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EFFECT OF THE DRAWING SPEED ON THE DELAMINATIONS IN THE TORSION TEST OF HIGH-CARBON STEEL WIRES

In this paper, an attempt was made to explain the causes of surface delamination in high carbon steel wires during the torsion test. For end wires with 1.7 mm diameter drawn at speeds of 5, 10, 15, 20, 25 m/s, technological tests were carried out. Then the susceptibility of the wire to plastic strain was determined. The microstructure analysis complemented the research. Analysis of the fracture torsion test showed that the wires drawn at speeds exceeding 15 m/s are delamination, which disqualify it as a material for a rope and a spring. The source of delamination in high carbon steel wires is their stronger strengthening, especially of the surface layer, which leads to a decrease in the orientation of the cementite laminaes and an increase in the degree of their fragmentation.

Keywords: drawing speed, wires, torsion test, surface delamination

1. Introduction

The process of multi-stage drawing at high drawing speeds of about 25 m/s causes intensive heating of the top wire layer [1] and a change in the conditions of lubrication and friction at the wire–drawing die contact. This often leads to a change in drawing conditions and in the properties of high-carbon steel wires. These wires are used for the production of ropes and springs, so products of which high mechanical and engineering properties, and especially a great number of twists, are demanded [2-7]. These wires are also required to exhibit a smooth fracture after a torsion test.

Issues related to wire torsion testing have been dealt with so far by many authors [8-16]. Previous research has shown that a poorly selected drawing technology and too high wire strain hardening cause a considerable decrease in the number of twists and contribute to the formation of delaminations in wire drawn.

In the torsion test, there occurs tangential stress in the longitudinal and transverse directions and normal stress at an angle of 45°. Delaminations in the torsion tests exist in wires that are characterized by low susceptibility to redundant strain in the cross-section and a poor elongation in the longitudinal sections [11].

Godecki [8] has found that the formation of surface delaminations in wire torsion may only occur under the influence of longitudinal tangential stress that cause a crack parallel to the wire axis to form. This crack bends and transforms into a spiral crack.

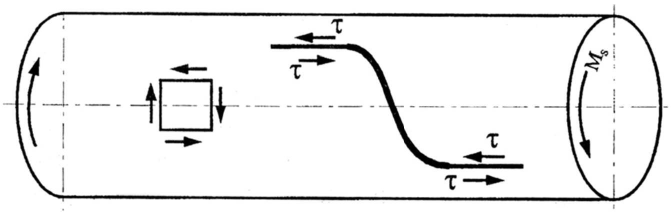

Fig. 1. The scheme of surface lamination forming during wire twisting [8]

To sum up, it can be stated that the resistance of wire to the occurrence of tangential stress depends on the homogeneity of the material and its strain hardening. Therefore, the study has undertaken to determine the effect of high drawing speeds on the occurrence of surface delaminations in the wire torsion test.

2. Material and technology

The starting material for the drawing process was 5.5 mm-diameter wire rod of grade high-carbon steel C78D (Table 1, Fig. 3), which was subject to patenting, pickling and phosphatizing processes.

The process of drawing 5.5 mm-diameter wire rod into 1.70 mm-diameter wire was carried out in 12 draws (Table 2) on a Koch multi-stage drawing machine, type KGT 25/12, in a drawing speed range from 5 to 25 m/s, using conventional drawing dies of an angle of $2\alpha = 12^{o}$ (Fig. 2).

