DELAMINATION OF HARD DRAWN EUTECTOID STEEL WIRES

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ABSTRACT

Commercially drawn eutectoid steel wires with tensile strengths in the range 1750-2000 MPa were subjected to tensile and torsion testing after static strain ageing. It is shown that delamination in torsion testing can be ascribed to two causes - surface defects and longitudinal shear bands. The former effect becomes dominant as the proof stress of the wire increases, while the latter is enhanced by static strain ageing and may be correlated with the amount of uniform elongation in a tensile test. Further drawing of a statically aged wire will eliminate the shear band initiated delamination.

KEYWORDS

Steel wire; wire drawing; torsion tests; strain ageing; carbon steels.

INTRODUCTION

High strength wires with tensile strengths of about 2000 MPa are commonly produced by continuous cold drawing of patented eutectoid carbon steel rod. For a eutectoid steel the cold drawn wire strength is determined by the initial pearlite interlamellar spacing and the total amount of reduction, but factors controlling ductility are less well understood. Ductility is particularly important when the wire is subject to further plastic deformation during manufacture e.g. ropes or springs, and poor ductility will limit the potential strengthening available from the wire drawing process.

Over the years, the torsion test has evolved as a convenient method of testing wire ductility, and most specifications for high strength wire require a minimum number of twists to failure (N) for a standardised gauge length (usually 100 x d, the wire diameter). Maximum ductility occurs when there is uniform twisting along the gauge length and the final fracture is straight and transverse to the wire axis i.e. ductile failure on the plane of maximum shear stress. Strain localisation and delamination (longitudinal splitting) are qualitative indications of a decrease in ductility, resulting in smaller N values.

The characteristics of wire delamination have been described by Godecki (1969). The initial crack occurs almost parallel to the wire axis after a small strain.

On further twisting the crack extends along the gauge length and becomes a helix in the direction of wire twist. The wire shortens and final fractures may be ragged or straight.

Previous work (Godecki, 1969; Duckfield, 1972; Middlemiss and Hague, 1973) has shown that a minimum amount of total deformation during wire drawing is necessary to produce delamination, with the likelihood increasing for greater drafts and drawing speeds. These observations indicate that strain ageing is a primary cause of delamination. Dynamic strain ageing (DSA) occurs as the wire temperature increases during drawing due to larger draft reductions, increased drawing speed or greater total reductions. DSA results in an increase in tensile strength and a decrease in tensile ductility as measured by reduction of area.

While there has been some activity in reducing DSA by more efficient removal of heat during drawing (Cahill and Jones, 1978; Nakamura and co-workers, 1976) there is little information on subsequent ageing effects occurring after drawing. The purpose of the present work was to study the torsional and tensile behaviour of commercially drawn wire after static strain ageing (SSA).

STEELS

The two 3.87 mm dia. wires received for testing were drawn at 2 m/s and 7.5 m/s (finishing speed) from 8.0 mm dia. lead quenched rod, through eight dies with an overall reduction of 76.8%. Individual draft sizes were in the range 15-19% reduction. The steel chemical analysis was 0.81C, 0.66 Mn, 0.24 Si, 0.032 P, 0.026 S, 0.056 Al and 0.006 N_2. Average die exit temperatures were 110°C and 175°C for the 2 m/s and 7.5 m/s wires respectively.

EXPERIMENTAL AND RESULTS

Tensile testing was carried out on an Instron machine at a crosshead speed of 2 mm/min, using a 25 mm extensometer to record the stress-strain curve until necking occurred.

Torsion testing was carried out on an instrumented hot torsion machine (Weiss, Skinner and Everett, 1973) adapted with end chucks for the testing of wires. Gauge lengths were approximately 55 mm and the testing speed was 1 RPM, giving a strain rate of 4×10^{-3} s^{-1}. A 6.4 kg weight was attached to the free end of the wire in order to apply a small tensile load during testing. Contact pyrometer measurements showed that the temperature rise during testing was less than 20°C. Torque-rev curves were plotted for each test on an X-Y recorder.

