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FRACTURE TOUGHNESS MEASUREMENT OF SMALL CRACKS IN HIGH STRENGTH STEEL WIRE

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ABSTRACT

High strength pearlitic steel wire, typically used as tyre bead, can fail during production due to the propagation of naturally occurring longitudinal and transverse flaws. These can lead to failure when the wire is deformed and straightened to produce the desired cast for ease of coiling. The wire has had significant processing costs added to it at this stage, and the prevention of this type of failure is of concern to the wire drawing industry. At the present time, there is no understanding of the influence of process variables, such as flaw size and the amount of deformation that is induced for straightening.

The fracture toughness of this grade of wire was unknown, and could not be determined by standard test techniques due to the small dimensions of the wire (1.83mm diameter). Small transverse flaws were produced by fatigue crack propagation from spark-eroded notches. Compliance measurements and the direct-current potential drop method were used to demonstrate stable crack propagation before unstable failure. The measured fracture toughness (J_{1c} =18kJm^{-2}) was consistent with the toughness of steels with coarser pearlite microstructures (an interlamellar spacing of 0.15µm, as opposed to 0.003µm), measured in conventional test specimens with long cracks [5]. The measured toughness has been used to predict the behaviour of longitudinal flaws during the wire straightening process. This paper reports part of a project which aims to produce a process control model.

KEYWORDS

Wire, Steel, High-Strength, Toughness, Fracture, J-Integral, and Potential Drop Technique

INTRODUCTION

The material being investigated was hard-drawn pearlitic steel wire, 1.83mm diameter, 0.8 wt.% carbon, with a tensile strength of 2.1GPa, and a yield strength of 1.8GPa. Analysis of the fracture performance of this wire requires a better understanding of the failure mechanism of the wire, and also the development of techniques to detect and monitor crack growth in small samples. A method to test wire containing transverse flaws (which are not usually the cause of failures) was simpler, so was investigated first. With the knowledge gathered from these tests, failure originating from longitudinal flaws (which usually cause failures) will be investigated in future work. **Figure 1** identifies the crack planes, Y-Z is termed longitudinal, and X-Z is termed transverse.

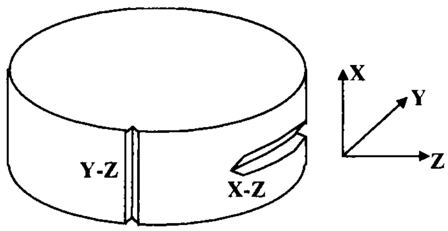

Figure 1. Crack plane identification

Cracked samples were produced by growing a fatigue crack from a spark eroded notch in the wire. To control the fatigue crack growth it was necessary to know the stress intensity (*K*) at the crack tip. Stress intensity factors for cracks (of length, *a*) in round bars (of diameter, *D*) were developed by James and Mills [1] and were suitable to use to calculate the required load (proportional to stress, σ) and subsequent stress intensity during sample preparation. Shorter cracks (less than 500μm) tended to have a semi-circular crack front for which the following equation was used;

$$\frac{K}{\sigma\sqrt{\pi a}} = 0.926 - 1.771\left(\frac{a}{D}\right) + 26.421\left(\frac{a}{D}\right)^2 78.481\left(\frac{a}{D}\right)^3 + 87.911\left(\frac{a}{D}\right)^4 \tag{1}$$

Longer cracks tend to have a straight crack front, producing higher stress intensities. Forman and Shivkumar [2] produced a closed form expression that fits well for cracks shorter than 1100μm, see Eqns. 2 and 3.

$$\frac{K}{\sigma\sqrt{\pi a}} = g\left[0.752 + 2.02\left(\frac{a}{D}\right) + 0.37\left(1 - \sin\frac{\pi a}{2D}\right)^3\right] \tag{2}$$

$$g = \frac{\frac{1.84}{\pi}\left[\tan\left(\frac{\pi a}{2D}\right) \Big/ \frac{\pi a}{2D}\right]^{1/2}}{\cos\frac{\pi a}{2D}} \tag{3}$$

Once the samples were produced, fracture tests were carried out on them. Analysis of the test data, using elastic-plastic fracture mechanics, was performed using the J-integral, following the original methods of Begley and Landes [3]. The J-integral can be viewed as the potential energy difference between two identically loaded specimens with different crack lengths. It measures the work available to drive crack growth and is analogous to strain energy release rate (G). Failure occurs when J reaches some critical value (J_{1c}), which is equivalent to G_{1c}.

METHODOLOGY

The philosophy behind the tests was to produce a set of samples containing a range of flaw sizes (150 – 1250μm). These were then pulled in tension and the load-deflection data was recorded. This data and the fracture surfaces were then analysed using fracture mechanics relationships to determine a fracture toughness value.