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TABLE 1

Chemical composes of steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	N	Fe
0.790	0.610	0.200	0.010	0.013	0.060	0.020	0.050	0.003	0.003	Remaining

TABLE 2

The distribution of single drafts G_p and total draft G_c

Draft	0	1	2	3	4	5	6	7	8	9	10	11	12
ϕ, mm	5.50	5.00	4.48	4.00	3.60	3.24	2.92	2.64	2.40	2.19	2.01	1.85	1.70
G_p, %	—	17.4	19.7	20.3	19.0	19.0	18.8	18.3	17.4	16.7	15.8	15.3	15.6
G_c, %	—	17.4	33.7	47.1	57.2	65.3	71.8	77.0	81.0	84.2	86.6	88.7	90.5

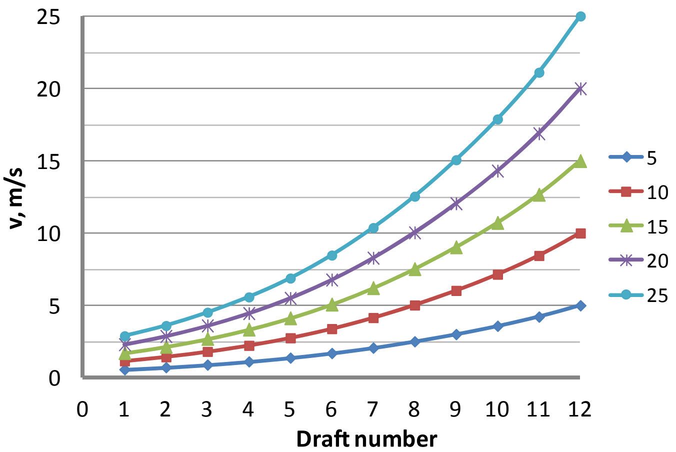

Fig. 2. The distribution of drawing speeds in the succeeding drafts for final speed: 5,10, 15, 20 m/s

3. The results and discussion

To determine the effect of drawing speed on the structural changes, metallographic examinations were made within the study using a scanning microscope. Figure 3 shows a pearlite structure being typical of high-carbon steel wire rod, while Figs. 4-6 depict the microstructures of wires after the drawing process.

The analysis of the metallographic photographs has found that a structural inhomogeneity occurs in the cross-section after the drawing process, with its degree being dependent on the drawing speed. At a total reduction of around 90%, fibrous texture occurs, which is typical of the drawing process. The investigation has found that, regardless of the drawing speed, a fragmentation of cementite lamellas occurs, while the higher the drawing speed, the more inhomogeneous the structure is. Such a structure is less resistant to torsion. The increased disturbance in the oriented flow of cementite lamellas in wires drawn at speeds exceeding 15 m/s, and particularly in their surface layers, might cause the formation of slip bands in multiple directions, not necessarily those crystallographically preferred. As a consequence, cementite lamellas are more prone to cracking. This phenomenon should be associated with a worsening of lubrication conditions and an increase in friction on the wire and die contact surface. This is confirmed by mechanical wire tests reported in work [1], which show that increasing the draw-

