# FATIGUE CRACK GROWTH AND CLOSURE BEHAVIOUR OF PRESSURE VESSEL C-Mn WELDED STEELS

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An experimental study was carried out to identify the fatigue behaviour of both base metal and butt weld metals of C-Mn pressure vessel plates. Results show that specimens from the weld metal exhibit for higher $\Delta K$ values greater crack propagation rate values than the base metal. Fractographic analysis evidences the presence of ductile static voids nucleated at inclusions together with striations in the weld metal. Values of m exponents in Paris equations are compared with different damage accumulated models considering the Coffin-Manson and Basquin coefficients determinated from LCF tests for both materials.

## INTRODUCTION

Pressure vessels made of A515 G70 steel are mainly used in thermal power stations. In this material, the risk of brittle fracture is extremely remote but ductile failure can occur caused by processing of weld defects. Fatigue is also a failure mode to take into account since pressure variations, although at low frequencies, are likely to exist. In the present work the fatigue behaviour of A515 G70 steel is analysed. The main parameters that have been studied are: level of prestraining in the plate material as defined by the shell different curvature, microstructure heterogeneities, specimen orientation (TL and LT) and crack propagation in the weld metal.

## MATERIAL AND EXPERIMENTAL PROCEDURE

The material used was a A515 grade 70 steel, a C-Mn steel applied in pressure vessels for thermal power stations. The material has been supplied

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by Mague (Portugal) as curved shell discs with the same nominal thickness (165 mm) and curvature (1500 mm inner diameter) than the vessel. Two half-discs were butt welded longitudinally by the submerged arc process and after that the material was stress relief treated .

The base material (0,22%C, 1,21%Mn, 0,030%P, 0,004%S) has a ferritic-pearlitic structure ($D_\alpha$=10,6 $\mu$m, $D_{pearlite}$ =6 $\mu$m, %pearlite=22%, $\sigma_{YS}$=318 MPa, $\sigma_{TS}$=633 MPa). The weld metal (0,085%C, 1,90%Mn, 0,012%P, 0,23%Si, 0,009%S, 0,45%Mo, $\sigma_{YS}$=417 MPa, $\sigma_{TS}$=824 MPa) is constituted by a ferritic matrix with a very fine carbide precipitation.

Differently oriented (LT and TL) standard CT specimens (W= 50 mm and B= 12 mm) were machined from different thickness levels with the notch placed at the base metal and at the weld metal. Fatigue crack growth testing was performed using a servohydraulic fatigue testing machine under load control in laboratory air. Constant load tests were performed at three different load ratios: 0,03, 0,3 and 0,5. Threshold values were measured using a manual load shedding technique. Crack closure measurements were made from unloading elastic compliance curves at each $\Delta$K level employing the Kikukawa procedure (1). Fracture surfaces were examined at a SEM.

## RESULTS AND DISCUSSION

The da/dN versus $\Delta$K curves corresponding to the base metal are shown in Fig. 1 for different R values. There is a strong influence of R on crack propagation in the threshold region, as it has been repeatedly reported. For da/dN $>10^{-8}$ m/c, there is a little influence of R for $\Delta$K values lower than 20 MPa$\sqrt{m}$. This different behaviour appears too in the m values of the Paris exponent equation (for R=0,03 m=3,9 and for R>0,3 m = 3).

The behaviour of the weld metal is shown in Fig. 2. In this case, in the Paris zone the difference between specimens tested at R=0,03 and R>0,3 is more evident than in the base metal. Values of m exponent range from 3,7 for R = 0,03 to 3,4 for R=0,5. By the other way, different orientations (LT and TL for base metal) and locations in the shell (C(center), S(high) and I(low) levels) do not introduce any atypical behaviour in crack propagation (see Fig. 1 and Fig. 2).

The effect of R on the Paris zone can be corrected taking into account the crack closure behaviour. For the base metal data, differences completely disappear after considering $\Delta K_{eff}$ instead $\Delta K$, but for the weld metal (Fig. 3), differences subsist between $R=0{,}03$ and $R>0{,}3$ for $\Delta K>20$ MPa$\sqrt{m}$, values for which there is not crack closure. If plasticity induced closure is not the predominant effect (the influence of R is not higher for higher $\Delta K$ values as it would be expected), roughness or particle induced closure must be considered. Evidence of presence of these two types of mechanisms has been shown by Schijve (2) and Allison et al. (3). On the other hand, considering the model proposed by Beevers and Carlsson (4) to quantify the closure originated by the presence of asperities, a particle of 1$\mu$m thickness placed at a 120$\mu$m distance from the crack tip would be sufficient to originate 3 MPa$\sqrt{m}$ closure value. So, the effect observed at $R=0{,}03$ in the base metal and in the weld metal up to 20 MPa$\sqrt{m}$ can be related to roughness or asperity induced closure.

