MODELLING SURFACE DEFECTS AS CRACKS: A NEW APPROACH TO THE FATIGUE LIMIT OF STEEL WIRES

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ABSTRACT

A model is presented, which allows a quantitative assessment of the influence of bulk properties and surface characteristics on the fatigue limit of drawn steel wires. The former are represented by the fatigue threshold, the latter by size and geometry of surface defects. It was shown that these can be treated like cracks.

KEYWORDS

Fatigue; crack growth; fracture; fatigue threshold; surface defects; steel wire.

INTRODUCTION

A basic understanding of the fatigue process in materials and structures requires an insight in its four constitutive phases : hardening or softening, crack initiation, crack growth and final fracture. Because they are most relevant for life time predictions, the crack initiation and the crack growth phases have been thoroughly, but separately studied. Even the approach of the two phases was often different : physical metallurgists and materials scientists focussed on crack initation problems, whereas crack growth was often, but not exclusively, treated from a mechanical point of view. Hence, it is not at all surprising that a gap originated between both approaches. The filling of this gap only recently started by studying short cracks and attempting to describe their growth behaviour in a similar way as had been done for long cracks. However, it soon became evident that both theoretical and experimental difficulties thwarted this approach. On the other hand, linear elastic fracture mechanics (LEFM) appeared to be no longer valid, because either the plastic zones became too important in relation to the crack length or the microstructure was too coarse compared to the same length, which prevented to treat the material as a homogeneous, isotropic continuüm; moreover, crack shape and orientation required special stress intensity calculations. On the other hand, crack growth measurements are extremely difficult to perform in the case of short cracks, and also the real "crack initiators" which prevail in structures are not at all easy to simulate in test specimens.

When we started a fundamental study of the fatigue behaviour of steel wires, we also tried to split the fatigue process in an initiation and a propagation phase, as we thought that both phases would be influenced by different microstructure related parameters. Two findings compelled us to abandon this hypothesis. The first was the impossibility to define the length of the initiation phase; although we could detect cracks as short as 30 μm (cfr. infra), we could not find evidence to set the limit of the initiation phase at 30, 100 or even 500 μm. To choose any of these limits seemed arbitrary. The second finding was that cold drawn steel wires always show some surface damage. As they were tested as drawn, viz. without further surface treatment, an analysis of crack origins by scanning electron microscopy showed the presence of crack initiators, which were a result of the cold drawing process, not the fatigue testing. Hence, the question arose whether these initiators could be treated as short cracks. If they would, then a fundamental understanding of the fatigue properties of steel wires could result from this study.

OUTLINE OF A NEW APPROACH

Our new approach to the study of the fatigue properties of steel wires is schematically shown in Fig. 1.

As a first step, we redefined, in agreement with recent literature, the fatigue limit as the maximum stress amplitude at which cracks, that are present before or created during the fatigue test, do not grow up to final fracture.

As a second step we used fracture mechanics to describe fatigue crack growth. According to this new paradigma, the limit between growth and non-growth of (long) cracks is defined by the fatigue threshold, the stress intensity factor range (ΔK_{th}) at which crack growth rates ($\frac{da}{dN}$) become infinitely small

$$\Delta K_{th} = \alpha \Delta\sigma \sqrt{\pi a} \quad \text{for} \quad \frac{da}{dN} \rightarrow 0 \qquad [1]$$

Because our preliminary study showed that surface defects act as fatigue crack initiators, our new hypotesis could be formulated as follows :

"the fatigue limit σ_e of steel wires is determined by the fatigue threshold ΔK_{th} and the surface depth a_o of defects, which behave like small cracks, according to the formula

$$\sigma_e = \frac{\Delta K_{th}}{2\alpha \sqrt{\pi a_o}} \qquad [2]$$

To check the validity of this hypotesis, two parameters viz., the fatigue threshold ΔK_{th} and the fatigue limit σ_e, were measured, so that the defect depth a_o could be predicted using formula [2]. Then, the defects from where fatigue cracks originated were measured. An agreement between measured and predicted defect depths would indicate the validity of the hypothesis.

