ANALYSIS AND PREDICTION OF RESIDUAL STRESS EFFECTS AS IMPROVEMENT OF THE FATIGUE STRENGTH OF WELDED JOINTS

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Post-weld fatigue strength improvement of welded joints through changing the residual-stress field are still not widely accepted in practice, mainly due to a lack of knowledge about the effect on crack-growth behaviour. This paper examines two residual-stress improvement methods applied to longitudinal attachments welded onto large specimens. Crack-growth rates are related to crack-opening stresses and to residual stresses. Correlations between crack-growth rates and effective stress intensity factor ranges, as well as between changes in crack-growth rates and changes in residual stress distributions are discussed. Finally, results obtained using an appropriate model based on fracture mechanics and taking into account residual-stress effects is presented.

INTRODUCTION

The design of good and fatigue-resistant details in engineering structures may not always be possible nor provide the necessary fatigue strength, or may become uneconomical. Methods which improve the fatigue strength of welded joints through changing the residual-stress field are still not widely accepted in practice in spite of their low cost, their high efficiency when compared to other methods and their easy execution. This is mainly due to a lack of knowledge about the effect of such methods on crack-growth behaviour. Further, predicting the improved fatigue life of welded structures is difficult. In general, previous work has been limited to the empirical determination of the increase in fatigue life, thereby precluding a more scientific study of promising methods.

The aim of the present work was to examine the effect of such improvement methods on large scale, welded specimens. In order to set up a crack-propagation model based on fracture mechanics, an extensive experimental study of crack-growth and crack behaviour as well as of the residual-stress distribution was necessary.

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SPECIMENS AND MEASUREMENTS

The specimen geometry and size is shown in figure 1. The preparation and improvement of specimens, which were made of a high strength structural steel, were performed by a commercial fabricator. Manual arc welding was chosen for the two-pass groove weld between the main plate and the longitudinal attachment. The two improvement methods examined here are needle peening and hammer peening. Details about these methods are given in (1); further information about the specimens and their fabrication can be found in (2).

Residual stresses were determined using the X-ray diffraction technique. In order to obtain the residual-stress distribution along the potential crack path at the weld toe, electrolytic erosion was used to remove very thin layers of material. Further information about measurements and interpretation of results can be found in (3). The continuous measurement of crack depth during the fatigue tests was carried out using a highly sensitive system based on the D.C. potential drop technique. The system was developed specifically for the specimen geometry used in this study (4). More details of the apparatus and its application to welded joints are given by Dubois and Bremen (5). CMOD measurements were made using a modified Elber gauge and a system which, again, was developed explicitly for carrying out a detailed study of welded joints. These measurements led to the determination of opening stresses for cracks as shallow as 0.1 mm. Further information about the measurement system and interpretation of results can be found in (6).

RESULTS AND DISCUSSION

The results of the residual-stress measurements are given in figure 2. Each of the three bands reported covers approximately 45 single measurements made at three different weld toes of one specimen. The results show that hammer peening changes the residual stresses to the greatest depth. The residual stresses near the surface are nearly the same for both improvement methods and approximately equal to -200 N/mm^2. They then vary almost linearily to the pre-peening, as-welded stresses at depths of approximately 1.4 mm and 4.2 mm for needle and hammer peening respectively.

All fatigue tests were carried out under constant amplitude and a stress ratio $R = 0.1$. Crack-growth measurement results are shown in figure 3. They show that the cracks propagate almost from the beginning of the fatigue test, for both as-welded and improved specimens. Hammer peening leads to the greatest retardation of crack propagation, often causing crack arrest.

The crack-opening stresses σ_{op} are plotted against crack depth in figure 4. While values for as-welded specimens fall very rapidly to a level of 40 N/mm^2 at a crack depth of 0.15 mm, values for hammer peened specimens stay at approximately 160 N/mm². Values for needle peened specimens show a decrease in the crack-opening stress over a much greater range of crack depth than for the as-welded specimens.