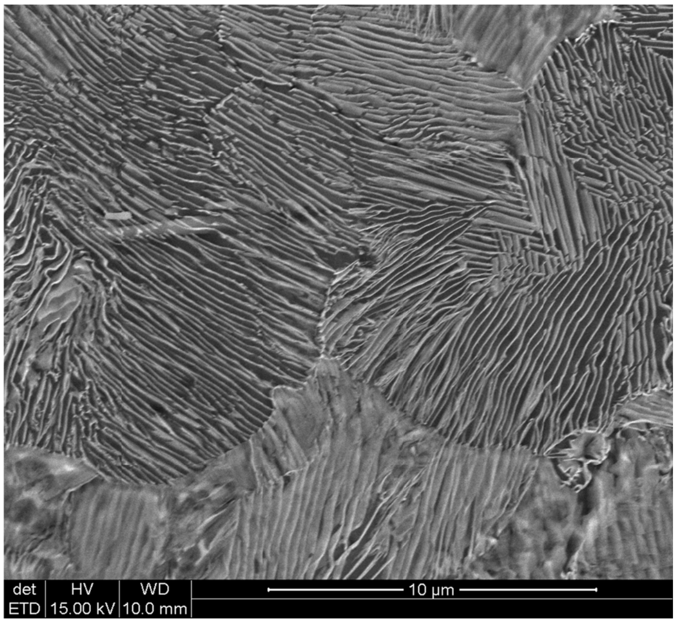

Fig. 3. Pearlite structure of wire rod after patenting; magn. 4000×

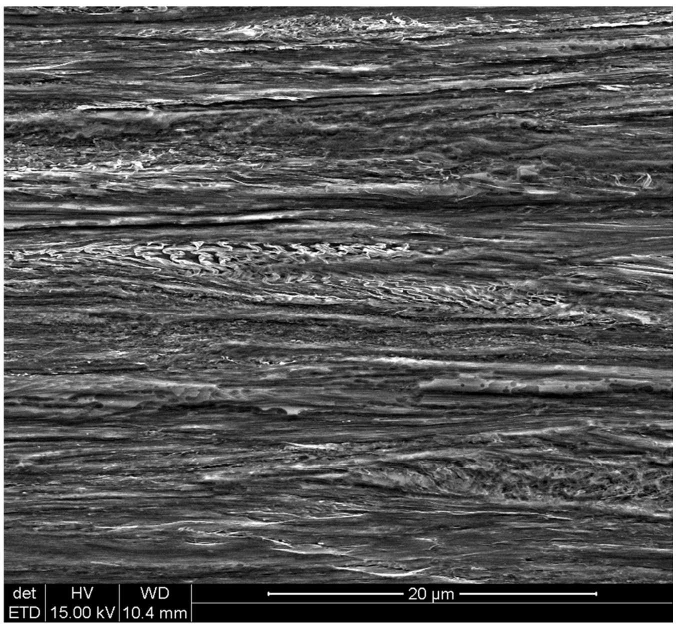

Fig. 4. Microstructure from regions close to the axis of final ϕ1.7 mm-diameter wire drawn in conventional drawing dies at a speed of v = 20 m/s; G_c = 90.5%; a longitudinal microsection

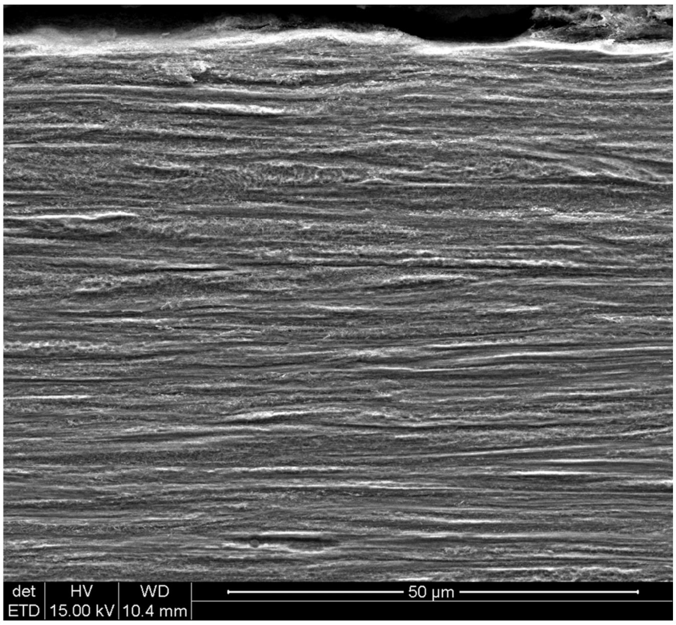

Fig. 5. Microstructure of the surface layer of final ϕ1.7 mm-diameter wire drawn in conventional drawing dies at a speed of v = 20 m/s; G_c = 90.5%; a longitudinal microsection

ing speed results in an increase in the mechanical properties of the wire, with a simultaneous reduction in its plastic properties.

To sum up, it can be concluded that a greater structural inhomogeneity and higher strain hardening of wire drawn at speeds exceeding 15 m/s should cause a drop in the number of twists. In view of the above, wire torsion tests were carried out within this study in accordance with the applicable standard PN-EN 10218-1:2012. The testing results are shown in Table 3.

To make a better analysis of the effect of drawing speed on the wire torsionability, the total γ redundant strain angle and the total ε_{lrz} true longitudinal strain formed during wire torsion testing were determined.

