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Assessment of microstructural influences on fatigue crack growth by the strip-yield model

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ABSTRACT

The strip-yield model is a common tool to calculate the cyclic crack tip opening displacement and the fatigue crack growth life of structures in case of isothermal fatigue loading. The incorporation of a temperature-dependent yield stress already enables its application in thermal fatigue analyses. A further extension of the strip-yield model is presented here together with simulation results: The rheological Masing model consisting of spring-slider elements connected in parallel is used to describe the material's stress–strain curve. It results in different yield stresses belonging to the numerous sliding frictional elements. These different yield stresses are randomly arranged along the crack ligament line instead of the usually applied constant yield stress. They depend on temperature as the procedure should still be used at non-isothermal loading. Besides an improved modelling of the mechanical material behavior the consideration of microstructural aspects of fatigue crack growth becomes possible by influencing the values of the yield stresses near the crack initiation site.

1. Introduction

In many areas of technology, structures are not only exposed to mechanical loads, but also to significant temperature changes. In many components such as thick-walled tubes the loading history implies locally large elastic–plastic strain ranges. In a previous concept study [1], a mechanism-based approach to thermo-mechanical fatigue was introduced. The process of fatigue damage accumulation was interpreted as fatigue crack growth. The cyclic crack tip opening displacement $\Delta\delta$ was established as crack driving force. It was calculated applying the strip-yield model of elastic–plastic fracture mechanics. As the model accounts for crack closure the cyclic crack tip opening displacements are effective ranges. The main advancement of the previous work [1] was incorporating temperature-dependent material properties in the simulation. In various research and development work concerning the strip-yield model during the last three decades (see for example Refs. [2–16]), such an extension had not been performed to the knowledge of the authors.

A demonstrator thick-walled tube with a continuous axial crack at the inner surface was used for exemplary calculations in the previous concept study [1]. The cyclic crack tip opening displacement was calculated for different temperature transients of a fluid inside the tube combined with a constant internal pressure. The function $\Delta\delta(a)$ (with the crack length a) enters the crack growth law

$$da/dN = C(\Delta\delta(a))^m \tag{1}$$

with the constants C and m and the number of cycles N. Its integration from an initial crack size a_{initial} which covers initial defects to a final (engineering) crack size a_{final} where the tube's life is assumed to be exhausted results in the fatigue life N_f.

The experimental evidence for laboratory material specimens concerning the influence of the corrosive reactor medium on the fatigue life as laid down in the research report Ref. [17] led to the definition of environmental fatigue correction factors

$$F_{en} = N_{air}/N_{water} \tag{2}$$

which are defined as the ratio of life in air at room temperature N_{air} to that in water at the service temperature N_{water}. The environmental fatigue correction factors for austenitic steels are themselves functions of temperature, strain rate and oxygen content. For ferritic steels, the sulphur content is an additional influence factor. As can be seen in Eq. (2), the environmental fatigue correction factors provide a general life reduction ($F_{en} \geqslant 1$) without going into much detail concerning individual mechanisms of the corrosive attack. A very simple way for considering the environmental fatigue correction factor in the mechanism-based approach developed in

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the previous work [1] is to multiply the crack growth rate constant C with the environmental fatigue correction factor F_{en}. This mathematical operation would perfectly reflect the life-reducing effect.

However, in Ref. [18] it is reported that the effect of corrosive environment is restricted to microstructurally short cracks. But the mechanism-based approach does not yet distinguish between microstructurally short cracks and longer cracks, the growth rate of which is no longer influenced by the microstructure in detail. In order to allow for a correction regarding environmental influences to the stage of microstructurally short cracks an extension of the model is required.

The material should be considered as microstructurally inhomogeneous. The individual bars in the yield strip should be supplied with a width according to the average grain size of the material. Their yield stresses should be fixed individually. The frequency distribution of the yield stresses should be derived from the rheological Masing model [19]. The local distribution in the ligament section is to be created in a random way, however, with the restriction that low yield stress bars are concentrated at the crack initiation site. The region of low yield stress bars should be addressable for inserting environmental factors acting specifically in this region. As the present feasibility study is a continuation of the previous concept study [1] most of the calculations concerning the macroscopic behavior of thermo-mechanically loaded structures have been re-used in the present study. Some items of the previous calculus are reproduced here for better readability.