With the maximum applied stress during the fatigue cycle being 200 N/mm², the effective stress range, $\Delta\sigma_{eff} = \sigma_{max} - \sigma_{op}$, is much smaller in the case of hammer peening than in the as-welded one, explaining the crack-growth retardation observed above. The effective stress range can be used to compute the effective stress-intensity-factor range, ΔK_{eff}, considering the correction factor for semi-elliptical cracks in a finite plate as well as the correction factor for stress concentration, determined by a finite element analysis of the welded joint (Castiglioni and Bremen (7)). Crack-growth rates are plotted against the effective stress-intensity-factor range in figure 5. Apart from the specimens considered above, results from stress-relieved or shot peened specimens, and results obtained with other stress ranges are also reported, for a total of 20 cracks. A band representing results obtained from CT specimens tested by EMPA (8) satisfactorily covers the results obtained from the welded and improved specimens.

FRACTURE MECHANICS MODEL

The crack-opening stress is defined as the remotely applied stress causing the crack tip to open. Therefore, the opening effect of this stress equals all the other effects tending to keep the crack closed, such as residual stresses and residual deformations due to crack-tip plasticity or surface roughness. Considering all these effects, a total stress-intensity factor can be written as :

$$K_{tot} = K_{app} + K_{res} + K_o \quad (1)$$

where K_{app} is the stress-intensity factor relative to applied stress, K_{res} is that relative to residual stresses and K_o results from all other effects, such as residual deformation due to crack-tip plasticity. K_{res} can be computed using the residual-stress distributions and the procedure proposed by Albrecht and Yamada (9). A new formulation of K_o, is proposed in (2).

Equation (1) was used to predict the effect of residual stresses on the fatigue life of the welded joint, by considering a rather conservative residual stress distribution based on measurements, and two crack-propagation laws covering the experimental results of figure 5. Fatigue life predictions and fatigue test results are shown in figure 6. Hammer peening gives the greatest fatigue life improvement, as would be suggested by the crack-growth and the residualstress results. For as-welded and needle peened conditions predictions properly cover the experimental results, whereas the effect of hammer peening is underestimated. This may be the result of considering a conservative residual-stress distribution and of neglecting the shape change of the weld toe caused by this improvement method. More test results and further theoretical studies are needed to draw final conclusions.

The model also predicts crack slow-down and arrest as shown in figure 7. Although again underestimating the stress range where transition takes place, the shape of the shaded areas defined by the two crack-propagation laws considered strongly resemble the experimental results (figure 3).

CONCLUSIONS

The following main conclusions can be drawn :

- the effect of the improvement methods studied is almost exclusively a modification of crack propagation rates,
- changes in residual-stress distribution explain the fatigue life increase,
- a crack-propagation model based on the effective stress-intensity-factor range can describe the effect of such improvement methods through linear superposition of a stress-intensity factor related to the residual stresses.

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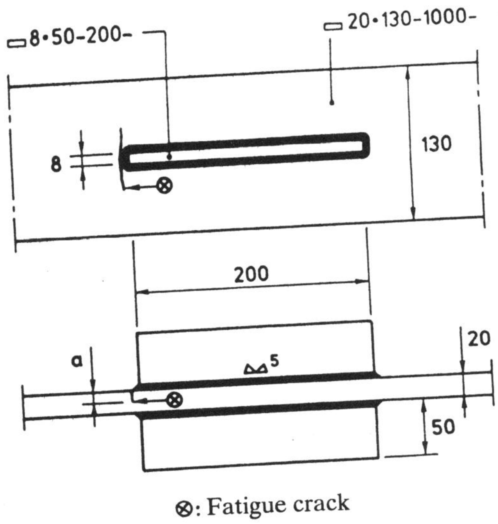

