ECF19 Effect o Residual Stresses Induced by Bending on Fatigue Crack Initiation

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Abstract. The wide use of high strength low alloy steel, with yield stress more than 1000 MPa, reduce weight of steel's structure and extended length between supports. The plates are usually bending in proper shape during manufacturing process. The compress and tension residual stresses are introduced in bended part of plate. Fatigue crack in plastic deformed part, with tension residual stress, initiates under lower amplitude of dynamic loading than in non-deformed plates. The aim of paper is presented the experimentally obtained difference in fatigue crack initiation and propagation between deformed and no-deformed part of plates in order to establish model for fatigue limit determination of deformed material.

Introduction

Cold bending is common fabrication process for produce components of steel structures. During this bending process the high levels of residual stresses are introduced. Due to high compressive plastic strain on inner-corner the tensile residual stresses occurred inside and compress residual stresses outside. In case when bended component is subjected to cyclic dynamic loading the relaxation of residual stresses can appear, as was reported in references [1, 2]. Such effect is also often used on just welded structures in order to reduce peaks of residual stresses. It has been shown that any potential residual stresses relaxation would occur within the few first cycles. Therefore, real effect of residual stress on fatigue cracking behavior is possible to figure out by experimental testing. Goal of paper is find effect of residual stresses induced by bending. In order to find this goal the same or as much similar biaxial loading (bending+tensile) stress is going to apply on specimens made from same material with and without residual stresses.

Experimental testing

The experimental studies were planned to produce the cracking behavior on bended specimens with different residual stresses level and specimens without residual stresses. All specimens have a same thickness. In the bended specimens the bending opening stress had been applied during the tensile loading. Specimens without residual stresses where subjected to four bending in order to achieve same bending stress magnitude. Most loaded part at the bended specimens is inner corner at the center line of bending angle. In this area significant bending and slightly tensile stresses occurred. The residual stress distribution through thickness was determined by numerical simulation of bending. The final results of residual stresses distribution are shown in Fig. 1. Due the relaxation of material, the experimental measurement by x-ray deflection shows that tensile residual stresses are in range of 380 MPa until 480 MPa.