The samples were prepared by spark eroding a notch to a depth of either 100µm or 200µm (the former being used to produce cracks shorter than 450µm) using thin copper foil (50µm) at a low voltage (100V). A fatigue crack was grown from this notch, its length was monitored using a calibrated potential drop technique. The cracks were grown in stages, and the load was reduced as the crack grew progressively longer, to minimise the effect of plastic zone on the toughness measurements. The initial load range was 1200N (R = 0.1), decreasing to 250N. The maximum stress intensity factor at the end of pre-cracking was approximately 10MPa√m.

Fracture tests were carried out by pulling the samples in tension at 1mm per minute. The British Standard for fracture testing [4] was followed as closely as possible. The load and deflection data were recorded using a load cell and an extensometer (gauge length 10mm), both of which were calibrated. Previous work on similar wire by Gasterich et al. [5] suggested that monitoring the change in compliance (associated with crack growth) as a way of determining the point of failure might give a large amount of scatter. If this was found to be the case an alternative method, the direct current potential drop technique, would be investigated hopefully to give a more accurate result.

The fracture surfaces were then cleaned in an ultrasonic bath using acetone and mounted on scanning electron microscope stubs. The fracture surfaces were investigated, and crack lengths recorded. The surfaces were expected to consist of 3 regions; spark eroded notch, fatigue pre-crack, and unstable crack growth. The interrupted fracture samples were expected to consist of 5 regions; spark eroded notch, fatigue pre-crack, ductile crack growth, post fracture-test fatigue crack, and unstable crack growth.

RESULTS

All the fracture surfaces were analysed using a field emission gun scanning electron microscope and the crack lengths recorded. Distortions of the images at low magnification were accounted for in the measurements. The surfaces showed the different regions of crack growth as expected. **Figure 2** is an image of a typical sample. Picture **(a)** shows the point at which the crack length was measured, images **(b)** and **(c)** show the different regions seen on the fracture surface.

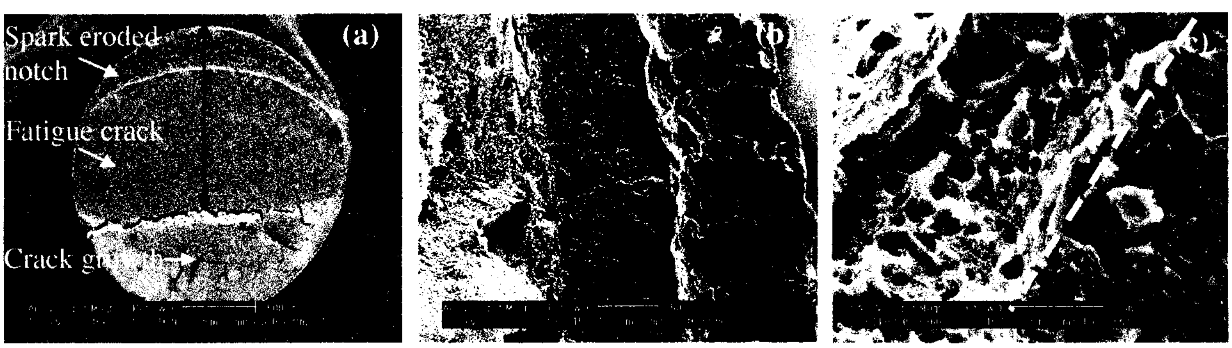

Figure 2. (a) Measurement of crack length, (b) Appearance of (right to left) spark eroded notch, fatigue crack and crack growth. (c) Close-up of fatigue/ductile failure interface.

Analysis of the test data using the compliance based method to determine the point of failure gave a large degree of scatter, and a higher than expected value of J_{1c}. Therefore the crack lengths were monitored using the calibrated direct-current potential drop technique used to monitor the fatigue pre-crack length. The point at which the crack length grew was taken as the point of failure and the sample was then pulled to failure. Interrupted fracture tests were performed to verify that the direct-current potential drop technique was accurately detecting the onset of crack growth (and, therefore, measuring J_{1c}). These involved stopping the fracture test when crack growth was detected and then growing the crack to failure under fatigue conditions.

Fracture surface analysis
Crack growth was predicted to occur when the voltage driving the current through the wire changed from increasing linearly with strain (corresponding to the change in cross-sectional area as the wire was pulled), to non-linearly (**figure 3**).