Figure 1 Geometry of welded specimens, total length of main plate : 1000 mm

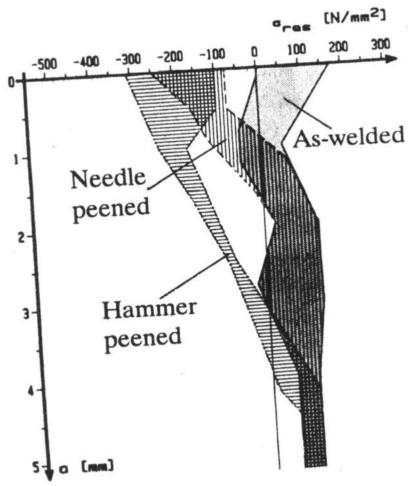

Figure 2 Residual-stress distribution measured at weld toes

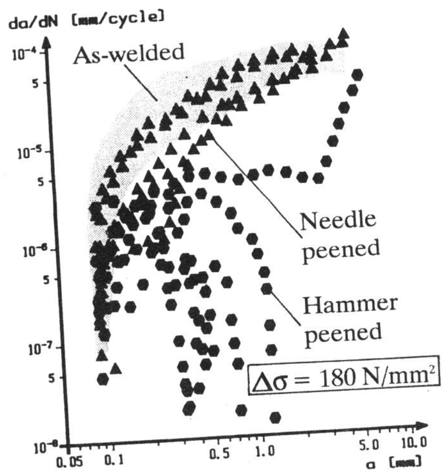

Figure 3 Crack-growth rates against crack depth

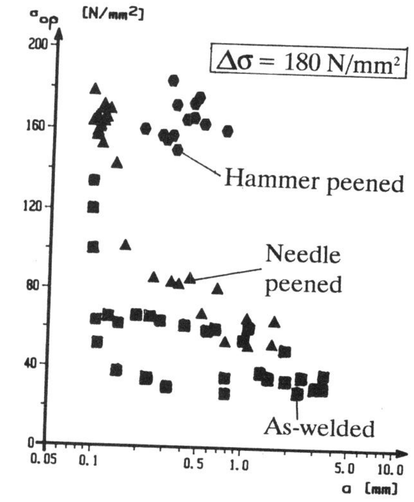

Figure 4 Measured crack-opening stresses against crack-depth

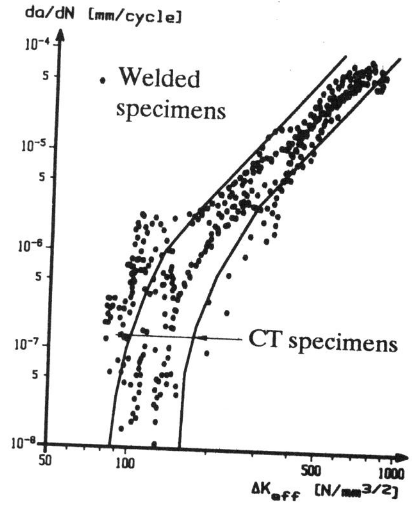

Figure 5 Crack-growth rates against effective stress-intensity-factor range

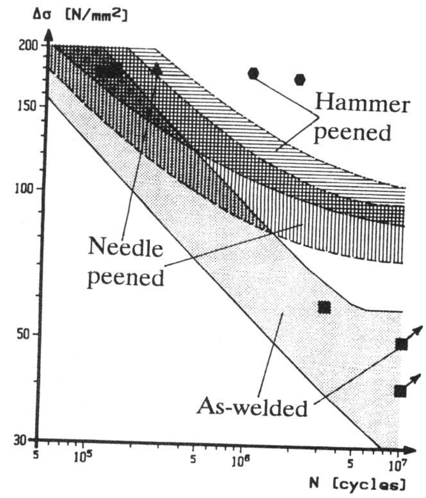

Figure 6 Predicted and experimental fatigue lives for improved welded joints

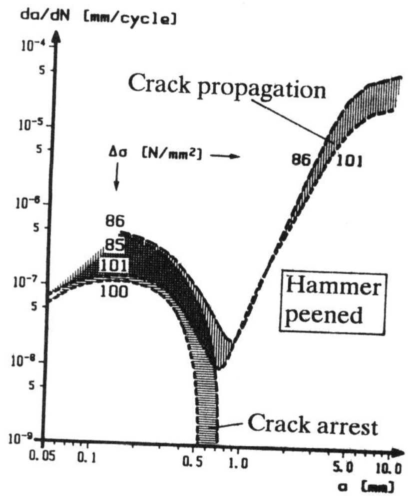

Figure 7 Predicted crack-growth for hammer peened welded joints