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EFFECT OF RESIDUAL STRESSES ON FATIGUE CRACK PROPAGATION AT ROOM TEMPERATURE IN A FERRITIC-AUSTENITIC WELDED JOINT

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ABSTRACT

Dissimilar ferritic-austenitic welded joints present in several nuclear reactor components are frequently subjected to fatigue.In this context we have measured the fatigue crack growth rate in a ferritic-austenitic welded plate using compact tension specimens.

The most significant observation made is an important decrease of the crack propagation rate,linked to a high level of crack closure when cracks reach the ferritic-austenitic boundary. The reason for this is shown to be the presence of high residual stresses produced during the welding operation. Measurement of these stresses are made using a hole drilling method modified to allow determination of non-uniform stress fields.This method is based on the existence of a special function called transmissibility function.

From the stress measurement results, first the residual stress intensity factors are derived using a weight function method and then a quantitative crack propagation analysis is performed. The results obtained give a satisfactory explanation to the observed decrease in the crack propagation rate and the crack closure phenomenon.

INTRODUCTION

Ferritic-austenitic welded joints are often found in nuclear reactors where usually the larger components are made with low alloy steels and the smaller components, such as the piping, with stainless steels. The shear size of these junctions makes them on one hand very difficult to fabricate and the other hand prone to formation of complex microstructures [1-3]. Their in service behavior requires a detailed knowledge of the fatigue properties and, in particular, the fatigue crack propagation rate [4-6].

The aim of this paper is to provide such data and show that the crack growth rate is strongly modified in these junctions at the proximity of the weld interfaces and that these changes can be explained essentially by taking into account the residual stresses in the joint.

MATERIALS AND METHODS

Joint Fabrication

The welded joint studied here, (70 mm thick) is a bimetallic junction between Type A533B and Type 316L steel plates.The cladding is applied in a manual process using 20 Cr,10 Ni (309L and 308L) type electrodes in two sequences: the first with preheating at a minimum temperature of 125°C and the second without preheating.

A stress relieve heat treatment after the first sequence is applied. The welding itself is made using an automatic process under solid flux with a 20 Cr,10 Ni (308L) type wire.A final stress relieving heat treatment is carried out for 75 h at 610°C (Fig.1)

Joint structure

The structures of the different materials involved in the joint are as follows:

- A533B base metal: ferritic-bainitic structure (A),
- 309L and 308L cladding and 308L weld metal: dendritic structures (B),
- 316L base metal: austenitic structure with an average grain size of about 150 µm (C), and
- martensitic zone (D): this zone appears during the fabrication of the welded joint due to diffusion of carbon and chromium [1-3]; it is located in the cladding near the interface of the cladding with the ferritic steel.

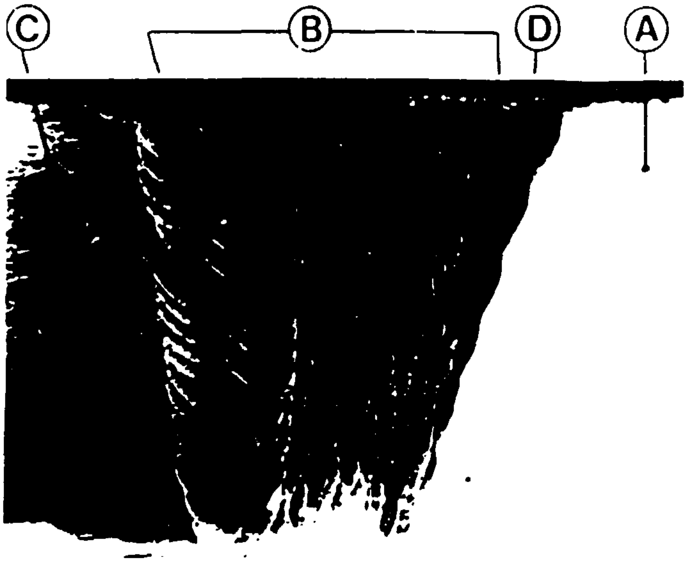

Figure 1. Constitution of the bimetallic junction

Crack propagation tests

Crack propagation specimens used are of CT 50-20 (W= 100 mm, thickness B= 20 mm) type.