Comparing jointly base metal and weld metal results and considering 95% confidence limits scatter bands, the fatigue behaviour is similar in both cases for $R=0{,}03$ (Fig. 4a). On the contrary, crack propagation for $R=0{,}5$ is higher in the weld metal, being the differences more evident for higher $\Delta K$ values (Fig. 4b). Fractographic analysis in base metal specimens evidences that the fracture is completely flat and amorphous. In contrast, in the weld metal specimens, together with striations there are static voids nucleated at inclusions or carbides (Fig. 5). For $\Delta K$ lower than 20 MPa$\sqrt{m}$, void volume fraction is very low (lower than 2%), but for $\Delta K=30$ MPa$\sqrt{m}$ it increases up to 7%, and saturates for higher $\Delta K$ values. If the voids are nucleated at the crack tip process zone, crack propagation would be easier, driving to higher macroscopic da/dN values. If the presence of the static voids is comparable to the fatigue behaviour of a porous material, it is possible to consider the modified Paris equation proposed by Bompard and François (5):

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{D^{m+1}}$$

where D is the relation between the effective area and the total area. The new m exponent value diminishes (m=3) and the difference between base metal and weld metal practically disappears.

Fig. 6 corresponds to threshold data plotted against R. The two different microstructures (base metal and weld metal), orientation and thickness shell level do not seem to have a decisive influence in $\Delta K_{th}$. In the same figure, $\Delta K_{theff}$ values are introduced, showing that for the two materials an effective threshold between 3,5 and 5 MPa$\sqrt{m}$ can be considered.

Fatigue crack propagation in the Paris zone has been studied considering different models proposed in the bibliography. Some of these models need the knowledge of the material cyclic behaviour. In Table 1 previously determined results (6) corresponding to cyclic stress-strain curves and LCF Basquin and Coffin-Manson equations are reported. In Table 2 m experimental values are compared with calculated theoretical data. When a CTOD-based model is assumed (m=2), differences in da/dN between experimental and theoretical values are important. Taking into account accumulated damage-based models, following the Antolovich et al. (7) proposed model (m=2/c) or following Kujawski and Ellyin (8) (m=2/(b+c)) m data closer to experimental values are obtained. For the two models, C Paris equation constant includes a "process zone" coefficient. Nevertheless, the best fit of the experimental data obtained in this work allows to process zone sizes which do not correlate with microstructural parameters.

## ACKNOWLEDGMENTS

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Table 1 Coefficients of Hollomon, Basquin and Coffin-Manson equations

| Material | Hollomon | | Basquin | | | Coffin-Manson | | |
|---|---|---|---|---|---|---|---|---|
| | $k'$ | $n'$ | $\sigma_f'/E$ | b | r | $\varepsilon_f'$ | c | r |
| B. Metal | 867 | 0,158 | $3{,}77.10^{-3}$ | 0,086 | 0,953 | 0,566 | 0,553 | 0,992 |
| W. Metal | 806 | 0,114 | $3{,}27.10^{-3}$ | 0,053 | 0,971 | 1,633 | 0,709 | 0,998 |

Table 2. Experimental and predicted m values for base metal and weld metal.

| Material | $m_{exper.}$ | CTOD | 2/c | 2/(b+c) |
|---|---|---|---|---|
| Base Metal | $2{,}91 \pm 0{,}06$ | 2 | 3,6 | 3,1 |
| Weld Metal | $3{,}00 \pm 0{,}06$ | 2 | 2,8 | 2,6 |