2. Geometry, material and loading

The examined component is a straight, infinitely long, thick-walled tube with a continuous axial crack at the inner surface. Its outside radius is $R_O = 135$ mm and its inside radius is $R_I = 95$ mm. The tube consists of the austenitic steel 1.4550 (X6CrNiNb18-10, AISI 347). As far as possible the material data are taken from another previous report [20]. Specifically, the report includes the values of the Young's modulus E, the cyclic yield stress σ_{cy}, and also the cyclic hardening coefficient and exponent, K_0 and n_0, at three different temperatures (see Eq. (10)). These data are listed in Table 1. Furthermore, Poisson's ratio $\nu = 0.3$ and Young's modulus $E = 190{,}000$ N/mm^2 averaged for the considered range of temperature 20 °C $\leqslant T \leqslant$ 350 °C are used. The values of density ρ, specific heat capacity c, thermal conductivity k, secant coefficient of thermal expansion α_{th} and the monotonic ultimate tensile strength R_m are taken from Ref. [21]. They are tabulated in Tables 1 and 2.

The tube is loaded by the varying temperature T_F and by the constant pressure p_F of a fluid flowing through the tube. The (time dependent) heat transfer coefficient h_{FT} between fluid and tube takes into account flow conditions (see Fig. 5 for examples of given loadings). The tube is insulated from the environment.

3. Application of the strip-yield model

3.1. Determination of the stress intensity factor sequence

The strip-yield model reduces the task to perform calculations applying non-linear, elastic–plastic material behavior for cracked structures to superpositions of solutions obtained by applying the linear theory of elasticity to these structures. It internally uses the structure of an infinite plate with an internal crack of the length $2a$ loaded by a nominal stress S. The nominal stress the model operates with has to map the stress intensity factor K at the real structure and is calculated using the equation $S = K/\sqrt{\pi a}$. Therefore, for every time step the crack length-dependent stress intensity factor is determined from the corresponding stress distribution at the real structure, namely the tube with an infinitely long axial crack of depth a at the inner surface. This is done using the result of a finite element calculation of the real structure (more precisely, the stresses in circumferential direction over the wall thickness) and the method of weight functions where the weight function for axial cracks in hollow cylinders according to Ma et al. [22] is applied.

Consequently, the 'elastic solution' of the uncracked structure has to be provided. Here, the thick-walled tube described in Chapter 2 is regarded as linear elastic deformable continuum. Due to the rotational symmetry of the structure a two-dimensional model can be used. The rectangular model with the length

Table 1
Material data – part I [20,21].

T	°C	20	200	350
E	N/mm^2	208,000	173,000	186,000
σ_{cy}	N/mm^2	454	233	226
K_0	N/mm^2	951	403	426
n_0		0.118	0.087	0.101
R_m	N/mm^2	510	370	335

Table 2
Material data – part II [21].

T	°C	20	100	200	300	400
ρ	10^{-9} Ns^2/mm^4	7.93	7.93	7.93	7.93	7.93
c	10^9 mm^2/(s^{2}K)	0.47	0.47	0.49	0.50	0.52
k	N/(sK)	15	16	17	19	20
α_{th}	10^{-6}/K	16	16	17	17	18

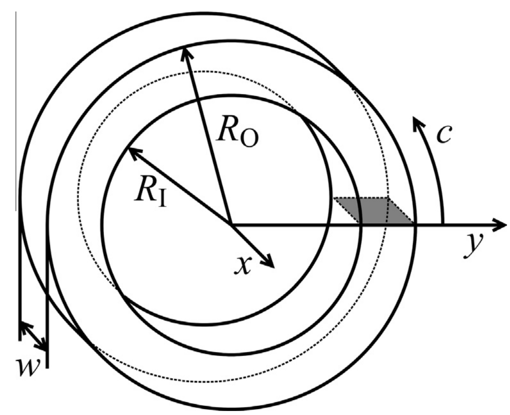

Fig. 1. Model of the tube.

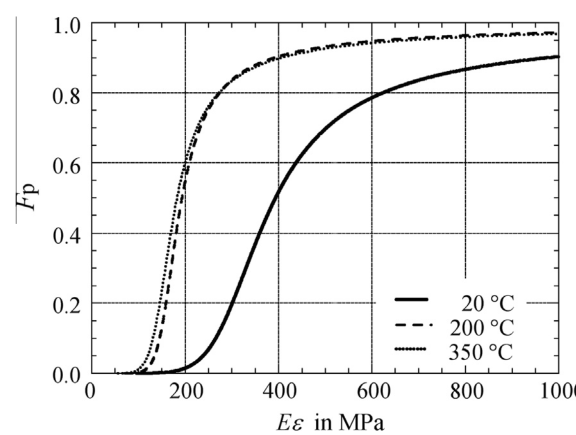

Fig. 2. Distribution function F_p for the yield stress $E\varepsilon$ at different temperatures (after Eq. (11), material data from Table 1).