In his study [17], Knap has derived relationships, from which it is possible to calculate the total angle of redundant strain, γ, Formula (1), and the true longitudinal strain, ε, Formula (2), namely:

$$\mathrm{tg}\gamma = \frac{R2\pi n}{200R} = \frac{\pi n}{100} \tag{1}$$

where: R – wire radius, n – number of twists.

$$\varepsilon_l = \ln\sqrt{1+\left(\frac{\pi n}{100}\right)^2} \tag{2}$$

The calculation results are provided in Table 3.

The examination of wire fractures after a torsion test has found, on the other hand, that wires drawn at high speeds exhibit a tendency to surface delamination, as confirmed by the sample fractures of wires drawn conventionally at a drawing speed of v = 20-25 m/s, shown in Figures 6 through 8. By contrast, Figure 9 shows a regular, smooth fracture after a torsion test for wire drawn at a drawing speed of v = 10 m/s.

TABLE 3

The number of twists, N_t; the values of redundant strain, γ, and true longitudinal strain, ε_l, in the torsion test for final wires drawn at a drawing speed of 5, 10, 15, 20, and 25 m/s, respectively

v, m/s	N_t	γ	ε_l
5	40,8	52,05	0,486
10	40,9	52,12	0,487
15	40,2	51,64	0,476
20	39,3	51,01	0,463
25	37,2	49,46	0,430

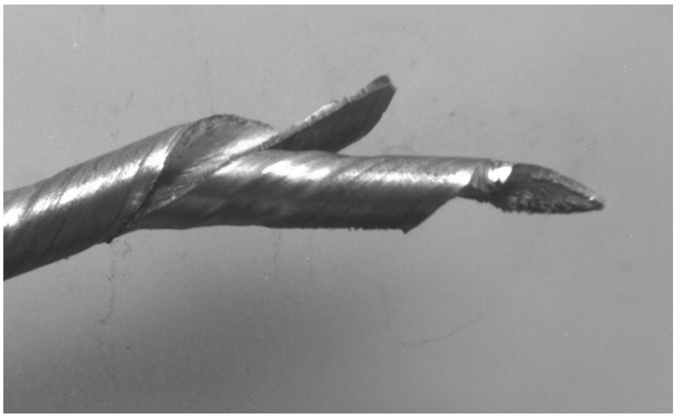

Fig. 6. A fracture of final ϕ1.7 mm-diameter wire drawn at a drawing speed of v = 25 m/s; a characteristic spiral delamination of the wire is visible in the picture

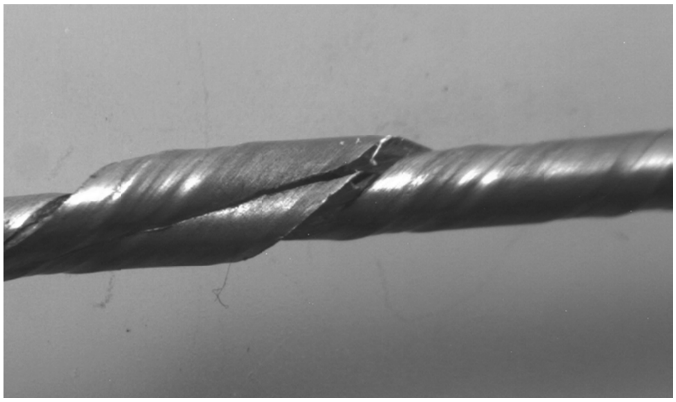

Fig. 7. A fracture of final ϕ1.7 mm-diameter wire drawn at a drawing speed of v = 20 m/s; a characteristic spiral delamination of the wire is visible in the picture

The delaminations in wires drawn ad speeds not exceeding 15 m/s, shown in Figures 6 through 8, confirm the adverse effect of high drawing speeds on the engineering properties of wire. In the author's view, the numerous delaminations formed in wires drawn at high speeds should be associated with poorer lubrication conditions, higher strain hardening and low plasticity properties. For wires drawn at a speed of 10 m/s, only a slight decrease in the number of twists was noted, and wires after torsion testing were characterized by a smooth fracture (Fig. 9). The claim about poorer plastic properties of wire drawn at speeds exceeding 15 m/s is confirmed by Figures 10-11.

