A QUANTITATIVE ASSESSMENT OF THE INFLUENCE OF SURFACE CONDITION ON THE FATIGUE LIMIT OF DRAWN STEEL WIRES

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ABSTRACT

The influence of the surface conditions on the fatigue limit of drawn steel wires can be assessed using a model which takes into account the depth and geometry of surface defects, and the fatigue threshold. This model has been used to rationalise the beneficial influence on the fatigue limit of electrolytic polishing after wire drawing or in between two wire drawing steps. Furthermore, the effect of surface strengthening by cold rolling (as a simulation of shot peening) has been explained as well.

KEYWORDS

Fatigue; crack initiation; fatigue limit; fatigue threshold; fracture; surface treatment; inclusions; electrolytic polishing; steel wire.

NOMENCLATURE

\( \alpha \): geometrical factor in K-formula

\( \sigma_{e, \text{exp}} \) and \( \sigma_{e, \text{c}} \): experimentally measured and calculated fatigue limit

\( t_{p} \): polishing duration

\( R_{a} \): surface roughness amplitude

INTRODUCTION

Steel wires are mostly used in applications where they are subjected to dynamic loading of various types: regular vibrations (e.g. valve springs), irregular vibrations (e.g. piano wires) and even shocks (e.g. elevator or crane ropes). Hence, the fatigue limit of steel wires is of major practical interest. Because most wire users only specify the required tensile strength, materials selection and wire drawing processes have now been optimised in order to reliably obtain tensile strengths beyond 3000 MPa. If the general rule would be applicable that the fatigue limit equals one third to one half of the tensile strength, one would expect fatigue limits between 1000 and 1500 MPa. Unfortunately, this is not true: Pomp (1931) and Gil (1934) showed 50 years ago that the fatigue limit to tensile strength ratio decreases from 0.3 (at \( R = 0 \)) or more for patented or slightly drawn steel wires to about 0.2 or even less for highly drawn (to \( \varepsilon = 3 \)) steel wires. This general trend has been more
recently confirmed by Becker (1978) and Kloos (1978), and by our own work (1982) (Fig. 1). Many attempts have been made to improve the fatigue limit to tensile strength ratio. In order to make a similar attempt in a rational and efficient way, we decided to set up a fundamental study of the parameters which control the fatigue limit of steel wires. In the literature mentioned above (1931, 1934) a dichotomy in the arguments can be found: on the one hand, it is clear that bulk parameters play a role, but on the other hand it is evident that the surface conditions are important as well, as fatigue cracks almost always start from the wire surface.

![Graph showing fatigue limit of drawn, pearlitic steel wires](image)

**Fig. 1. Fatigue limit of drawn, pearlitic steel wires**

Hence, we developed a model (Verpoest, 1982), in which both groups of parameters could be assessed in a quantitative way (Fig. 2).

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 to final fracture.

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

\[
\Delta K_{th} = \sigma_e \sqrt{a} \quad \text{for} \quad da/dN \rightarrow 0
\]

Therefore our new model could be formulated as follows:

"the fatigue limit \( \sigma_e \) of steel wires is determined by the fatigue threshold \( \Delta K_{th} \) and by the surface depth \( a_0 \) of defects, which behave like small cracks, according to the formula
Quantitative Assessment of the Influence of Surface Condition

\[ a_e = \frac{\Delta K_{th}}{2a_0} \]

(2)

in which \( a \) is a geometrical factor.

Fig. 2. Modelling surface defects as cracks

This model has been experimentally verified on drawn steel wires with tensile strengths between 1500 and 2200 MPa. From the measured fatigue limit \( \sigma_e \) and fatigue threshold \( \Delta K_{th} \) (for details, see Verpoest, 1982), the initial defect depth \( a_0 \) could be predicted, assuming that these surface defects have the same (semi-circular) geometry and hence the same \( a \)-value as the fatigue cracks. However an extensive scanning electron microscope study revealed different types of crack origins:

a. holes or inclusions near the wire surface
b. thin martensite layers, due to bad lubrication and which had fractured during the next wire drawing step
c. the meeting points of two longitudinal grooves.

For each crack origin type, a different value of the geometrical factor \( a \) has to be calculated as a function of the defect depth-to-width ration \( a/c \). These \( a \)-values range between 0.67 for semicircular defects (i.e. holes, inclusions, \( a/c = 1 \)) and 1.1 for wide, shallow cracks (i.e. broken martensite, \( a/c < 0.1 \)).

A good agreement was found between predicted and observed crack origins (Fig. 3).

