FATIGUE STRENGTH AND FATIGUE CRACK INITIATION OF STEEL NOTCHED PLATES UNDER CYCLIC AND RANDOM LOADING

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Notched plates from JIS SM570Q high strength steel for welded structures were tested under cyclic and random loading. Double edge notches were machined on the specimens and stress concentration factors were 1, 2, 3 and 4. Random loading was corresponding to Rayleigh distribution of stress ranges and it was applied as randomized loading blocks. During the loading the maximum stress was kept constant and equal to yield strength thus it is considered that complex residual stresses are avoided. Fatigue crack initiation under constant amplitude loading and random loading was observed. A new damage parameter is proposed to correlate fatigue lives under random loading.

INTRODUCTION

The good design practice for welded joints requires that the local stresses at the hot spot may reach levels that the joint has a finite life which is greater than the expected life by a factor of safety.

The advances in the fatigue research show that the fatigue crack propagation is controlled by the fatigue crack closure for the base material [1] but for welded joints containing high tensile residual stresses the crack closure may not be observed even under variable amplitude loading [2].

The welded joints initially have some geometric discontinuities and micro cracks due to the welding. For welded joints, which are subjected to random loading histories the crack initiation and propagation stages are the most important consideration in fatigue design. The fatigue analyses for most of the engineering structures have been carried out using a constant amplitude S-N curve, that is obtained under completely reversed loading or for a low stress ratio, e.g. R=0 for the welded structures. But it is well known that under such conditions crack closure may occurs. Under random loading the cycles with small stress range can be more damaging than these under constant amplitude loading due to the

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small crack closure under random loading. It can be found [3] that the random loading with a large mean stress value or load sequences for which the maximum stress was kept constant give non-conservative results related to a complete reversed loading. If high mean stress random loading is related to the S-N curve with same mean stress, the Miner's rule give satisfactory results [4]. A reason for high mean stresses can be the presence of the tensile residual stresses in the welded joints. The residual stresses may play and important role in the random fatigue of welded structures, and a properly taking into account of these stresses is very important. The fatigue life increases with compressive residual stress and reduces due to tensile residual stress [5,6].

The aim of this study was to investigate the fatigue strength and crack initiation life on notched specimens by applying constant amplitude and random loading histories under the condition of keeping the maximum stress constant and equal to the yield strength of the investigated material.

EXPERIMENTAL DETAILS

The material used in this experiment was JIS SM570Q steel. The chemical composition (wt.%) was 0.14 C, 0.26 Si, 0.53 Mn, 0.013 P, 0.002 S, 0.01 Ni, 0.02 Cr. The mechanical properties of this steel were 611 MPa yield strength, 662 MPa ultimate tensile strength and 31% elongation. The steel plate was quenched at 910 ^{O}C and tempered at 620 ^{O}C.

The specimens were 50mm wide and 11.7 mm thick double edge notched plates. The specimens with elastic stress concentration factor K_t = 1.0(unnotched), 2.0, 3.0 and 4.0 were used. The testing machine used in this research was MTS-810 for 500kN. Initially constant amplitude tests were carried out in order to obtain the basic fatigue data for the material.

The maximum stress, σ_{max} , was kept constant at the yield strength, σ_y , while the stress range, $\Delta\sigma$, and therefore the minimum stress, σ_{min} , was changed. thus simulating the welded joint behaviour. The random loading was corresponding to a Rayleigh distribution of stress ranges [2]. The random loading was approximated by block loading divided into 16 to 10 steps. The total number of cycles for each block, Σn_i , was 10000 cycles. The stress histories were repeated until failure of the specimen.

The order of stress steps was randomized according to a table of random numbers. Some specimens were tested under two step loading (beach mark tests) to investigate the early crack initiation under these conditions. These tests were designed that about of 10 beach marks (BM) to appear on the fractured surface.

In order to obtain the desired stress pattern the command signal was primary tuned on a dummy specimen. The maximum stress was kept constant within 0.5%. All tests were conducted on load control mode in the air at room temperature. The number of cycles to crack initiation were determined by a thin (0.05 mm) enameled wire bonded onto the notch of the specimen.

Fractographic observations on the fatigue crack growth were made using scanning electron microscope Hitachi 2400.