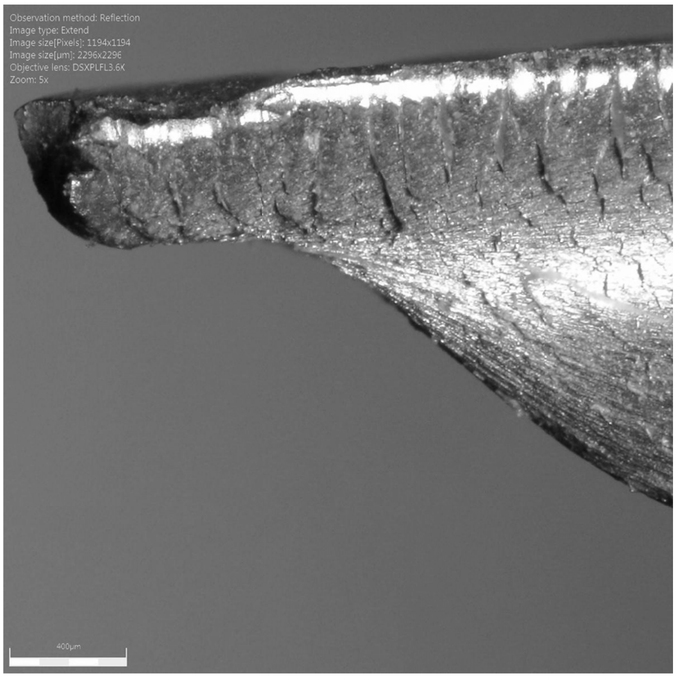

Fig. 8. A fracture of final ϕ1.7 mm-diameter wire drawn at a drawing speed of $v = 25$ m/s in a torsion test; a characteristic fracture surface of delaminated wire with numerous cracks

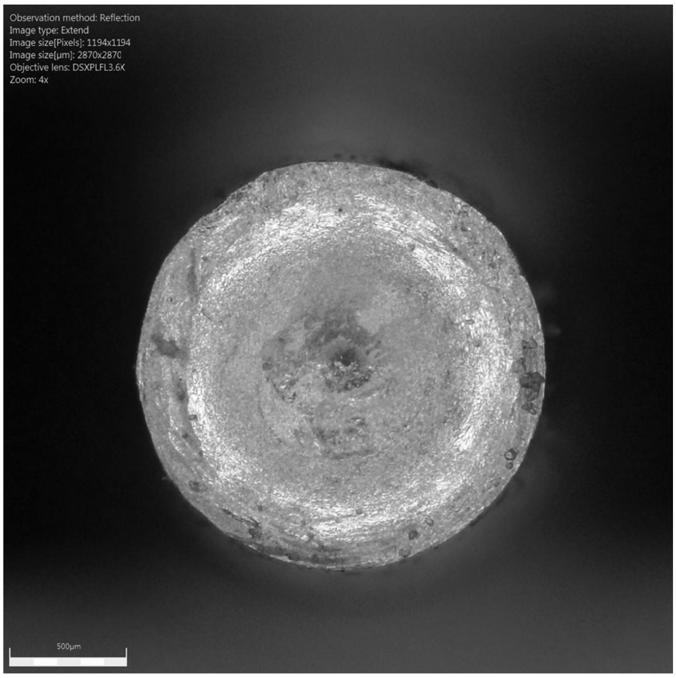

Fig. 9. A fracture of final ϕ1.7 mm-diameter wire drawn at a drawing speed of $v = 10$ m/s in a torsion test; characteristic surface of a smooth fracture

The test results illustrated in Figures 10 and 11 show that drawing speed significantly influences the redundant strain angle and total longitudinal strain of wire in the torsion test. Wires drawn at a drawing speed of 25 m/s, in comparison to wires drawn at 5 m/s, exhibited, respectively, a γ strain angle smaller by 5% and a ε_l longitudinal strain smaller by 11.4%. The lower magnitudes of longitudinal strain in torsion testing of high-speed drawn wires confirmed both their poorer plastic properties and their lower deformability. The poor longitudinal deformability of individual wire layers, combined with the high inhomogeneity of the structure in the wire cross-section, resulted in the formation of surface delaminations.