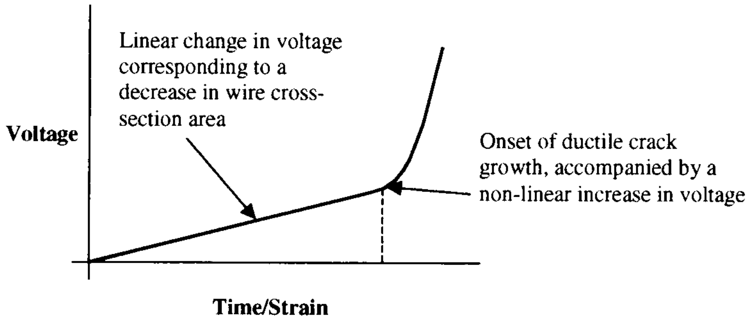

Figure 3. Generic Voltage versus Time/Strain plot produced using a direct current potential drop technique to monitor crack growth.

Analysis of the interrupted fracture samples using a scanning electron microscope show that this change in gradient of the voltage does correspond to crack growth (**figure 4**).

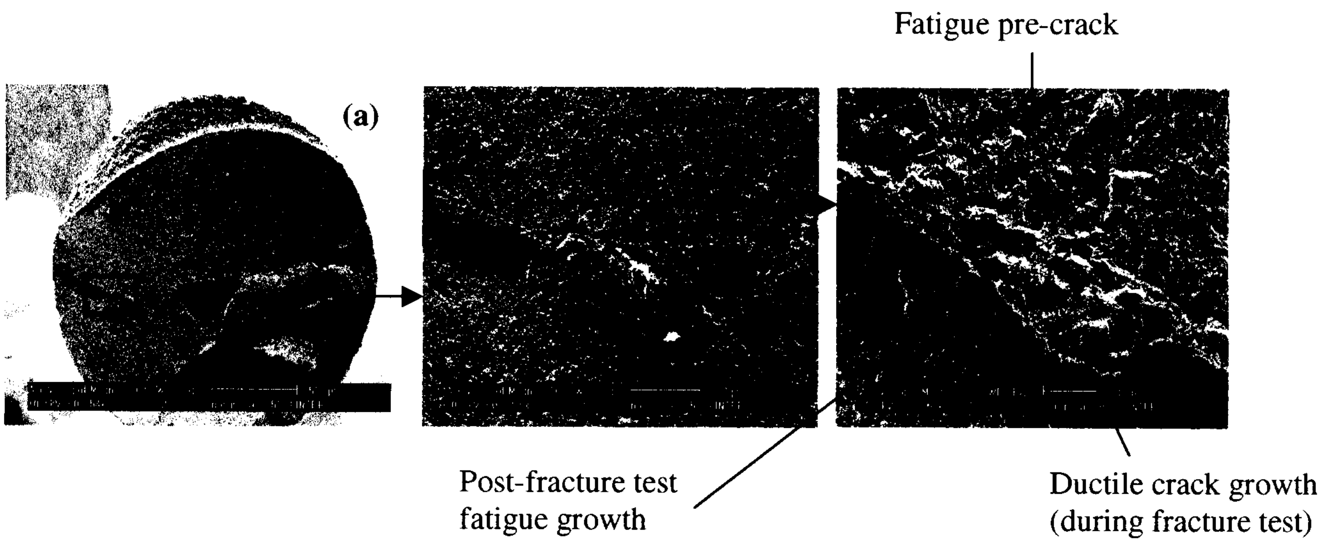

Figure 4. Interrupted fracture test sample. Image c shows the fatigue pre-crack, ductile crack, then post fracture test fatigue crack, that prove that the potential drop technique does detect the onset of crack growth.

The spark-eroded notch is a crescent, of approximate length 200μm. From this notch a fatigue pre-crack was grown, the striations of which could barely be resolved (approximately 1μm between each). Below this is a very fine band (approximately 40μm wide) of ductile crack growth, which occurred during the fracture test (ductile dimples can be seen in **figure 4 (c)**). At this point the increase in voltage became non-linear and the fracture test was stopped. Below this is a region of post fracture fatigue growth, showing the same characteristics as the pre-crack. Finally a region of fatigue crack growth can be seen which occurred when the critical crack length was reached (during post-fracture fatigue growth).

Determination of J_{Ic}

Analysis of the load-deflection data using linear-elastic fracture mechanics showed that K_Q was not a material constant. This indicated that elastic-plastic conditions applied at the crack tip, and that plastic deformation was not insignificant. The J-integral analysis followed the original methods of Begley and Landes. **Figure 5** is a graph of J versus deflection which was used to then determine J_{Ic}, J increases with increasing deflection.