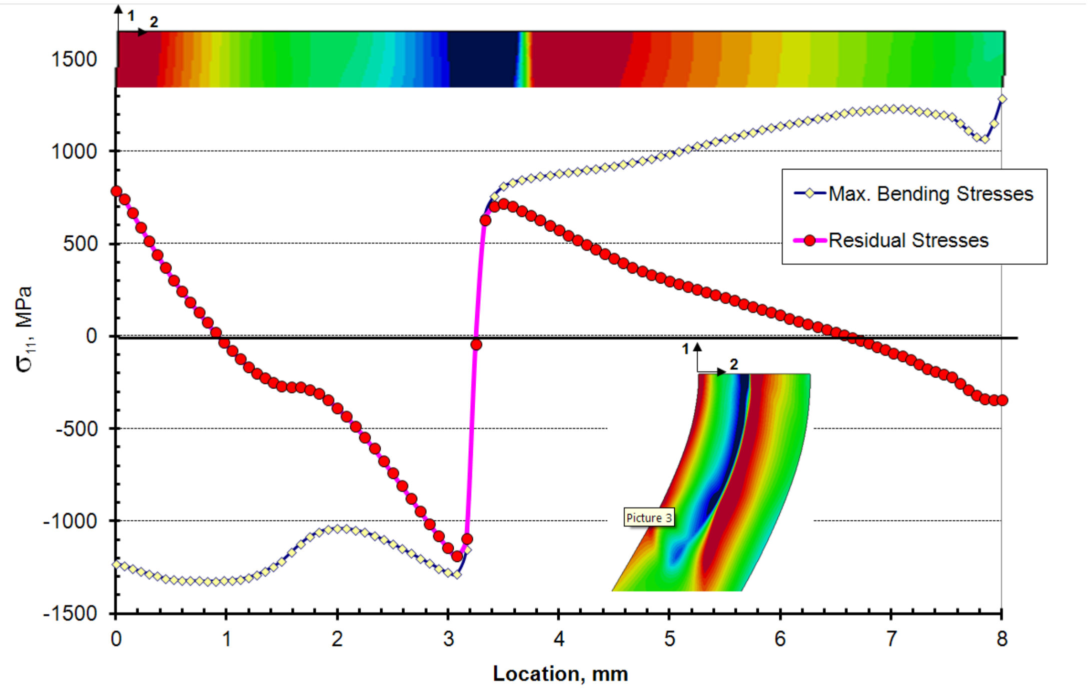

Fig.1. Residual stress distribution after bending

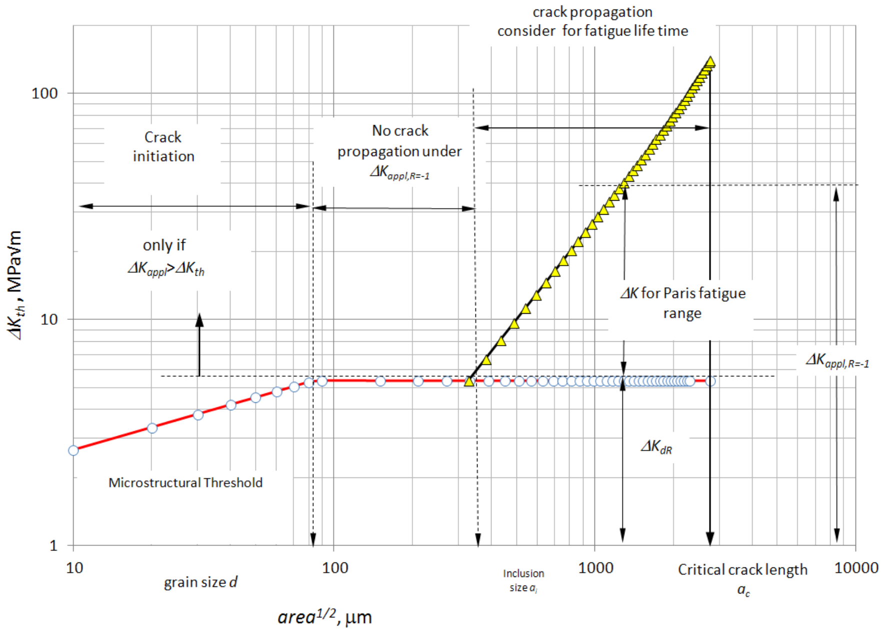

Fig.2 Fatigue threshold as a function of $area^{1/2}$

In order to determine S-N curve of bended and non-bended specimen the Chapettie’s model for fatigue crack threshold determination had been applied, as is shown in Fig. 2. The difference between the total applied driving force and the material threshold for crack propagation defines the effective driving force applied to the crack, as schematically shown in Fig. 6. The initial crack length is given by the position of the strongest microstructural barrier if the material were free of cracks or crack like flaws. This intrinsic resistance is considered to be microstructural threshold for crack propagation as [3]:

$$\Delta K_{dR} = Y \cdot \Delta\sigma_{eR}\sqrt{\pi \cdot d} \tag{1}$$

where Y is the geometrical correction factor. In most cases the nucleated microstructurally short surface cracks are considered semicircular, and the value of Y would then be 0.65. Because the plain fatigue limit depends on the stress ratio R, the microstructural threshold also does. The value of d is usually determined by the microstructural analysis, as grain size $d = 5$ μm.

The pure fatigue crack propagation threshold $\Delta K_{th,R=-1}$ is equal to the lower value of equations [4]:

$$\Delta K_{th,R=-1} = 4 \cdot 10^{-3}(HV + 120) \cdot a^{1/3} \tag{2}$$

$$\Delta K_{th,R=-1} = -0.0038 \cdot \sigma_u + 15.5 \tag{3}$$

Where the pure fatigue crack propagation threshold ΔK_{th} as function of crack length, and $\Delta K_{th,R=-1}$ (a constant value for given tensile strength or hardness) are in MPa·m$^{1/2}$, the crack length a in mm, the Vicker's hardness HV in kgf/mm^2 and the ultimate tensile strength σ_u in MPa. Quantitative analysis of fatigue crack growth requires a constitutive relationship of general validity be established between the rate of fatigue crack growth, da/dN, and some function of the range of the applied stress intensity factor, ΔK (crack driving force). Besides, it has to take into account the threshold for the whole crack length range, including the short crack regime where the fatigue crack propagation threshold is a function of crack length. Among others, the following relationship meets these requirements [5]