Tensile Results

In the as drawn condition the wire drawn at 7.5 m/s was about 200 MPa stronger than that drawn at 2 m/s, and SSA more rapid, since the maxima in tensile strength and proof stress occurred at lower ageing temperatures (Fig. 1). The increase in proof stress was more marked than that of tensile strength, so that for both wires the 0.2% PS/TS ratio increased from 0.82 as drawn, to 0.94 after ageing at 200°C.

There was no correlation of reduction of area values with ageing temperature. For both wires, fracture surface examination showed that the final separation was achieved by radial and longitudinal splitting, and there was some variability in number and intensity of splits from specimen to specimen. However, the amount of uniform elongation was inversely related to the change in proof stress, as shown in Fig. 1.

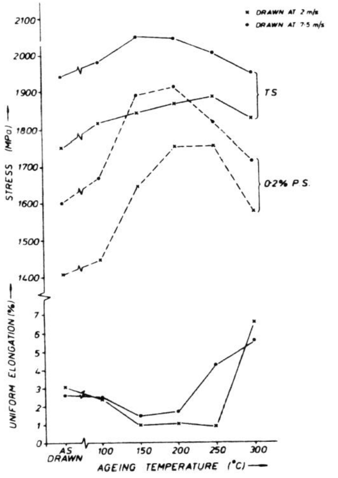

Fig. 1. Effect of ageing 1 hour at temperature on tensile properties.

Torsion Results

During uniform twisting the shear strain $\gamma = \pi d N / \ell$, where d and ℓ are the specimen diameter and gauge length respectively. For cases where straining was not uniform, γ was derived from the angle α, where α is the longitudinal angle of twist, measured by inscribing a straight line along the specimen prior to twisting i.e. $\gamma = \tan \alpha$. γ_d and γ_f are the strains to delaminate and fracture respectively.

Deformation Behaviour

The three main types of torque-rev curves observed in this research are shown in Fig. 2. Curve A represents uniform twisting behaviour with a slowly rising torque level as the number of twists increases. On curve B, the sudden drop in torque at position D signifies the onset of delamination. The torque is erratic on further twisting as the delamination spreads along the wire from the initiation point. Eventually, when the specimen is completely delaminated, the torque rises again in a steady manner. Ductility, as measured by N or γ_f, is lower than for curve A. This type of behaviour was found in wires containing seams or laps, or in defect-free wires after mild SSA treatments. Curve C also exhibits a large torque drop as delamination occurs, but in this case the torque level does not recover. Deformation continues to localise at the site of the delamination and the torque drops until fracture occurs at low strain values. This curve is indicative of severe SSA. Photographs of the three main fracture modes, corresponding to these curves, are shown in Fig. 3.

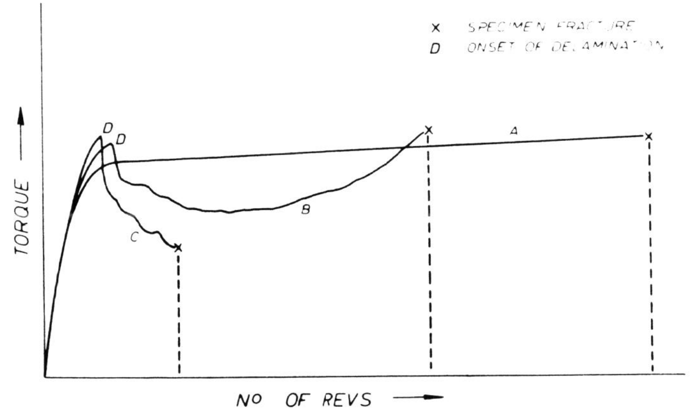

Fig. 2. Schematic torque-rev. curves.

Fig. 3. Torsional fracture modes. (ES - even and straight; LSS - localised, straight and split; LRS - localised, ragged and split).

2 m/s Wire

In the as drawn condition, specimens twisted uniformly and gave ductile shear or ES fractures at high strains ($\gamma_f = 1.2 - 1.4$).

Preliminary studies of ageing response showed that there was no change in ductility after one hour at 100°C, but delamination occurred at 150, 200 and 250°C, and γ_f values were considerably reduced. On ageing for one hour at 300°C, there was no delamination and an ES fracture was obtained with $\gamma_f = 0.9$.