Tests are performed at room temperature on servohydraulic fatigue testing machines, in the load controlled manner, at a frequency of 20 HZ and an R ratio of 0.15.

Crack lengths are measured on the two sides of the specimen at the maximum cycle load with an optical instrument.

Residual stress measurements

Residual stress measurements are performed using a hole drilling method modified to allow determination of non uniform stress fields.

The roset disposition is shown in Figure.2

The most important hypothesis used here, is the existence of a special function called transmissibility function, which associates the deformations measured during drilling to the residual stresses at a given depth [7], (Fig.3). This function is determined by performing stress measurements during the hole drilling in plate specimens under tensile loading.

The measured strains at the depth of P=xD (where D is the hole diameter) are ε_1, ε_2 and ε_3.

The corrected strains ε'_1, ε'_2 and ε'_3 at the same depth are given by the following equation:

$$\varepsilon'_i = \frac{\Delta\varepsilon_i\,(x,\ \Delta x)}{\Delta x}\left[\frac{dT(x)}{dx}\right]^{-1}$$

where T(x) is the transmissibility function.

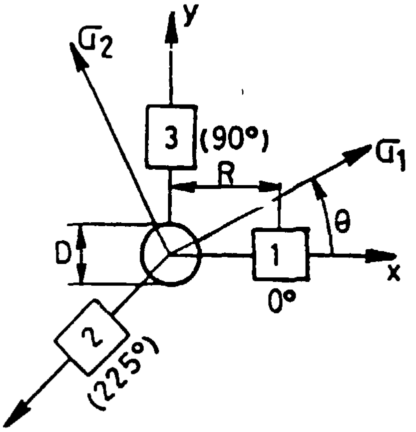

Figure 2. Roset disposition

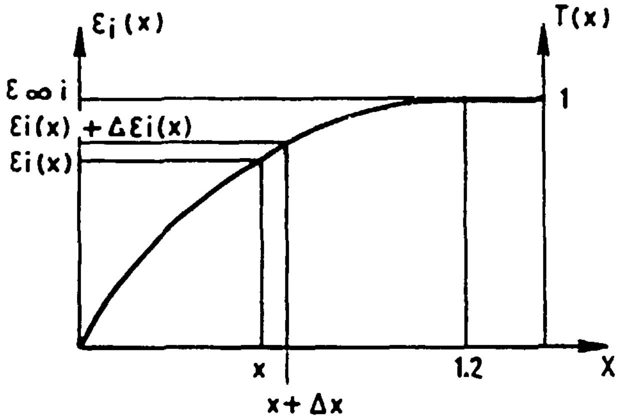

Figure 3. Transmissibility function

Residual stresses are calculated by the following relationships as the classical asymptotic method:

$$\sigma_1 = \frac{S}{4A} + \frac{D}{4B\text{Cos}2\theta}\ ; \quad \sigma_2 = \frac{S}{4A} - \frac{D}{4B\text{Cos}2\theta}\ ; \quad \theta = \frac{1}{2}\ \text{Arctg}\frac{S-2\varepsilon'_2}{D}$$

if:

$$S = \varepsilon'_1 + \varepsilon'_3 \qquad D = \varepsilon'_1 - \varepsilon'_3$$

$$4A = -\frac{1+\mu}{2E}\times\frac{a^2}{R^2} \qquad 4B = -\frac{2a^2}{ER^2} + \frac{3\,(1+\mu)}{8E}\times\frac{a^4}{R^4}$$

Several tests were performed to verify the validity and the reproducibility of the method. Stress measurements were made on samples submitted to tensile (uniform stress field) or bending (non uniform stress field) loads. The results obtained showed that the concept of the transmissibility function was well founded [6].