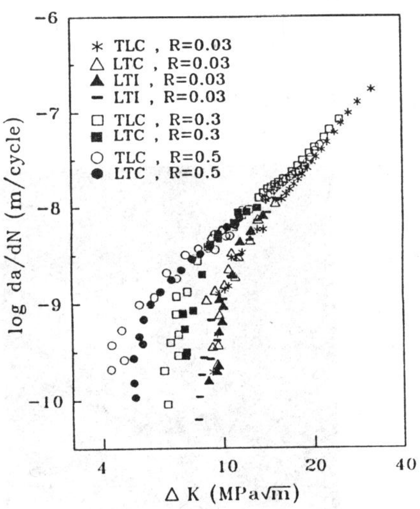


Fig. 1 Crack propagation data for base metal

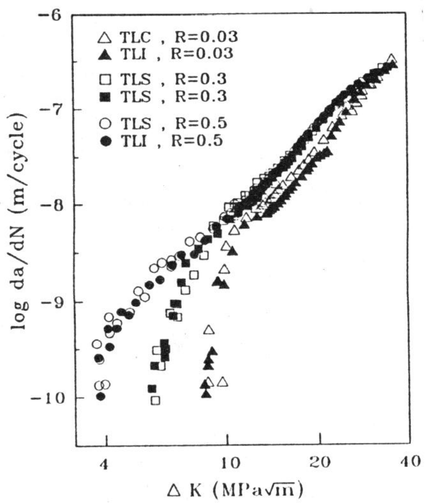


Fig. 2 Crack propagation data for weld metal

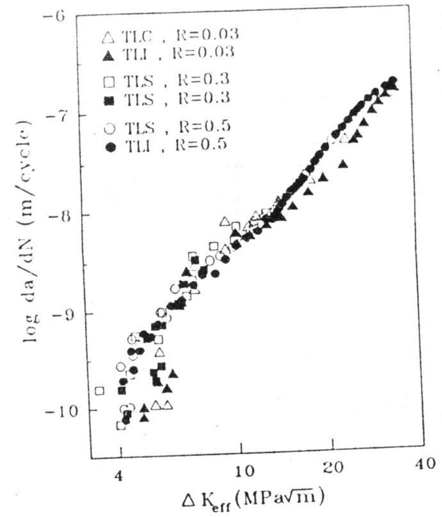


Fig. 3 da/dN versus $\Delta K_{eff}$ for weld metal

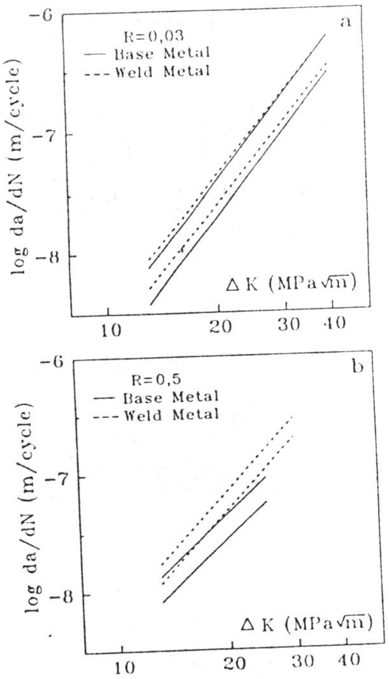


Fig. 4 Scatter bands (95% c.l.) of crack growth results

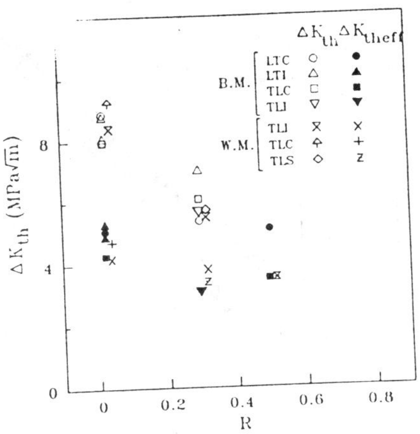


Fig. 6 Threshold $\Delta K_{th}$ and $\Delta K_{theff}$ values as a function of R.

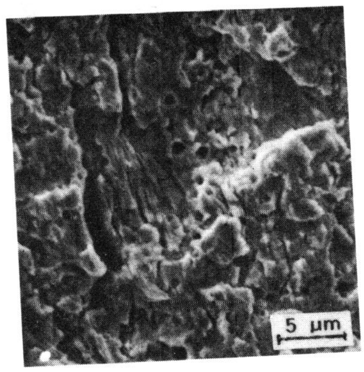


Fig. 5 Mixed voids and striations in weld metal ($R=0{,}5$, $\Delta K = 32$ MPa$\sqrt{m}$)