RESULTS AND DISCUSSION

Fatigue life analysis

Figure 1 correlates the fatigue lives with stress ranges under constant amplitude cyclic loading. It is observed that fatigue strength becomes smaller with increasing the stress concentration factor. The parameters m and C of S-N curve, eq. (1), are given in Fig. 1.

$$\Delta\sigma^m N_f = C \tag{1}$$

The results from the beach mark tests are shown in the same figure. To represent the BM tests the equivalent stress range, as described bellow, is used. The BM tests were used to detect the crack initiation. The open symbols represent the numbers of cycles to crack initiation and solid symbols correspond to the numbers of cycles to failure. It is clear that for this material the fatigue crack propagation took a small part of the total fatigue life under constant and variable amplitude loading. The fatigue cracks initiated from the oxide layer for unnotched specimens, while they initiate from the milling surface for the notched specimens. No influence of the different Kt value on the crack initiation life was observed in BM tests. Dowling [7] investigated the different possibilities for equivalent stress based random loading fatigue analysis. The equivalent stress van be estimated as follows,

$$\Delta\sigma_{eq} = \left[\sum \Delta\sigma_i^m n_i \Big/ n_{eq}\right]^{1/m} \tag{2}$$

where $n_{eq} = \sum n_i$, $n_i = n_i$ for all $\Delta\sigma_i$ according to the modified Miner's rule, or $n_i = n_i$ for $\Delta\sigma_i > \Delta\sigma_w$ and $n_i = 0$ for $\Delta\sigma_i < \Delta\sigma_w$ [2]. It is clear that equivalent stress will depend on the equivalent number of cycles, and for example, when allpying the Miner equivalent stress, some un-conservative results are obtained. To avoid this, a new damage parameter based on Miner linear damage rule is proposed,

$$D^* = \frac{\sum (\Delta\sigma_i n_i)^m}{n_{eff}} \tag{3}$$

The effective number of cycles is $n_{eff} = \sum n_i$, where $n_i = n_i$ for $\Delta\sigma_i > \Delta\sigma_w$ and $n_i = 0$ for $\Delta\sigma_i < \Delta\sigma_w$. Using (1), the new damage parameter can be rewritten as,

$$D^* = C / N_f \tag{4}$$

The results from using the new damage parameter, D^* , are presented in Fig.2. For notched specimens with Kt=3 and 4 the experimental results coincide well with S-N curve under constant amplitude loading and all the data point are within the 95% confidence scatter bands. For the case of Kt=1 and 2 conservative estimations are obtained. A possible reason is the change of stress levels into a large plastic field in front of the notch. It have to be pointed out that when using the new damage parameter, the results will not coincide with the material fatigue limit. It worth noting that using the equivalent stress approach [11] has an advantage that only slope m from the constant amplitude S-N curve is necessary, but it depend on the equivalent number of cycles. The new damage parameter D^* does not depend on slope m but depends on the parameter C only, therefore the new damage parameter can be used to correlate fatigue data. This is considered as an advantage, also the value of m is very sensitive to fatigue constant amplitude results.

Fractographic analysis

Normally the observation and measurement of the position of the crack tips during the fatigue loading is done by optical traveling microscope. For these specimens however this was not done as when the test was stopped, the crack tip may become blunted from the high tensile stress and therefore retardation of the crack growth will take place.In Fig. 3 and 4 the micro fractographs of the tested specimens under constant amplitude and random loading are shown respectively. Significant difference is observed between both constant amplitude and random loading tests. The fatigue striations are clearly observed under constant amplitude loading but plenty of microcracks are visible on the fractured surface under random loading. Under random loading and for the BM tests the traces of crack propagation (beach marks) can be observed by naked eye, Fig.5,6. They were counted to evaluate the cycles for crack propagation. In this picture the notch root is on the right hand side. At the final stage of crack propagation a considerable amount of ductile tearing was observed.

CONCLUSIONS

The $\sigma_{\max} = \sigma_y$ condition tests under constant amplitude and random loading were performed on notched SM570Q steel. The following conclusions were obtained.

(1) New damage parameter based on the linear damage rule was proposed. The results shows good correlation for random loading fatigue of notched specimens with Kt4 and Kt3. Conservative estimations were obtained for the Kt1 and Kt2 specimens. This new approach can be used for a fast evaluation and correlation of the fatigue data with the constant amplitude S-N curve.

(2) The crack initiation life take the predominantly part of the total fatigue life. It was confirmed in constant amplitude, beach-mark and random loading tests.

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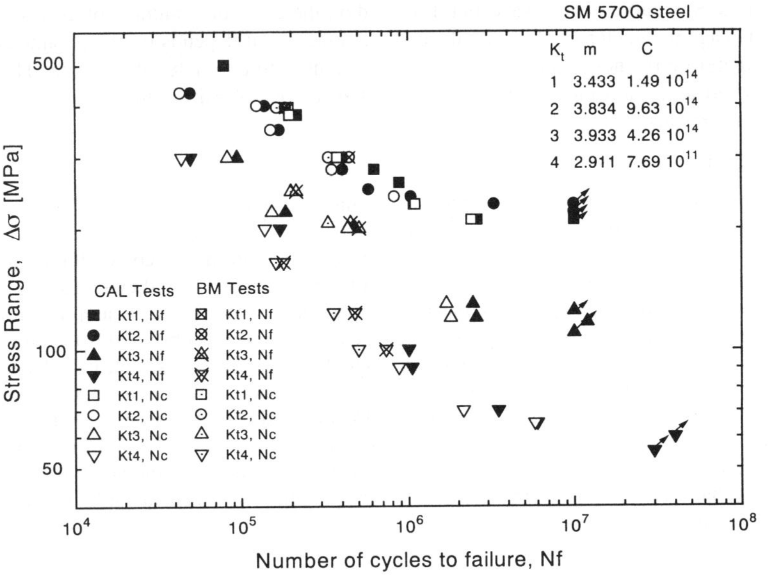

