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Fracture mechanics based determination of the fatigue strength of weldments

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Abstract

A fracture mechanics model which shall be applied to the fatigue strength determination of weldments has to focus on various aspects such as: (a) the description of mechanical and physical short fatigue crack extension which is characterised by yielding conditions which do not permit the application of the common ΔK concept and by the gradual build-up of the crack closure effect, (b) a consistent methodology for determining the initial crack size, (c) based on this, the determination of a fatigue limit, (d) the treatment of multiple crack propagation at load levels above this limit, (e) the variation of the local geometry along the weld toe, and (f) statistical effects. The paper gives a limited overview of the work the authors did in this field during the last years within the German project cluster IBESS. A model is presented and briefly discussed which covers the questions above.

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Keywords: Weldments, fatigue strength, fracture mechanics, fatigue crack propagation

1. Stages of the lifetime of a component subjected to cyclic loading

The fatigue lifetime of a component subjected to cyclic loading can be roughly subdivided into three stages: crack initiation, fatigue crack propagation and fracture. Frequently, the initiation stage is seen as the phase during which the crack is nucleated and subsequently extended to a size externally visible. However, on closer look, it may be further subdivided into the actual initiation phase characterized by the accumulation of plastic deformation frequently at defects such as inclusions, pores etc. and the subsequent phase of short crack propagation Murakami (2002). Note that the early crack propagation and arrest of microstructurally short cracks forms the background of the fatigue life phenomenon Miller (1999). At stress levels higher than the endurance limit a limited number of cracks will further propagate and develop to what is designated as mechanically/physically short cracks. In contract to the micromechanically short cracks the size of which is in the order of micromechanical features such as the grain size, mechanically short cracks are comparable in size to the plastic zone ahead of its tip.

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They can be described by continuum mechanics-based fracture mechanics, however not by the linear-elastic ΔK concept because the plastic zone size is in the order of the crack size. Instead, the crack driving force has to be given as an elastic-plastic parameter. The specific meaning of the term "physically short" is that the crack closure mechanism is not yet fully developed but gradually increases from no closure effect of the initial crack to a constant value when the crack reaches the size of the so-called long crack. The propagation of the latter can be described by the common da/dN-ΔK curve concept. Usually the propagation phase of the mechanically and physically short crack, the sizes of which roughly overlap, constitutes the major part of fatigue life.

2. The Model

2.1 Elastic-plastic cyclic crack driving force

Following a proposal of McClung (1997) the cyclic J integral is determined by

$$\Delta J = \frac{\Delta K^2}{E'} \cdot \left[f\left(\Delta L_r\right) \right]^{-2} \tag{1}$$

with the ligament yielding correction term $f\left(\Delta L_r\right)$, deviating from the original, being defined by

$$\Delta L_r = \frac{\Delta\sigma_{app}}{2 \cdot \sigma_0} . \tag{2}$$

In Eqn. (2) the parameter $\Delta\sigma_{app}$ is the applied cyclic load and σ_0 is what the authors call a reference yield load which they use instead of the common limit load and for which they provide parameter equations in Madia (2014). For the further use in the fatigue crack propagation analysis, ΔJ is formally converted to ΔK_p with the index "p" standing for "plasticity corrected". With respect to the ligament yielding correction function $f(L_r)$ the method makes use of the common equations, e.g. in R6, Revision 4, (2009):

$$\Delta K_p = \sqrt{\Delta J \cdot E'},\ E' = \begin{cases} E & \text{plane stress} \\ E/\left(1-\nu^2\right) & \text{plane strain} \end{cases} \tag{3}$$

2.2 Gradual build-up of the crack closure effects

Crack closure means that the crack, during unloading, closes above zero stress level. The effect is caused by a number of mechanisms with the plasticity-induced, the roughness-induced and the oxide-induced are the most important ones Suresh (1998), for a more detailed discussion see Zerbst (2006). It is commonly expressed by a closure term U:

$$U = \Delta K_{eff} / \Delta K \tag{4}$$

Figure 1 illustrates the gradual build-up of the crack closure effect with increasing crack size. Up to the initial crack depth a_i, which approximately marks the transition from the microstructurally to the physically short crack (in reality there is a range), U=1, i.e., no closure effect exists. Then, U gradually decreases with increasing crack length until it reaches the constant value U_{LC} of the long crack phase. The determination of U(a) by the present model makes use of the fact that this is mirrored in the development of the fatigue crack initiation threshold ΔK_{th} such as illustrated in Figure 2 and described by an equation

$$\frac{U(a)-1}{U_{LC}-1} = \frac{\Delta K_{th}(a) - \Delta K_{th,eff}}{\Delta K_{th,LC} - \Delta K_{th,eff}} \tag{5}$$