$$\frac{da}{dN} = C \cdot (\Delta K_{appl} - \Delta K_{th,R=-1})^m \tag{4}$$

where C and m are Paris range constants obtained from long crack fatigue behavior and $\Delta K_{th,R=-1}$ is the crack growth threshold as lower value of Eq. (2) and (3). The fatigue crack propagation life from crack initiation up to critical crack length a_c can be obtained by integrating expression (4) and using expression (3) for the threshold of the material ($\Delta K_{th,R=-1}$). In the case of smooth specimens or spring after shot-peening, the stress can be considered constant for any crack length, equal to the nominal applied stress $\Delta\sigma_n$. The following general expression can be used to estimate the applied driving force as a function of crack length [3]:

$$\Delta K_{appl} = Y \cdot \Delta\sigma_{n+RS}\sqrt{\pi \cdot a} \tag{5}$$

where $\Delta\sigma_{n+RS}$ is the $\Delta\sigma_n$ nominal applied stress range and maximum tension residual stress σ_{RS}. The crack aspect ratio as a function of crack length has to be defined for the combination of component geometry and loading conditions, which allows definition of the value of the parameter Y as a function of crack length. In case of small embedment crack, where the crack is only few inclusion size, we are considering shape function by Y = 0.65. Inclusions size cluster of a_i=0.2 mm was determined by metallographic inspection of steel.

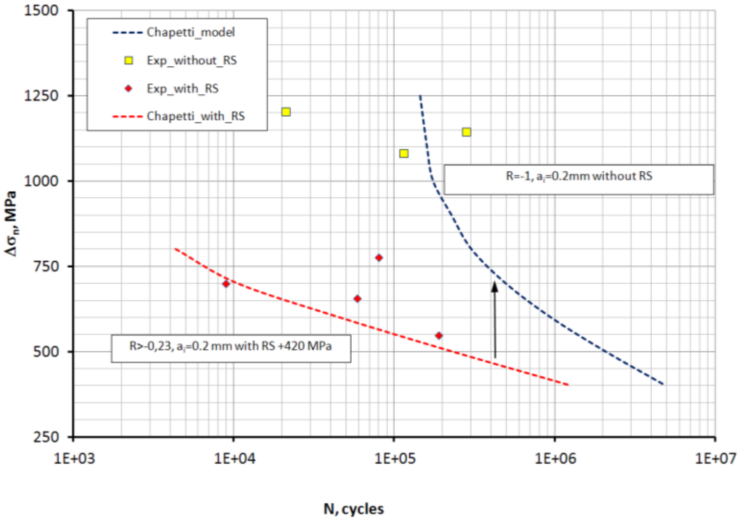

Fig. 3. Prediction of fatigue failure in form of *S*-*N* curve by using fracture mechanic approach and considering inclusions as initial crack size

Conclusions

Investigation shows that fatigue crack in plastic deformed part, with tension residual stress, had propagated under lower amplitude of dynamic loading than in non-deformed plates. Chapetti's model has been used for determination of a threshold ΔK_{th} from short crack of grain size until critical crack length. The Life time of material subjected to applied stress amplitude $\Delta\sigma_n$ from microstructural threshold up to critical crack length of high strength steel has been determine, by combining fracture mechanics parameters K_{IC}, fatigue propagation Paris range parameters C and m, and considering inclusion size a_i as crack initiation area. Results are presented in form of *S*-*N* curves. Model shows good agreement with experimentally obtained fatigue results for spring steel in Q+T condition with same inclusion size. Residual stresses has main effect only on loading stress ratio $R=(\sigma_{min}-\sigma_{RS})/(\sigma_{max}-\sigma_{RS})$, where R is usually negative in case of higher tensile residual stresses.

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