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# Influence of the load ratio on the threshold stress intensity factor range for heavily drawn steel wires

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ABSTRACT

The fatigue behavior of heavily drawn steel wires with a diameter of 175 μm and total strain of 3.5 has been studied. A new approach is used to estimate the threshold stress intensity factor range for crack growth ($\Delta K_{th,R}$) which is based on fatigue crack initiations at internal non-metallic inclusions. At these internal crack initiations a characteristic area is formed around the inclusion (in literature this region is called optical dark area, granularly bright facet or facet). This area corresponds to the short crack growth regime. The transition between short and long crack growth, which can be seen clearly by fractography, is used to estimate $\Delta K_{th,R}$.

$\Delta K_{th,R}$ is estimated for different stress amplitudes ($\sigma_a$) and load ratios ($R$). It is observed that $\Delta K_{th,R}$ is independent of $\sigma_a$ and that the fatigue crack growth is $K_{max}$ controlled for $R < 0.15$ and $\Delta K$ controlled for $R > 0.15$. The two asymptotes of the ($\Delta K$, $K_{max}$) graph, $\Delta K^*_{th}$ and $K^*_{max}$, are calculated to be $3.82 \pm 0.09$ and $4.47 \pm 0.16$ MPa $\sqrt{m}$ respectively.



## 1. Introduction

Heavily drawn steel wires have a wide spread of important applications. In some of these applications dynamic properties are crucial. Despite the fact that the properties of drawn steel wires changed due to the tendency of producing thinner wires with higher tensile strengths, little research on their dynamic properties was published during the last 10 years.

The threshold value for crack growth is the most important material property for fatigue since it defines the minimum loading conditions necessary for a fatigue crack to grow. This threshold value is usually expressed as the threshold stress intensity factor range for crack growth ($\Delta K_{th,R}$). $\Delta K_{th,R}$ depends on microstructural parameters, temperature and environment, but also on the load ratio ($R$ = minimum applied stress/maximum applied stress). Elber [1] explained the influence of the load ratio by using a crack closure mechanism that originates from the plastically deformed wake of the crack that makes contact with itself while some tensile loading is still applied. Other closure mechanism such as closure due to the surface roughness and oxidation were extensively described in literature [2–4].

More recent literature [5–8] shows that for very small crack growth rates (at or around $\Delta K_{th}$) plastic closure is insignificant. Vasudevan et al. [9] showed that the decrease of $\Delta K_{th}$ with $R$ is more dependent on environmental effects that alter the fatigue crack growth than on roughness/oxide induces closure. These experimental observations spurred interest in using two intrinsic material thresholds to explain the load ratio effects.

Vasudevan et al. [10] introduced a unified damage approach in which the fatigue crack growth is dictated by two crack tip driving forces, namely $\Delta K$ (causing cyclic plastic damage) and $K_{max}$ (causing crack tip rupture). In this approach the fatigue data can be plotted for any crack growth rate in terms of $\Delta K$–$K_{max}$ rather than $\Delta K$–$R$. Such $\Delta K$–$K_{max}$ plots at the near

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threshold crack growth rates yield two asymptotes relating to the critical values for $\Delta K$ and $K_{max}$, namely $\Delta K^*_{th}$ and $K^*_{max}$, which are the necessary requirements for a crack to advance. In literature it was shown that this unified damage approach successfully accounts for the load ratio effect [11–13] and is applicable for all $R$ values [14].

By the use of a new threshold determination method which is based on fatigue crack initiations at internal non-metallic inclusions it is possible to determine the threshold values for crack growth for these small diameter wires. In this study fatigue tests are performed on several $R$ values in order to determine $\Delta K^*_{th}$ and $K^*_{max}$, for the heavily drawn steel wires used in this study.

## 2. Experimental procedure

### 2.1. Material

The materials used in this study are brass coated steel wires with a diameter of 175 μm and an ultimate tensile strength (UTS) of 3187 ± 37 MPa. The wires were cold drawn to a total strain of 3.5. After wire drawing the wires are straightened (bend over pulleys in perpendicular planes) to introduce compressive residual stresses at the surface.