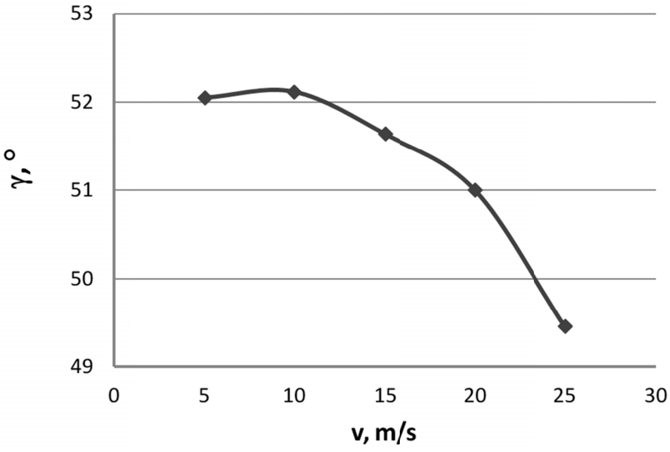

Fig. 10. Variation in redundant strain, g, in a torsion test for ϕ1.7 mm-diameter wires drawn at a speed of: 5, 10, 15, 20 and 25 m/s, respectively

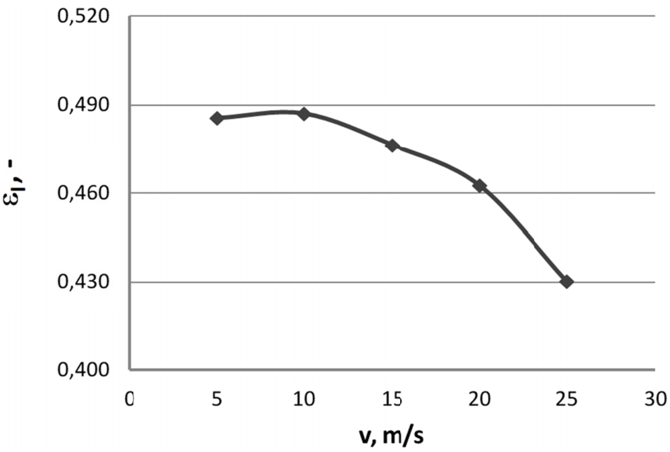

Fig. 11. Variation in true longitudinal strain, ε_l, in a torsion test for ϕ1.7 mm-diameter wires drawn at a velocity of: 5, 10, 15, 20 and 25 m/s, respectively

5. Conclusions

1. The investigation carried out within this study has shown that a structural inhomogeneity occurs in the wire cross-section after the multi-stage drawing process, with the degree of this inhomogeneity being dependent on the drawing speed.
2. It has been found that the formation of surface delaminations in high-carbon steel wires drawn at high drawing speeds exceeding 15 m/s is associated with a greater deformation unevenness, a reduction in plastic properties, and a reduction in the orientation of cementite lamellas and an increase in the degree of their fragmentation.

3. The surface delaminations formed during torsion testing of wire disqualify it from being used as a material for the manufacture of ropes and springs.
4. It is presumed that improving the lubrication conditions in the high-speed multi-stage drawing process by using new lubricants or hydrodynamic drawing dies should prevent surface delaminations from forming in rope wire.
5. The results reported in this paper can be used in industry in developing new technologies for the production of high-grade steel wire intended for springs and hoisting ropes.

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