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The effect of single overloads in tension and compression on the fatigue crack propagation behaviour of short cracks

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ABSTRACT

The crack propagation behaviour in cast quenched and tempered steel after one overload cycle in tension as well as in compression on short cracks is investigated in deep notched specimens. The overload cycle exhibits a significant influence on the fatigue life endurance, due to the formation of an overload plastic zones in front of the crack tip. The crack propagation after overload cycles is investigated by inspection of the fatigue threshold R-curve and fatigue crack propagation rate. Tension overload increased the long crack threshold and reduced the R-curve effect, whereas overloads in compression reduced the crack growth resistance and shifted the threshold value to larger crack extension. A simple FE simulation was also performed to investigate the variation in the contribution of plasticity induced crack closure during crack propagation after the overload. Macroscopic mechanistic and dislocation models are introduced to explain the results obtained.

1. Introduction

Fatigue crack propagation under variable load amplitude has been extensively investigated for a long time. A major breakthrough was made in the first half of last century by Miner [1] and Palmgren [2], who proposed a linear damage hypothesis to accumulate the damage under variable load amplitudes. However, research in the last few decades revealed the existence of a strong load interaction effect. A change in load amplitude leads to an alteration of the material fatigue properties, resulting in a load sequence dependency in the lifetime [3–7]. Such mechanisms as:

1. residual stress: overload introduces a residual stress field which interacts with the remote stress and affects the subsequent crack propagation [8],
2. crack closure: overload in tension leaves a plastic deformation which increases the crack closure stress intensity [9,10],
3. geometric variation: overload in tension can induce some geometric variation like plastic blunting [11,12], crack deflection or even change in crack front profile [13]. All of these variations lead to a reduction in the local driving force,
4. stain hardening: strain hardening can also take place within the tensile overload induced plastic zone [14,15],

can be followed by overload. In ductile material, a change in the contribution of plasticity-induced crack closure (PICC) is a direct consequence of overload. The crack propagation behaviour thereafter can be very complex especially near the threshold. For example, after a single tensile overload the increased PICC can reduce the fatigue crack growth (FCG) rates back to near the threshold regime and thereby promote oxide-induced and roughness-induced crack closure [16]. For that reason, prediction methods for crack growth are often of empirical nature. The prediction is often based on experiments with certain load time history patterns like single overloads during cyclic loading with a constant load amplitude, block loads or variable amplitudes which correspond to the real load time history in practice. In order to find out the physical reasons of the load variation effect, the current study focuses on one of the simplest cases; the effect of one cycle of large load amplitude (overload) in tension as well as in compression on short open cracks. The material fatigue properties are determined by the R-curve behaviour of the fatigue threshold of stress intensity and FCG rate by constant load amplitude.

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2. Material and experimental method

The experiments were performed on single-edge-notched-bend (SENB) specimens (Fig. 1) machined from quenched and tempered steel with a yield stress of 630 MPa and an ultimate tensile strength of 760 MPa. The fatigue properties of this material were already well investigated [17]. The R-curve of the fatigue threshold of stress intensity range and the FCG rates are summarised in Figs. 2 and 3. Pre-cracks are introduced at the root of a deep notch (about 4 mm) using compressive-compressive loading. The razor blade polished notch root radius is between 10 and 20 μm. 10,000 load cycles with $\Delta K = 18\ \mathrm{MPa}\sqrt{\mathrm{m}}$ were applied to the specimen at a load ratio of $R = 10$. The nucleated pre-crack exhibits about 30 μm in length. Cracks with such length are regarded as physical short cracks [18]. The pre-crack process was performed on a servo hydraulic testing machine at frequency of 10 Hz. One cycle of large load amplitude was applied on the pre-crack. The load was completely released (to $K = 0\ \mathrm{MPa}\sqrt{\mathrm{m}}$) thereafter. The determination of R-curve behaviour of ΔK_{th} was performed on a resonance testing machine with a testing frequency of 108 Hz. The crack length is measured by potential drop method. The detection limit of our measure device is about 10 μm. In order to obtain the R-curve, a step-wise increasing constant load method was used [19,20]. All tests were started at the intrinsic threshold values ($\Delta K = 3\ \mathrm{MPa}\sqrt{\mathrm{m}}$) of the investigated material [17]. For a ΔK smaller than the intrinsic threshold value, no crack propagation is possible. If the crack started to grow, the load amplitude was kept constant. If the FCG rate decreased to a rate lower than 10^{-8} mm/cyc, the ΔK was increased to the next step. At load ratio $R = 0.1$ and $R = -1$, a load increment of $2\ \mathrm{MPa}\sqrt{\mathrm{m}}$ was applied. At load ratio $R = 0.7$, the applied increment was reduced to $0.2\ \mathrm{MPa}\sqrt{\mathrm{m}}$ due to the high mean stress. After the ΔK exceeded certain value, crack kept extending in a proper way which is well known as stable crack propagation. The short crack behaviour inverted into long crack behaviour. This step is referred to as long crack threshold value ($\Delta K_{th,lc}$). For each loading step where the crack propagation got arrested, the total crack extension length was plotted with the current ΔK in one diagram. The fit curve of these data is the fatigue threshold R-curve. The investigation of stable crack extension is done by recording the fatigue crack growth (FCG) rate. More details about the experimental procedure can be found in [20]. A schematic representation of the current load time history including the compressive-compressive pre-crack process, single overload and step-wise increasing constant load method at a load ratio $R = -1$ is presented in Fig. 4. Four different overloads in tension $K_{ov} = 10\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $20\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $30\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $45\ \mathrm{MPa}\sqrt{\mathrm{m}}$ and two overloads in compression $K_{ov} = -30\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $-40\ \mathrm{MPa}\sqrt{\mathrm{m}}$ were investigated in the current study. The reason for the reduced variety in overloads in compression is that the short open pre-crack was introduced by compressive-compressive loading. The applied K_{min} during pre-cracking was $-20\ \mathrm{MPa}\sqrt{\mathrm{m}}$. Compressive overloads with an amount smaller than $20\ \mathrm{MPa}\sqrt{\mathrm{m}}$ are not regarded as overloads under such initial conditions. Therefore only two compressive overloads, -30 and $-40\ \mathrm{MPa}\sqrt{\mathrm{m}}$, were investigated in this