MATERIALS

This procedure was applied to five cold drawn, pearlitic steel wires of the same diameter (Ø 2 mm). To obtain five different tensile strengths, only the cold drawing strain and therefore the diameter at the last patenting treatment was varied. All other parameters were kept constant, the steel composition (0.66 % C, 0.72 % Mn) as well as the wire drawing processing. Mechanical stress relieving was applied after drawing. Table I shows the mechanical properties of these wires : with increasing drawing strain ε or reduction η, the yield stress σ_y and the tensile strength σ_u increase, but the reduction of area Z decreases. Surface condition is characterized by the surface roughness R_a and the maximum depth of surface defects $a_{L,M}$, observed on longitudinal sections by means of optical microscopy (Table II).

TABLE I - Mechanical Properties of the Five Pearlitic Steel Wires

code name	η (%)	ε (-)	σ_y (MPa)	σ_u (MPa)	Z (%)
2-1.3	27.6	0.32	1111	1321	58
2-1.5	61.0	0.94	1207	1469	63
2-1.8	85.5	1.93	1578	1855	57.9
2-2.1	90.5	2.35	1902	2099	51
2-2.1	91.9	2.51	1952	2218	49.5

EXPERIMENTAL PROCEDURE AND RESULTS

Fatigue Limit

The fatigue limit was measured in a statistical way, using a procedure proposed by Dengel (1). Tests were carried out on a servohydraulic fatigue testing apparatus at a frequency of 30 Hz. A constant mean tensile stress of 600 MPa was applied, and afterwards the fatigue limits at R = 0 and R = - 1 were calculated using a Goodman-Smith diagram.

Fatigue Threshold

To measure the fatigue threshold, crack growth was monitored by a high frequency (10 kHz), low current density (1A), AC-potential drop technique. (Verpoest 2,3).

Once a crack growed to about 200 μm length, a load shedding technique (at R = 0) was applied to obtain crack growth rates as low as 10^{-8} mm/cycle at final cracks lengths of 400 to 800 μm. A double logarithmic, linear regression was carried out on all data points with $da/dN < 10^{-6}$ mm/c, and the fatigue threshold was defined at 10^{-7} mm/c. Figures 2 and 3 show some typical results for lower strength (σ_u = 1300 MPa) and high strength (σ_u = 2200 MPa) steel wires.

It was found that the fatigue threshold decreases when the drawing strain, and therefore the tensile strength, increases. However, for high strength steel wires (σ_u 2000 MPa) the fatigue threshold remains constant at about 3.5 MPa $\sqrt{m}$. Comparison with literature data on pearlitic steels can hardly be done, because all but one data points are in the tensile strength range from 500 to 1000 MPa (Verpoest, 4). However, fatigue thresholds for martensitic steels follow the same trend (Ritchie, 5 ; Vosikovsky, 6 ; Lindley, 7 ; Gu, 8).

TABLE II - Fatigue Properties and Surface Characteristics of the fine Pearlitic Steel Wires

	$\sigma_{e,600}$ (MPa)	ΔK_{th} (MPa$\sqrt{m}$)	R_a (μm)	a_{LM} (μm)	$a_{o,c}$ (μm)	$a_{o,o}$ min → max
2-1.3	390	(7.89)	-	-	-	- - -
2-1.5	366	5.61	1.10	10	30.9	5.2→10.6→22.5
2-1.8	421	3.80	0.92	6 8	11.8	3.9→ 7.9→13
2-2.1	471	3.53	0.84	4 5	8.7	3.2→ 6.3→ 9.4
2-2.1	565	3.79	-	-	7.4	2.4→ 5.9→ 8.4

APPLICATION OF THE NEW APPROACH

Calculation of the Initial Defect Size

After reaching the fatigue threshold, the specimens were fractured by a tensile test. The fatigue crack always was semi-circular, with center at the crack origin. If one assumes that the crack grows concentrically, the initial defect can be treated as a semi-circular surface crack, for which the geometrical factor α equals 0.67.
So, the initial defect size can be calculated using formula [2]. Table II shows that this calculated value $a_{o,c}$ decreases with increasing tensile strength or wire drawing strain. This trend is in agreement with the evolution of the surface roughness (Ra) and of the defect depth (a_{LM}) as revealed by optical microscopy on longitudinal sections. The absolute values are quite different, the former because of the coarseness of the roughness measuring needle, the latter due to the low probability that the longitudinal sections cross the deepest defects. Hence, the calculated initial defect depths have to be compared with the real, observed crack origins.

