher loads were expected. These components are subjected to characteristic variable amplitude load sequences which have to be account; the stress ratio versus number of accumulated cycles of fatigue diagram for the most critical rosette showed that for a total of 13909 accumulated cycles, 75% of accumulated cycles had a stress ratio higher than 0.8, Morgado et al. (2009).

To attend to the influence of R ratio effect the following well known, generalized Paris´ law is taken into account (Eq. (5)).

$$\frac{da}{dN} = C_0\left(\Delta K - \Delta K_{th(R=0)}\right)^{m_0} \tag{5}$$

Considering the conservator experimental value of threshold of $\Delta K_{th(R=0.1)} = 14.02MPa\sqrt{m}$ and using the Eq. (6) with R=0.8, the parameters C_0 and m_0 of Paris modified law are obtained.

$$\Delta K_{th(R)} = \Delta K_{th(R=0)}\left(1-R\right) \tag{6}$$

In figure 10 are represented the propagation curves for reliabilities of 95%, 50% and 5% with the respectively C_0 and m_0 material constants.

From Fig. 9 and 10, considering reliabilities of 95%, Paris Law (Eq. (7)) and Modified Paris Law (Eq. (8)), were obtained.

$$\frac{da}{dN} = 1.20E-11\left(\Delta K\right)^{2,82}\left[m/cycle; MPa\sqrt{m}\right] \tag{7}$$

$$\frac{da}{dN} = 1.11E-11\left(\Delta K\right)^{2,97}\left[m/cycle; MPa\sqrt{m}\right] \tag{8}$$

4. RESULTS

Results of residual life are presented in Figure 11. These curves were obtained for 95% of reliability propagation curves by Paris and modified Paris laws.

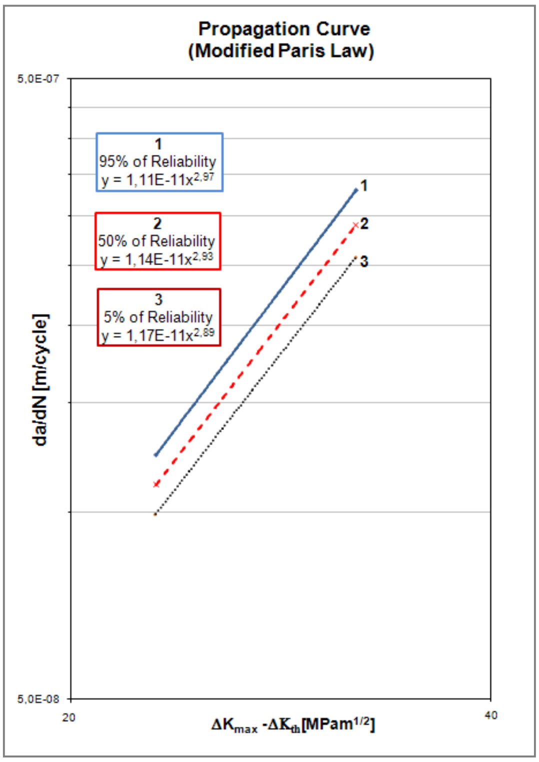

Fig. 10 - da/dN vs ΔK curve for Modified Paris Law, obtained from a set of raw data given for treatment of different reliability.

The residual life results in crack propagation from initial defect size of 0,8mm, located at the radius of curvature between the head and main body of the coupling of the locomotive with the first carriage of the freight train used to carry coal, have shown that:

- 10000 cycles, is the value of fatigue life for crack propagation obtained with the modified Paris law.
- 55000 cycles, is the value of fatigue life for crack propagation obtained with the Paris law.

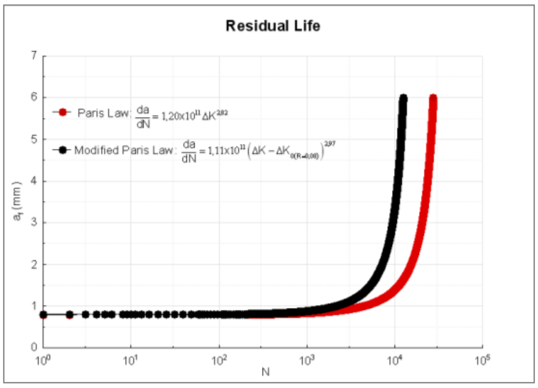

Fig. 11 -Residual life for fatigue crack propagation.

5. CONCLUSIONS

For safety, it is recommended by author to use the Modified Paris Law; which incorporates the threshold value of the stress intensity factor, ΔK_{th}, for the appropriate value of the stress ratio, R, taking into account the load spectra.

The results have shown also that a satisfactory prediction of fatigue life can be made in these components, taking into account a damage tolerance phase with a prediction for crack propagation, obtained with a Modified Paris Law relationship incorporating the threshold value for crack propagation. This will avoid unnecessary retirement of service at the onset of crack propagation when the results have shown that there still a significant residual life for crack propagation that can be appropriately used to extend with safety the life of these components provided adequate inspection procedures are carried out.

Nevertheless, the results of Paris Law can be used with careful and new inspection intervals for damage tolerance between 10000 cycles until 55000 cycles. For this solution, the author recommends that these intervals should be stricter.

6. REFERENCES

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