RESULTS

Fatigue crack propagation results

Two propagation directions have been used. In the first case (transverse propagation), cracks propagate from the ferritic steel, through the ferritic - weld interface. In the second case (longitudinal propagation), cracks propagate in the weld or cladding, in a direction parallel to the the interfaces. The results of the crack propagation tests are shown in Figures 6 and 7 (open captions).

Transverse propagation results obtained showed an important decrease in the crack propagation rate when the crack approached the weld interface. This effect continued to be observed even when the crack propagated through the weld metal.

Specimens tested in the longitudinal direction also exhibited a decrease in the crack propagation rate but the changes were smaller than those observed in the transverse direction. Fractographic examinations of the different specimens showed that the cracks did not remain in the notch-plane and that their propagation rate varied through the thickness. We believe that these changes are due to the residual stress fields mentioned hereabove.

Results of residual stress measurements

The residual stress fields were determined along the longitudinal and transverse crack propagation paths. In the transverse measurements, important variations of the residual stresses were found (figure 4).

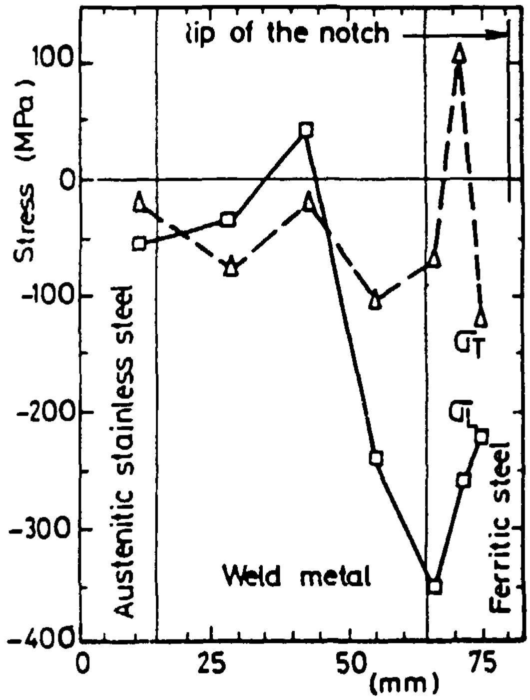

Figure 4. Residual stress profile in the transverse direction.

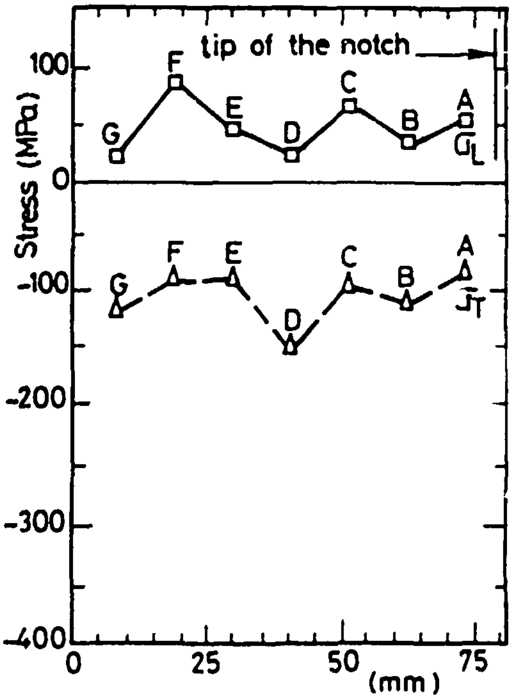

Figure 5. Residual stress profile in the longitudinal direction

These variations were located in the vicinity of the ferritic steel - austenitic cladding interface and for this reason their origin was associated with the differences between the thermal expansion coefficients of the ferritic and the austenitic steels. But the microstructural changes were also considered to be significant as the martensitic transformation occurred near the interface. It may be noticed that in this zone the equivalent stress is greater than 350 MPa and probably very close to the yield stress of the material.