Consequently, this model provides a useful tool to separate the influence of bulk properties (characterised by \( \Delta K_{th} \)) and surface condition (of which depth and geometry of specific defects are the most important feature) on the fatigue limit of steel wires.
Fig. 3. Comparison between observed (o) and predicted (full line with 95% C.L.) defect depths at \( R=0 \) (for a drawn, pearlitic steel wire, \( \sigma = 1800 \, \text{MPa} \))

AIM OF THE PRESENT WORK

The specific influence of surface defects in the fatigue limit can be visualised in a \( \sigma_e \) vs \( a_0 \) plot (Fig. 4).

Fig. 4. Influence of the surface defect depth and geometry on the fatigue limit of a drawn, pearlitic steel wire (\( \sigma_u = 1855 \, \text{MPa} \))
In formula (2), only $\Delta K_{\text{th}}$ is a materials constant; as the geometrical factor $\alpha$ varies between 0.67 (for semi-circular defects) and 1.1 (for shallow cracks), formula (2) should be represented in a double logarithmic plot by a set of straight lines with slope $-1/2$. In Fig. 4, the two extreme lines are plotted for a drawn pearlitic steel wire with a tensile strength $\sigma_u = 1855 \text{ MPa}$ and a fatigue threshold $\Delta K_{\text{th}} = 3.80 \text{ MPa} \sqrt{\text{m}}$. From accelerated fatigue tests on this steel wire, we collected a set of 18 crack origins, each of them characterised by a defect depth $a_o$, a depth to width ratio $a/c$, and hence a geometrical factor $\alpha$. For each defect, the corresponding expected fatigue limit of the steel wire can be calculated, using formula (2). In this way we obtain a set of $\sigma_u = f(a_o)$ data points on Fig. 4; the mean value of these calculated fatigue limits viz. $\sigma_{u,c} = 444 \text{ MPa}$ coincides quite well with the experimentally determined fatigue limit at 50% fracture probability ($\sigma_{u, \text{exp}} = 466 \text{ MPa}$).

The most important benefit from this exemplary calculation is that it teaches us three ways to improve the fatigue limit of steel wires [Fig. 5, formula (2)]:

A. by increasing the fatigue threshold $\Delta K_{\text{th}}$
B. by reducing $\alpha$, and hence increasing the depth-to-width ratio of defects
C. by decreasing the defect depth $a_o$

The effect of measure A exclusively depends on volume characteristics such as strength and ductility, and microstructural parameters. The effect of measures B and C on the contrary is merely determined by change of the surface condition of the wire. The present work considers to what extent the fatigue limit could be increased, only by improving the overall surface smoothness. As the overall surface roughness is the result of many material and drawing process parameters, it was decided to improve the surface smoothness by a simple treatment, namely electrolytic polishing. Two variables were separated; on the one hand, the stage at which polishing was carried out (after wire drawing or in between two drawing steps), on the other hand the duration of the polishing (after wire drawing). Furthermore, it is intended to check the quantitative model for predicting the fatigue limit [formula (2)].

Fig. 5. Influence of surface condition on fatigue limit (schematic)
INFLUENCE OF POLISHING DURATION

In the first part of this study the polishing duration was optimised, looking for the maximum fatigue limit improvement.

Experimental

This part of the study was carried out on drawn, pearlitic steel wire (0.66%C, 0.72%Mn) with a tensile strength of 1855 MPa. Electrolytic polishing of drawn wires was done in a H$_3$PO$_4$ (45N) solution, saturated with CrO$_3$, at 90°C; current density was 100A/dm$^2$. Seven polishing durations were chosen: 30 seconds, 1, 2, 4, 6, 8 and 10 minutes (in steps of 1 min.).

Overall Roughness

Peripheral roughness measurements (0.08 mm cut-off length, 16 measurements per wire) clearly show that the overall roughness drops to one third of the original value after 4 minutes polishing. Longer polishing times only have a minor influence (Fig. 6).

![Figure 6: Surface roughness ($R_a$) as a function of polishing duration ($t_p$)](image)

Fatigue Limit

In order to reduce the long testing time usually spent in the statistical determination of the fatigue limit, an alternative procedure was followed: the number of cycles to failure was determined at a fixed mean stress (700 MPa) and stress amplitude (+650 MPa). These fatigue tests were carried out on an Amsler Vibrophore at a frequency of 60 Hz. Prior to fatigue testing, residual stresses were removed by pre-stressing the wire to 90% of the tensile strength.
Figure 7 shows that the mean number of cycles to failure $N_f$ doubles after only 30 seconds and triples after 1 minute of polishing. Longer polishing times only slightly improve the number of cycles to failure. From the knowledge of Wöhler-curves for this type of steel wire, it could be concluded that the fatigue limit for these polished wires ($t_p \geq 2^\prime$) equals $700 \pm 625$ MPa, or $\sigma_{p,0} = 645$ MPa (at $R = 0$). Previous studies (Verpoest, 1982) showed that the fatigue limit of unpolished wires equals 466 MPa, which means that the fatigue limit can be increased by almost 40% by electrolytic polishing.