Fig.1. Correlation of number of cycles to failure, Nf, and cycles to crack initiation, Nc, with stress range for constant amplitude (CAL) and random amplitude loading (RAL).

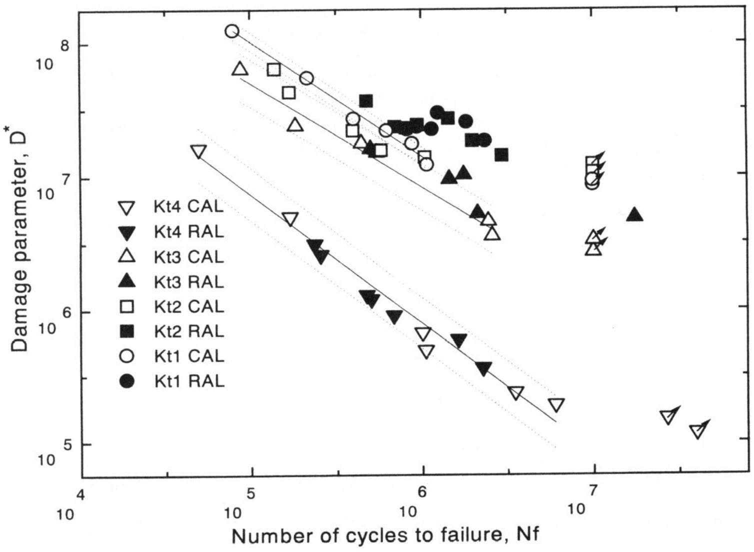

Fig. 2. Correlation of number of cycles to failure, Nf, with damage parameter, eq(3).

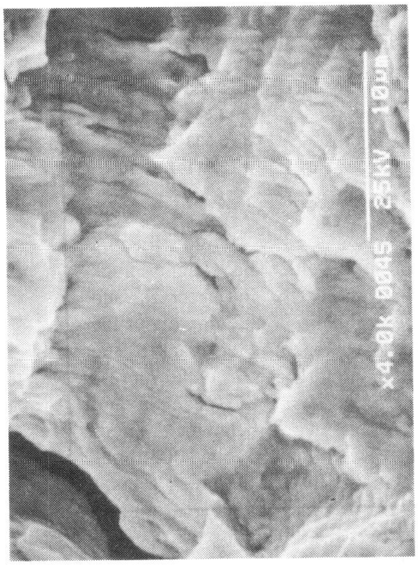

Fig.3. Fatigue striations for constant amplitude loading.

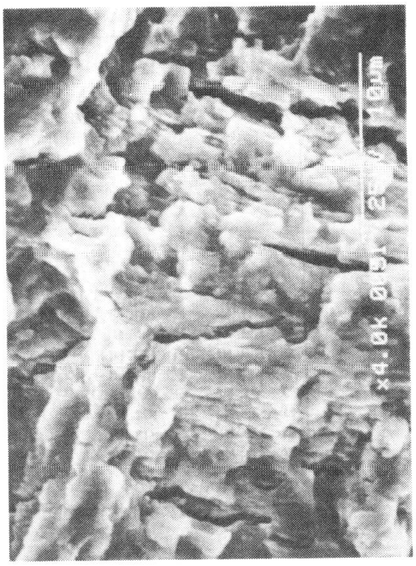

Fig.4. Fatigue striations for random amplitude loading.

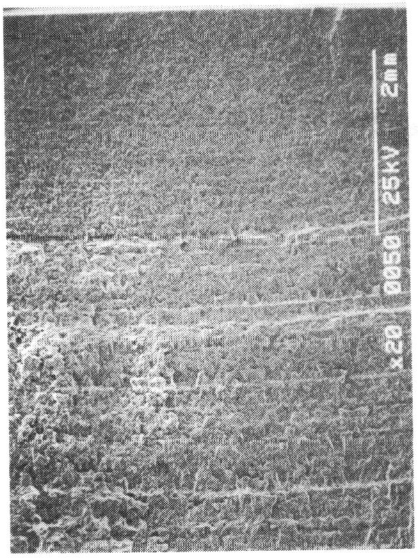

Fig.5. Beach marks under random amplitude loading.

Fig.6. Beach marks under beach-mark test.