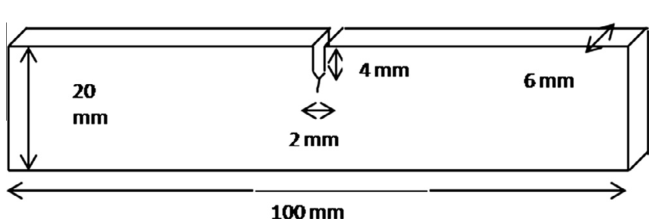

Fig. 1. Geometry of single-edge-notched-bend (SENB) specimen.

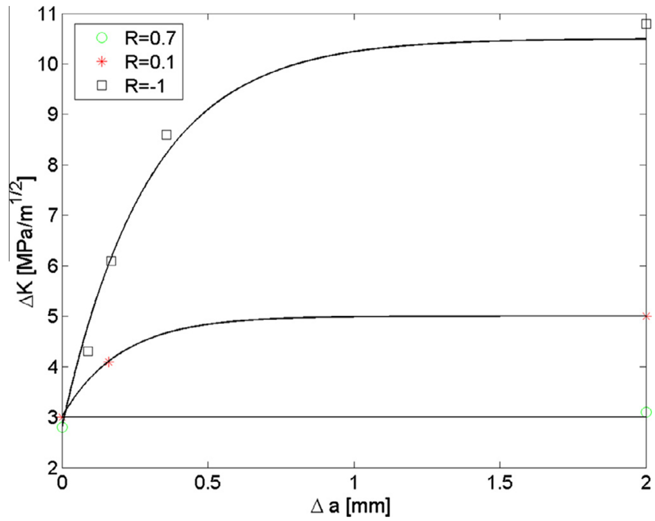

Fig. 2. The R-curves of fatigue threshold of stress intensity range ΔK_{th} at load ratio $R = -1$, $R = 0.1$ and $R = 0.7$. The R-curves are determined by a fit curve of the measure data.

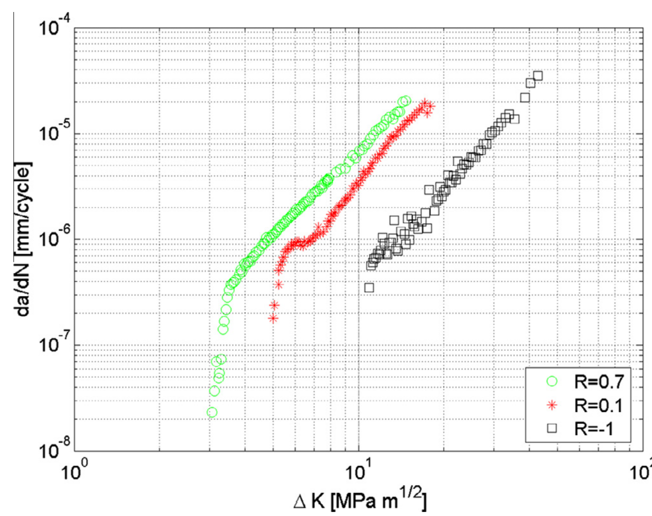

Fig. 3. The FCG rates of the investigated quenched and tempered steel at load ratio $R = -1$, $R = 0.1$ and $R = 0.7$.

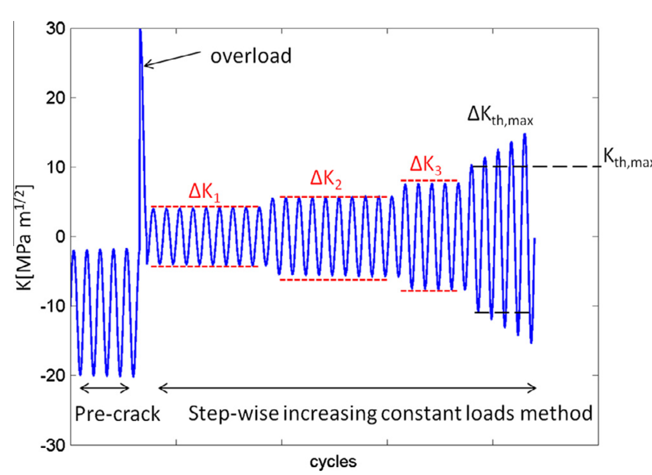

Fig. 4. Schematic presentation of the load time history in the overload experiment $K_{ov} = 30\ \mathrm{MPa}\sqrt{\mathrm{m}}$ at a load ratio of $R = -1$.