More detailed studies were undertaken to determine the kinetics of SSA induced delamination. Wires aged for different times at 125, 150 and 175°C gave the following times necessary for delamination (t_d) respectively - 1.6×10^4s, 1.5×10^3s and 2.1×10^2s. By plotting log t_d against 1/T (°K^{-1}), it was possible to measure an apparent activation energy of 130 kJ/mol, which is similar to that derived by Yamada (1976) from electrical resistivity measurements on a heavily drawn eutectoid Fe-C alloy.

7.5 m/s Wire

These wires showed variable behaviour in the as drawn condition, since some wires delaminated, whereas others did not. High magnification examination of the steel surface revealed the presence of shallow longitudinal defects (seams and laps up to 0.1 mm deep), which were always the sites for delamination (Fig. 4). By stopping the test on delamination and sectioning the wire, it was shown that the crack extended into the specimen centre. Further twisting caused the crack to spread along the gauge length, as described by Godecki (1969). Fracture strains were slightly lower than for the 2 m/s wire ($\gamma_f = 0.9 - 1.2$). Since the presence of surface defects rendered the wire unsuitable for determining t_d from SSA studies, further experiments were carried out on reduced diameter specimens. These were obtained by centreless grinding to 3.3 mm dia, with copious cooling to prevent heating of the wire.

Reduced Diameter Specimens

Removal of the surface layers of the 7.5 m/s wire eliminated the delamination on torsion testing, so that uniform twisting behaviour with ES fractures ($\gamma_f = 0.95 - 1.05$) occurred. Similar results were obtained after ageing for 6×10^2s at 100°C. However, after 1.2×10^3s and 1.8×10^3s, specimens delaminated at γ_d values of 0.16 and 0.14 respectively. Examination of the specimen surface showed many longitudinal shear bands, which were easily detected by the offset of the grinding marks. One of these shear bands had become the site of the delamination (Fig. 5). The same effects also occurred in reduced diameter 2 m/s wires, and careful examination of the original diameter aged wires confirmed that strain localisation into longitudinal shear bands was a feature of the ageing process.

Types of Delamination

Torque-rev records showed that delamination, whether initiated by surface defects or shear bands, always occurred at low strains ($0.05 < \gamma_d < 0.3$) with a tendency for γ_d to decrease with increased severity of SSA, which also caused an increase in the torque value, as expected from the large increase in proof stress noted in the tensile tests. However,

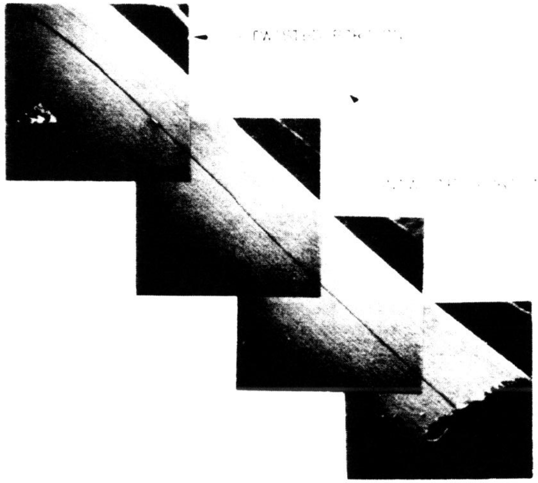

Fig. 4. Torsion specimen (7.5 m/s wire). Surface defect leading to delamination.

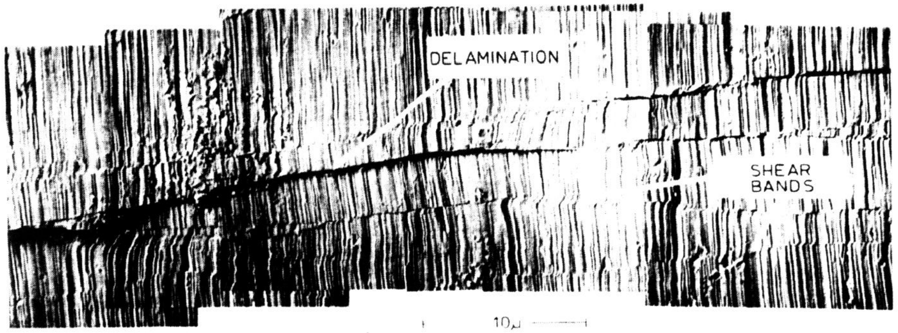

Fig. 5. Torsion specimen surface. Reduced diameter wire. Aged 30 minutes 100°C.