For the transverse stresses which are perpendicular to the interface, positive values were found near the interface, whereas for the longitudinal stresses which are acting along the crack propagation path in the present tests, very important levels of compressive stresses were found in the same area.In the cladding and in the weld, the residual stresses had small values. The austenitic base metal - weld metal interface was found to be a slightly in compression.

Contrary to the transverse measurements which exhibited large stress gradients, the residual stresses in the longitudinal direction were rather constant throughout the weld (Fig.5).

The longitudinal and transverse stresses were found to fluctuate respectively around 50 MPa and 100 MPa. This was in good agreement with the results of the previous measurements carried out in the same area. The absence of a residual stress field gradient indicates that welding is a continuous process and that the residual stresses are only translated along the weld if one stays away from the edges. It is for this reason that a generalizable quantitative approach of the effect of the residual stresses can be made.

DISCUSSION

Qualitatively the compressive stresses found in the two propagation directions explain the observed decrease in the crack growth rate during the different tests. In the case of the transverse propagation, the crack growth rate stays under its normal value even when the longitudinal stresses become positive.

To account for this behavior, the effect of the residual stresses is represented by a stress intensity factor - like parameter, K_{res}. Applying the superposition principle this parameter was calculated, as if the normal to the crack residual stress always acts on the crack lips, which are, in fact, free surfaces with a nil normal stress.

Different weight function methods have been used (Buchalet [8]), (Buckner [9]), (Chell J [10]), and all can be written in the following form:

$$K_{res} = \int_0^a m(x,a) . \sigma_{yy} (x) \, dx$$

where: σ_{yy} (x) is the residual stress normal to the crack propagation path
m(x,a) is the weight of σ_{yy} (x)
a is the crack length

With this formulation, it is possible to combine the effects of the stresses acting along the crack according to the superposition principle. We must note that in fact the chosen weight function methods are applicable in the case of imposed stress loading. Residual stresses are actually generated by incompatible strains leading to a strain imposed loading and so the applicability of the weight function method must be restricted to small amounts of crack propagation, probably less than 0.5 times the size of the ligament. The results of the application of the different methods are very close. As expected, in the case of the transverse propagation, the residual stress intensity factors are negative even when the stresses are positive. A value of about -50 MPa√m is found for the propagation near the α–γ interface.

Neglecting any opening value of K, for fatigue crack propagation we propose to calculate an "effective" ΔK, noted ΔK_{eff}, in the following way [11]:

$$\Delta K_{eff} \equiv K_{max} + K_{res}$$

where K_{max} is the value of the maximum applied K during the test and calculated in the usual manner.

Using ΔK_{eff} instead of ΔK moves the (da/dn, ΔK) plots near the Paris law of each different material of the junction (Figures 6 and 7).

The agreement is good with regards to the hypothesis and the approximations of the different methods used here, but an overestimation of the K_{res} of a few MPa√m is introduced.

A residual stress redistribution which has been measured in some cases may be at the origin of this phenomenon, leading to lower levels of K_{res}.