Observation of Real Crack Origins

An extensive scanning electron microscope study was carried out on about 150 steel wires, fractured in Locati-type accelerated fatigue tests to assess the fatigue limit (cfr. supra). The cracks initiated at stress levels only slightly higher than the fatigue limit. So, we can be sure that the crack origins found in this study are representative for the surface defects which cause fatigue failure when cycling the steel wires at stresses just above the fatigue limit.
The mean observed initial defect depths are given in Table II which shows that $a_{o,o}$ follows the same trend as $a_{o,c}$; the mean value is slightly lower, but the spread on the results is very important (from half to almost double the mean value).
We also found that the crack origins have different forms, and therefore different depth-to-half-width-ratio's a/c (see fig. 1). The SEM study revealed that crack origins can be classified in three groups :

a. broken martensite (fig. 4) : poor lubrication can cause a local overheating of the wire during the wire drawing process; when the wire leaves the drawing die, a thin martensite layer is formed by sudden cooling; during the next drawing step, this martensite is fragmented forming shallow cracks (low a/c-ratio).
b. two grooves (fig. 5) longitudinal grooves are typical surface features in drawn steel wires; we found that many fatigue cracks originated at the point where two grooves came very close to each other (intermediate a/c-ratio).
c. holes (fig. 6) : they are caused by surface inclusions, which drop out during wire drawing or fatigue testing; sometimes the inclusions are still present (high a/c-ratio).

From these observations, it clearly follows that the assumption made above, namely that the crack origin is semicircular (a/c = 1), is not valid : each individual surface defect has its own a/c-ratio, as shown in fig. 1. Hence, the geometrical factor α has to be adapted as well. From data by Newman (9), the following relation (valid for semi-elliptical surface cracks) was derived :

$$\alpha = -0.139\left(\frac{a}{c}\right)^2 - 0.314\,\frac{a}{c} + 1.123 \qquad [3]$$

After introducing [3] into [2], we can determine the 95 % probability bands for the calculated defect depths $a_{o,c}$ as a function of the defect geometry a/c : fig. 7 (A&B). In the same plots, each observed crack origin, as characterized in the SEM-study by a depth $a_{o,o}$ and a ratio a/c, is represented by one dot.

DISCUSSION : VALIDITY OF THE NEW APPROACH

Higher Strength Steel Wires

Figure 7B is representative for the higher strength steel wires ($\sigma_u \geq 1800$ MPa) : the agreement between the measured and the predicted defect depth is very good. This means that for these wires (2-1.8, 2-2.1, 2-2.2) the three dimensional surface defects can indeed be treated as two dimensional small cracks, for which equation form [2] is applicable. For the "broken martensite" type of crack origin, this is quite obvious : long, shallow cracks are already present before the fatigue test. For the other two types, the crack origins are in fact three dimensional, irregular notches. Figure 6 shows how even these defects can be treated as cracks :

a. two grooves (fig. 5) : due to the heavy wire drawing deformation very fine cracks are present at the corners of the central ribbon (I); at these corners, the stress intensity factor is high (α = 0.82), so the cracks grow and meet each other, forming a through crack in the central ribbon (II), with an even higher K-value (α = 1.12); finally, this crack reaches the bottom line of the two grooves, forming a semi-elliptical crack with a lower α-value : this is the critical crack depth.
b. holes : a similar model can be developed, as again a small corner crack can easily spread over the inner surface of the hole : moreover, contrary to the very elongated grooves, these holes indeed act as three dimensional notches, increasing the local stresses at their bottom and hence facilitating the development of cracks around the hole.

The fact that the (long crack based) formula [2] can be used to relate defect depth and geometry, fatigue threshold and fatigue limit, means that these defects can be treated as long cracks. Further calculations and observations (4) indeed proved that the plastic zones are small and the microstructure fine relative to the defect depths.