an exact correlation of γ_d with SSA kinetics proved difficult in aged 2 m/s wire. Specimen surface examination showed that in some cases the delamination followed the fibre direction of the wire i.e. orientation of the elongated cementite lamellae. This behaviour is expected in surface defect initiated delamination, but was also found in aged 2 m/s wire where shear bands were evident. In other cases, the original crack was parallel to the torsion specimen longitudinal axis, i.e. on the plane of maximum longitudinal shear stress and at an angle to the fibre direction. This behaviour was never found in unaged specimens, and was clearly associated with shear band induced delamination. Aged specimens also showed intermediate behaviour, with crack branching at shear band intersections. While minor linear surface defects become more favoured sites for delamination as SSA progresses, they are not the reason for the very low γ_f values found in severely aged specimens. On further twisting, defect induced delamination spreads along the specimen, whereas deformation continues to localise in the original area of the cracked shear bands, leading to a localised ragged fracture and low N values.

By eliminating surface defect induced delamination, it was thought that reduced diameter specimens would be suitable for estimating the ageing response of the 7.5 m/s wire. However, initial ageing studies have unexpectedly shown that ageing is more rapid in the 3.3 mm dia. wires, and it is possible that surface heating effects were present in the centreless grinding operation.

Further Drawing

Experiments have shown that ageing induced delamination is reversible, in that subsequent plastic deformation can remove it. Part of the 2 m/s coil was aged at 200°C for one hour and then drawn slowly to 3.73 mm dia. (7.1% reduction of area). On torsion testing there was no delamination; twisting was uniform with an ES fracture of $\gamma_f = 1.26$ i.e. similar to the as received condition.

While ageing at 200°C for one hour resulted in a large increase in proof stress of about 350 MPa (Fig. 1), the subsequent draw caused a decrease to about the level of the as drawn wire (1500 MPa) while the tensile strength continued to increase (to 1960 MPa). The amount of uniform elongation increased to 2%. It can be assumed that dislocations locked by the ageing treatment have been freed by the subsequent draw so that homogeneous plastic deformation can occur at lower stresses. It was interesting to note that the as received wire showed an increase in proof stress on further drawing to the same reduction, signifying that any ageing effects affecting dislocation mobility were slight.

Further drawing of the 7.5 m/s wire did not eliminate delamination, since this was surface defect initiated.

DISCUSSION

The present work has shown there to be two causes of delamination during torsion testing of hard drawn eutectoid steel wires - surface defects and longitudinal shear bands. The latter failure mechanism assumes more importance as SSA proceeds, and is responsible for low N values in torsion testing.

DSA occurring during wire drawing is considered to affect subsequent ductility in two ways: (a) by raising the stress level necessary to move dislocations and so increasing the likelihood of defect initiated shear cracking at the aligned cementite-ferrite interface of the drawn pearlite; and (b) by reducing the work hardening capacity of the steel so that shear band localisation is more likely. Both effects would increase with the amount of drawing reduction and higher drawing temperatures.

Correlation of delamination behaviour with tensile reduction of area is not expected since the failure mechanism is different, but the amount of uniform elongation would seem to be an important parameter since strain localisation is common in alloys having a low work hardening rate. High 0.2% PS/TS ratios also signify reduced work hardening capacity and the wires studied by Godecki (1969) always delaminated when the ratio was above 0.85 (obtained by increased drawing reduction), which was also the case for the wires studied here, (obtained by SSA). It has been shown that the susceptibility of SSA wires to shear band delamination can be reduced by further drawing, or by overaging, both procedures causing an increase in the amount of uniform strain in tensile testing.

The relatively slow ageing kinetics of the 2 m/s wire indicates that no deterioration in torsional properties would be expected at room temperature for several hundred years. The main effect of increasing the drawing speed to 7.5 m/s is to render the steel more susceptible to surface defect induced delamination, through an increase in the stress necessary for plastic flow rather than a change in the work hardening behaviour.

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