### 2.2. Fatigue tests

Fatigue tests were preformed on a hydraulic Schenk fatigue machine with a linear actuator PLZ 7 and a 1 kN load cell. The experiments done in this study are stress driven pull–pull fatigue tests. The fatigue tests were performed at five different load ratios: $R$ = 0.05, 0.2, 0.4, 0.5 and 0.6. The fatigue tests at $R$ = 0.5 are performed at three different stress amplitudes $\sigma_a$ = 665, 707 and 748 MPa. The other fatigue tests were performed at stress amplitudes of 956 ($R$ = 0.05), 1123 ($R$ = 0.2), 854 ($R$ = 0.4) and 561 ($R$ = 0.6) MPa.

All fatigue tests were performed at a frequency of 60 Hz and with a gauge length of 80 mm. The fatigue tests were performed in a controlled environment with a relative humidity of 54 ± 4% and a temperature of 20.4 ± 0.3 °C. All fatigue fractures were examined with scanning electron microscopy (SEM) using a FEI XL30 FEG system.

### 2.3. Threshold determination method

For the heavily drawn steel wires investigated in this study, about one out of four samples fractures internally at non-metallic inclusions. This internal fracture mode shows a fish eye appearance, which was also observed for high strength steels [15]. Around the non-metallic inclusion a very rough area is observed, which is called facet area (FCT) in this paper. Fig. 1 shows clearly the appearance of this FCT area. The edge of the FCT area is characterized by the transition of mixed mode crack growth to mode I crack growth. In SEM this transition can be identified clearly (Fig. 1).

The $\Delta K$ value of the FCT area ($\Delta K_{FCT}$) can be calculated using Murakami's formula for internal cracks of an arbitrary shape:

$$\Delta K_{FCT} = 0.5 \cdot \Delta\sigma \cdot \sqrt{\pi \cdot \sqrt{\text{area}_{FCT}}} \tag{1}$$

with $\Delta\sigma = \sigma_{max} - \sigma_{min}$ and area$_{FCT}$ is the area of the FCT projected on a plane perpendicular to the applied load.

To get a better understanding on the relevance of the FCT area, an effort is made to present the internal fatigue crack growth in a Kitagawa diagram [16]. The left side of Fig. 2 shows a schematic representation of the Kitagawa diagram.

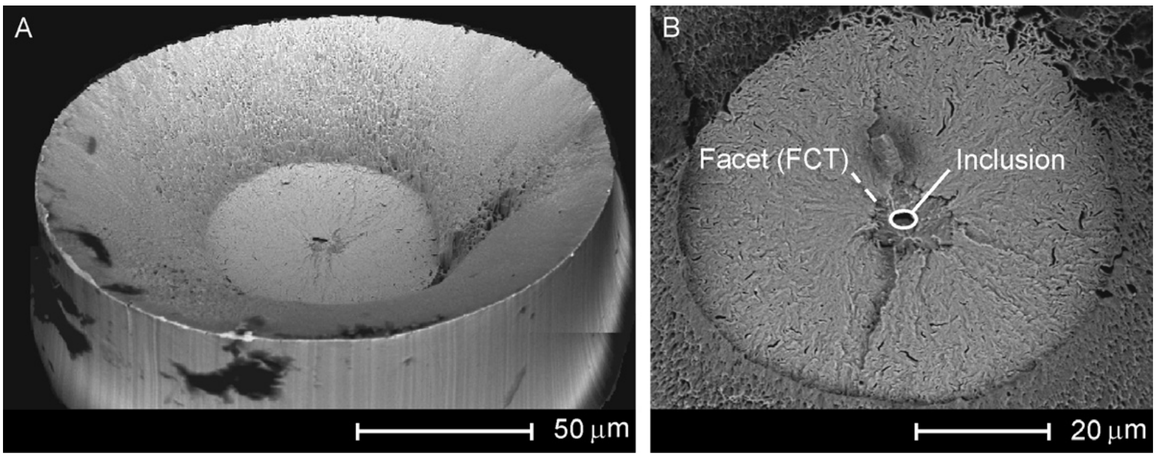


**Fig. 1.** Left: fish eye fracture. Right: FCT area.