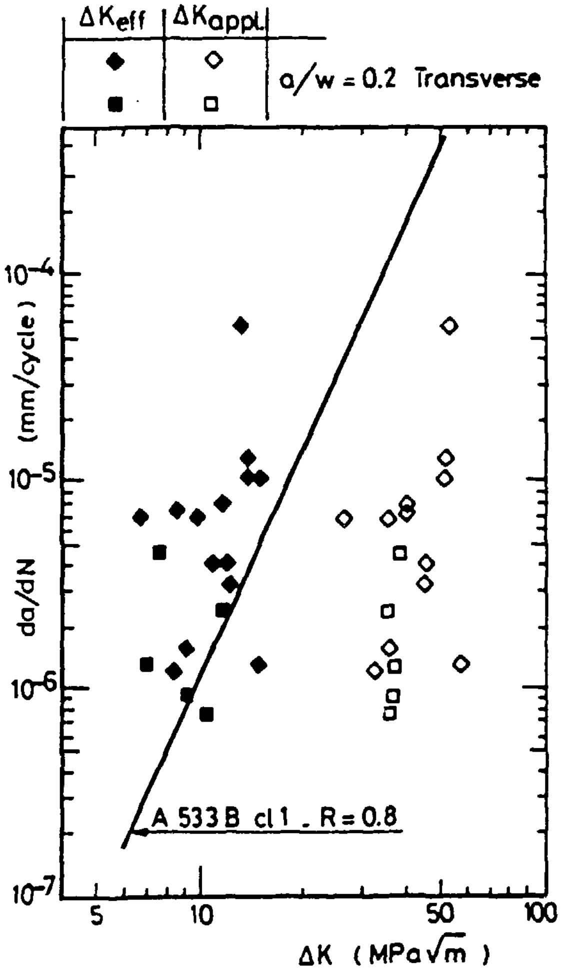

Figure 6. Crack propagation in the ferritic steel using ΔK_{eff}.

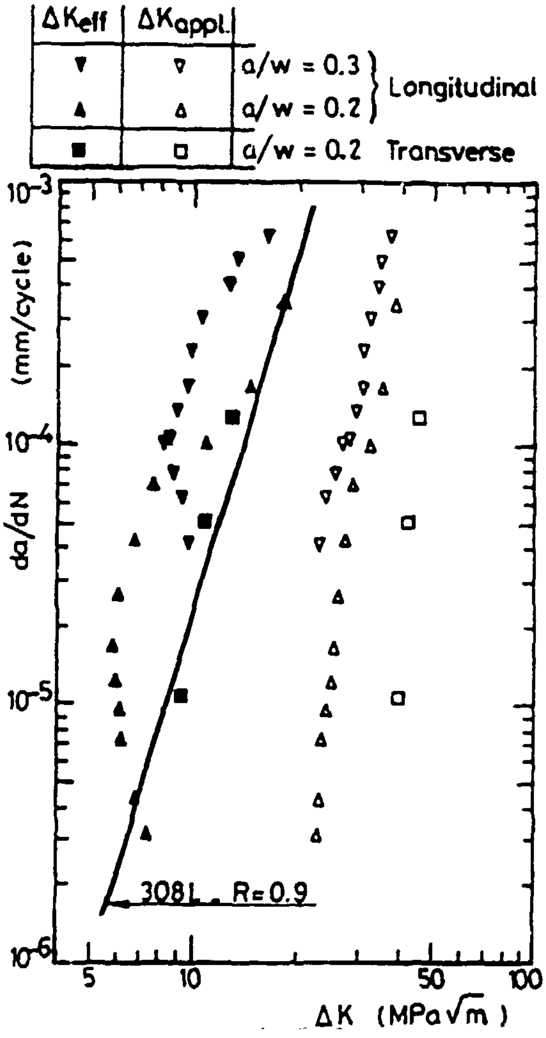

Figure 7. Crack propagation in the cladding using ΔK_{eff}

CONCLUSIONS

Several conclusions can be drawn from this study, the most significant are:

1. Residual stresses can be measured experimentally using a modified incremental hole drilling method in weld junctions with dissimilar metals.
2. The effect of these stresses on the crack propagation rate across the dissimilar junctions can be taken into account through a residual stress intensity factor K_{res} which can be calculated with the weight function methods.
3. In a first approximation, the concept of ΔK_{eff} calculated by the following approximation:

$$\Delta K_{eff} \cong K_{max} + K_{res}$$

permits to show that the crack growth rate in each part of the joint is nearly the same as that observed in each material separately.
4. A more refined analysis of the problem however must take into account three dimensional effects, the evolution of the residual stress profiles through the thickness instead of a mean stress, the real stress intensity factors at each point of the crack front which is in fact 3-D, and the residual stresses in a numeric way instead of a residual stress intensity factor calculated by weight functions.

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