As pointed out earlier, this improvement of the fatigue limit can be a result of a reduction of the surface defect depth $a_0$ and/or of the geometrical factor $\alpha$ (Fig. 5), the latter being a result of an increased depth-to-width ratio of the surface defects. To classify the exact cause, all crack origins of the polished wires were analysed by scanning electron microscopy. Previous work (Verpoest, 1982) showed that in unpolished wires 50% of the fatigue cracks started at the meeting point of two longitudinal gooves, 25% at a broken martensite spot and 25% at an inclusion or a hole. The present SEM study revealed that 90% of the fatigue cracks in polished steel wires start at an inclusion (Fig. 8); only 10% started at an (unclear type of) surface damage.

As most of the inclusions have a high $a/c$ ratio (0.8 to 1), the improvement of the fatigue limit is not only a result of a reduction of the mean defect depth $a_0$ (down to the size of the largest inclusion), but also of the decreasing geometrical factor $\alpha$.

If we introduce in formula (2) for an idealised inclusion, $\alpha = 0.67$ ($a/c = 1$) and $\sigma_e = 645$ MPa for polished wires (with an unchanged $\Delta K_{th} = 3.8$ MPa/\sqrt{m}$), we find $6.3 \mu m$ as the size of the inclusions which act as crack initiators.
Fig. 8a. An inclusion as crack initiator in a polished wire

Fig. 8b. A hole (formerly an inclusion) as crack initiator in a polished wire
This is in good agreement with the inclusion size determined by conventional methods. Two conclusions can be drawn from the first part of the present study: on the one hand, the fatigue limit of polished wires should be further increased by decreasing the size of the largest inclusions, and not by longer polishing durations which do not remove inclusions. On the other hand, the theoretical fatigue limit of inclusion-free drawn pearlite could indeed reach a value of 50% of the tensile strength, as a simple polishing upgrades the $\sigma_e/\sigma_u$ ratio from 0.25 to 0.34: however, in reality the maximum value is limited by the inclusion size.

**POLISHING ON INITIAL OR FINAL WIRE DIAMETER?**

If one would want to use electrolytic polishing as an industrial process to improve the fatigue limit of steel wires for economic reasons, it should be carried out as early as possible in the wire drawing process, because both the surface and the wire length are smaller at larger wire diameters. In the second part of the present work, a comparison was made of the effectiveness of the polishing treatment on the initial and on the final wire diameter respectively.

**Experimental**

Two sets of tests were carried out, both on pearlitic steel wire (0.65%C, 0.72%Mn).

**A.** In a first series of tests, wires were drawn to an "initial" diameter of 4 mm ($\sigma_u = 1500$ MPa). Half of the test specimens were polished for 7 x 1 minute at 65 A/dm$^2$ in the above mentioned solution. Polished and non-polished wires were further drawn to a final diameter of 2 mm ($\sigma_u = 2100$ MPa), and again half of the specimens were polished (5 x 1 ' at 80 A/dm$^2$).

**B.** In a second series, the initial diameter was 3.2 mm ($\sigma_u = 1500$ MPa). Again, half of the test specimens were polished, but for only 5 x 1 minute at 65A/dm$^2$. Further drawing to a final diameter of 2 mm increased the tensile strength to 1800 MPa, again, half of the specimens were polished.

**Fatigue Tests**

In order to assess the fatigue properties in a reasonable test time, the number of cycles to failure was determined under a fixed fatigue loading condition (700 ± 600 MPa for test series A, 725 ± 525 MPa for test series B).

The mean number of cycles to failure for both test series is listed in Tables 1 and 2:

<table>
<thead>
<tr>
<th></th>
<th>Polishing on final diameter</th>
<th>NO</th>
<th>54 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polishing on initial diameter</td>
<td>NO</td>
<td>43 400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>YES</td>
<td>94 500</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>116 500</td>
<td></td>
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</tbody>
</table>

**TABLE 1 Mean Number of Cycles to Failure for Test Series A**
TABLE 2 Mean Number of Cycles to Failure for Test Series B

<table>
<thead>
<tr>
<th>Polishing on final diameter</th>
<th>NO</th>
<th>YES</th>
</tr>
</thead>
<tbody>
<tr>
<td>polishing on initial diameter</td>
<td>NO</td>
<td>81 400</td>
</tr>
<tr>
<td>YES</td>
<td>94 000</td>
<td>&gt; 500 000</td>
</tr>
</tbody>
</table>

Discussion

These test series lead to somewhat conflicting conclusions. From test series A, one could conclude that polishing on initial diameter has a greater influence than polishing on final diameter. On the contrary, test series B suggests that polishing on initial diameter has a slight influence, whereas polishing on final diameter has a large influence.