Lower Strength Steel Wires

Figure 7A shows that the new approach cannot be applied to lower strength steel wire (σ_u < 1600 MPa) : the observed crack origins are much smaller than the calculated ones. A future publication will make clear that LEFM is invalid for these lower yield stress wires, and that a simple, approximative elasto-plastic treatment restores the fitting between calculation and observation. For these wires, defects indeed become "short" cracks, as pointed out in the introduction.

CONCLUSIONS

A new approach to the understanding of the fatigue properties of steel wires has been developed, and shown to be succesful, provided some elasto-plastic corrections are made for lower strength steel wires. This new approach allows to separate the influences of surface and bulk properties on the fatigue limit of steel wires. Bulk properties are characterized by the fatigue threshold, whereas the size and shape of individual surface defects (and not the overall surface roughness) are the most important surface characteristics. Further studies will show that the influence of polishing and oxidation (rust forming before wire drawing) can be explained in a similar way by this model.

REFERENCES

1. Dengel, D. (1978). In "Verhalten von Stahl bei Schwingender Beanspruchung", Verlag Stahleisen, Düsseldorf, 23.
2. Verpoest, I. et al. (1981). Fatigue of Eng. Mat. & Struct., 3, 203.
3. Verpoest, I. et al. (1982). In "Crack Length Measurement II", EMAS, Warley, (U.K.).
4. Verpoest, I. (1982). Ph.D.-thesis, Cath. University, Leuven, Belgium.
5. Ritchie, R.O. (1977). Metals Science, 11, 368.
6. Vosikovsky, O. (1979). Eng. Fract. Mech., 11, 595.
7. Lindley, T.C. and Richards, C.E. (1982). In "Fatigue Thresholds", EMAS, Warley (U.K.).
8. Gu, H. and Knott, J.F. (1981). In "Fatigue Thresholds", EMAS, Warley (U.K.).
9. Newman, J.C. (1979). In "Part-Through Crack Fatigue Life Prediction", ASTM-STP 687, 16.

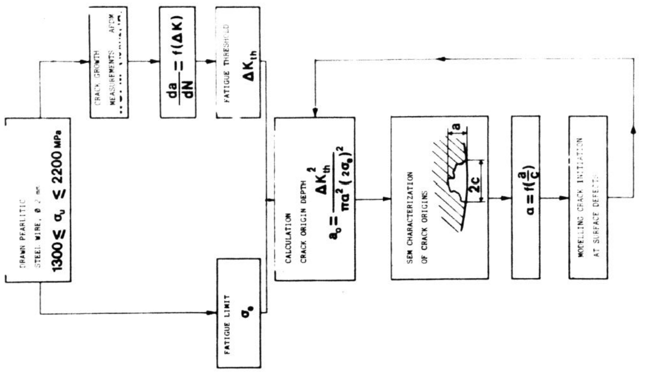

Fig. 1. Schematic representation of the fundamental study of the fatigue behaviour of steel wire.

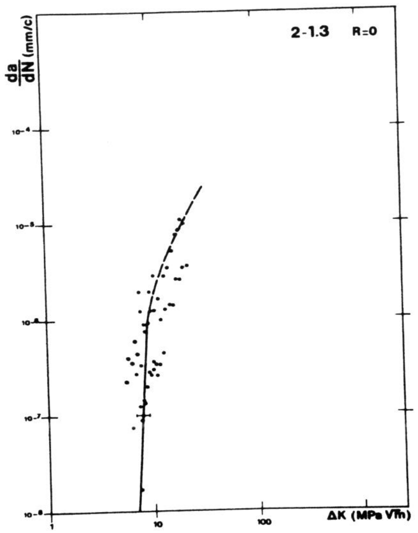

Fig. 2. Fatigue crack growth rate versus stress intensity factor range for wire 2-1.3 at R=0.