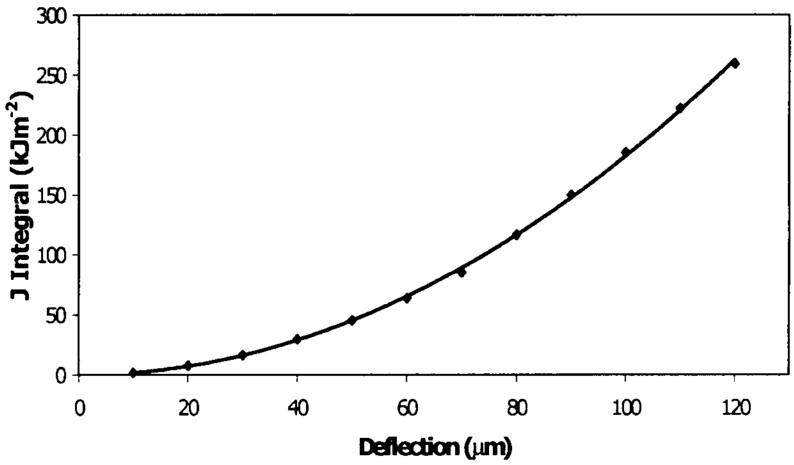

Figure 5. Graph of J versus Deflection calculated from fracture test data using Begley and Landes methodology [3]

Figure 6 is a graph of J_{Ic} versus crack length for the compliance and potential drop techniques. A much lower average J_{Ic} of 18kJm^{-2} was found for the latter, with a scatter of 7kJm^{-2} for longer cracks (greater than 500μm), and 11kJm^{-2} for shorter cracks. This scatter cannot be attributable to the effect of crack shape, or error in the measurement of crack length.

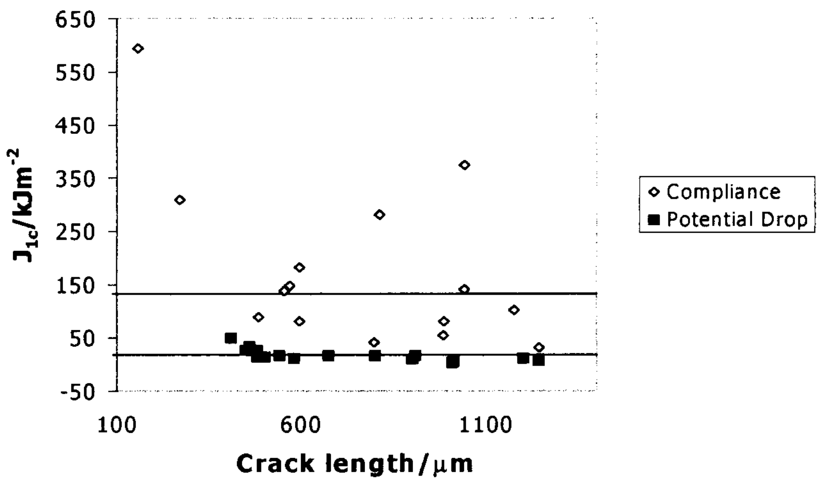

Figure 6. J_{Ic} versus Crack length, average J_{Ic} = 18kJm^{-2}, showing the improvement in consistency of results by using the DCPD technique to detect crack growth.

DISCUSSION

The large amount of scatter produced using this compliance based method corresponded well with the range of scatter seen in a similar material by Gasterich et al. [5], which covered the toughness values for initiation and propagation. This suggested that due to the compliance based nature of the tests, and the relatively small change in stiffness accompanying- crack growth, the point of failure (i.e. onset of crack growth) was not being detected. The use of the direct current potential drop technique to monitor crack growth during the fracture tests gave a J_{1c} value which was nearer to that determined by Gasterich [5] and contained only a small degree of scatter.

Investigation of the fracture surfaces in the field emission gun scanning electron microscope showed that ductile crack growth did occur when the voltage increase became non-linear. Therefore, the toughness value recorded at that point will be the J_{1c} value for this wire containing flaws in the X-Z direction (**figure 1**).

There is an increase in toughness for shorter cracks. This is probably due to the crack tip becoming more constrained by the surrounding material moving from the central region of the wire (where plane strain conditions apply) towards the outer surface. In this region material is constrained from flowing and relieving the stresses acting on the crack tip. This leads to failure at a lower applied load than for plane stress conditions. When the crack tip exists nearer the surface of the wire the material surrounding it is less constrained and can flow and blunt the crack tip. This means that to cause failure, a larger applied load is required to reach the critical stress.

CONCLUSIONS/FURTHER WORK

- The direct current potential drop technique can be used to accurately detect crack growth in small diameter wire specimens.
- Shorter cracks have a higher toughness, attributable to the increase in constraint.
- The toughness value calculated is the J_{1c} for the wire.
- $J_{1c} = 18 kJm^{-2}$, which can be used in a finite element model of the wire containing cracks lying in a different orientation (Y-Z, rather than X-Z). Artificial short longitudinal flaws will be assessed in test conditions that simulate the twisting and bending of wire production. This will determine whether failure criteria is mixed mode or predominantly mode I.

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