This conflict can be rationalised by careful examination of the fatigue crack origins of the wires polished at final diameter. In test series A, inclusions happen to be three times (out of B tests) the crack initiator, whereas in test series B, no inclusions were found as crack initiator. So, the inclusions drastically decrease the mean number of cycles to failure of the series A wires, polished at final diameter, and hence minimise the influence of the polishing at final wire diameter.

This conclusion again stresses the fact that the effectiveness of the polishing treatment is limited by the inclusion content. Furthermore, the smaller influence of the polishing treatment on initial diameter in test series B, could be explained by the shorter polishing time (5x1min at 65A/dm is on the limit of the polishing time needed for heavily drawn, and so smoother wires of diameter 2mm). So, polishing could not have been completed, resulting in a rougher initial wire. When tested in the "non-polished at final diameter" condition, there will be no great difference in number of cycles to failure for both conditions (81000 vs. 94000). As polishing on final diameter is carried out on almost equally rough specimens, it will be equally efficient (number of cycles to failure increases from 81,000 resp. 94,000 to 277,000 resp. 500,000).

EFFECTIVENESS OF SURFACE STRENGTHENING

Shot peening is often applied to improve the fatigue strength of steel wires. It is believed that the higher fatigue limit is a result of the combined beneficial influence of compressive residual stresses in and of increased strength or hardness of the surface layer. In order to clarify whether the above mentioned fatigue strength enhancement by electrolytic polishing can be maintained after shot peening, polished as well as non-polished wires were rolled before fatigue testing.

Experimental

Wires from test series A and B (cfr. supra) were rolled in the non-polished and polished condition. This "rolling" treatment is usually applied to steel wire fatigue specimens, in order to avoid fatigue fracture in the grips, which would lead to invalid test results. The rolling equipment has been developed by Amsler as a tool for their Vibrophore. It consists of a set of three rolls: two are flat and support the wire; the third has a sharp edge (curvature=0.5mm) and has only a small contact zone with the wire, so that high compressive
stresses can be easily applied. By turning the wire around its axis, a spiral contact line is formed, leaving behind a plastically deformed and flattened wire. Hence, it is not surprising that experience has shown that this "rolling" treatment is a handy and efficient simulation of shot peening.

Fatigue tests were carried out in the same way as, for the non-rolled wires of test series A and B (cfr. supra).

<table>
<thead>
<tr>
<th>TABLE 3 Effect of Surface Strengthening on Number of Cycles to Failure in Fatigue Tests (cfr. supra)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>TEST SERIES A: (700 ± 600 MPa)</td>
</tr>
<tr>
<td>not polished</td>
</tr>
<tr>
<td>polished</td>
</tr>
<tr>
<td>TEST SERIES B: (700 ± 525 MPa)</td>
</tr>
<tr>
<td>not polished</td>
</tr>
<tr>
<td>polished</td>
</tr>
</tbody>
</table>

Results of both test series (Table 3) clearly show that the "rolling" treatment is the most efficient of polished steel wires. In this case, the fatigue limit is increased to a value higher than the stresses applied in these tests (N_f > 10^6 cycles). Rolling of unpolished steel wires brings only a limited advantage.

Discussion

As has been shown in the first section of this study, the main effect of electrolytic polishing is the removal of two types of surface defects: broken martensite layers and longitudinal grooves. The former will be further fractured during the rolling treatment. The latter will not disappear, but will be simply closed as the roll passes (with high local loads) perpendicularly to the longitudinal grooves. Hence, most of the fatigue cracks in non-polished, rolled wires originate at closed (overlayed) longitudinal grooves (Fig. 9). The resulting fatigue strength is relatively low, because the worsened defect geometry (wide and shallow, with sharp groove edges) is not sufficiently balanced by improved strength and compressive residual stresses. To the contrary, the defect geometry of the inclusions, which are the almost exclusive crack initiators in polished wires, is not affected during the rolling treatment; as a consequence, this treatment to increase the fatigue strength is most effective on polished wires.

CONCLUSION

According to a model, developed in a previous study, the beneficial influence of electrolytic polishing after wire drawing on the fatigue strength of pearlitic steel wires can be rationalised. It was shown that the depth as well as the geometry of surface defects changes, leaving the inclusions as the only remaining crack initiators. Effectiveness of polishing on initial wire diameters largely depends on polishing conditions. Finally, rolling (as a simulation for shot peening) is shown to be more beneficial to polished than to non-polished wires.
REFERENCES