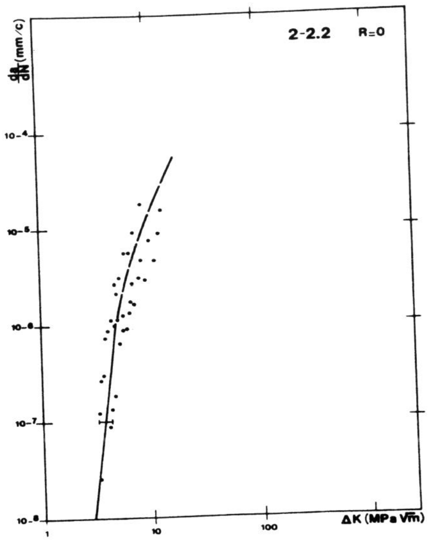

Fig. 3. Idem fig. 2 for wire 2-2.2 at R=0.

crack surface

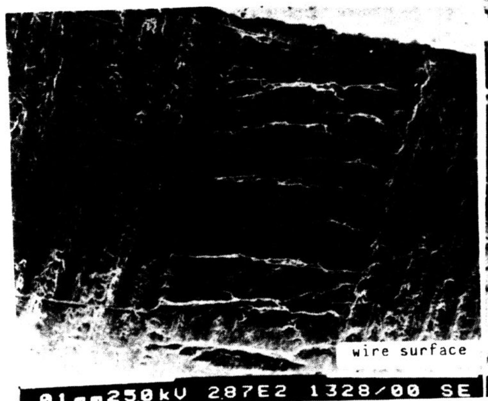

Fig. 4. Fatigue crack origin: broken martensite

Fig. 6. Fatigue crack origin: hole

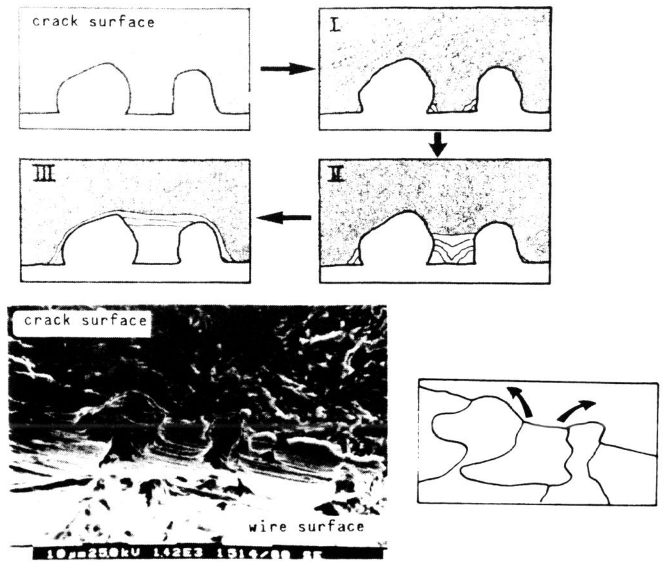

Fig. 5. Crack initiation at two longitudinal grooves.

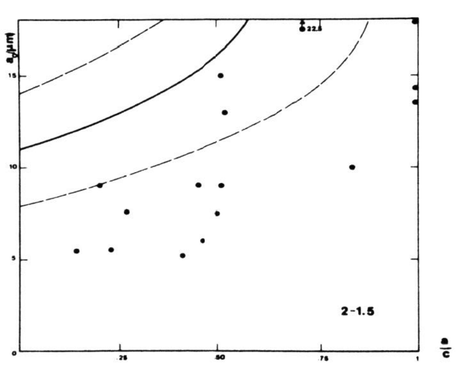

Fig. 7A. Comparison between observed (o) and predicted (full) line with 95% confidence limits) defect depths for wire 2-1.5 at R = O.

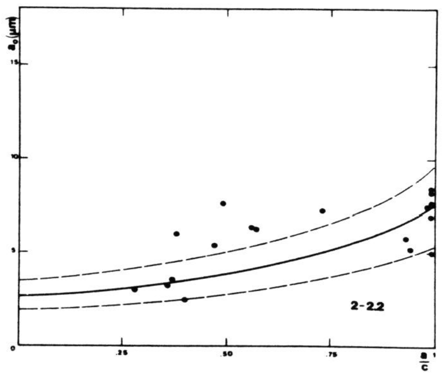

Fig. 7B. Idem fig. 7A for wire 2-2.2 at R = 0