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THE EFFECT OF DRAWING SPEED ON THE AGEING OF HIGH-CARBON STEEL WIRE

The paper analyzes the effect of ageing on the variations in the mechanical and technological properties of steel wire. The process of drawing 5.5 mm-diameter wire rod into 1.70 mm wire was carried out in 12 draws on a Koch KGT multi-stage drawing machine in the drawing velocity range of 5-25 m/s. Finished 1.7 mm-diameter wires after, respectively, 1, 24, 720 and 8760 hours of the completion of the drawing process were subjected to testing to determine their mechanical and technological properties. The yield strength, *YS*; tensile strength, *UTS*; uniform elongation, A_r; total elongation, A_c; reduction of area, *Z*; number of twists, N_t; and the number of bends, N_b, have been determined.

It has been demonstrated that variations in mechanical properties occur after the multi-stage drawing process due to ageing, with their degree and mode being dependent on the drawing speed.

Keywords: steel, wire, drawing speed, strain aging, mechanical properties

1. Introduction

The process of multi-stage drawing at high drawing speeds of around 25 m/s causes intensive heating up of the top wire layer [1], an impairment of the lubrication conditions and an increase in friction at the wire-drawing die contact. Tests described in work [2] have shown that drawing speed affects the mechanical properties, deformation unevenness and the extent of defect structure. So, it should be expected that drawing technology has also an influence on the ageing phenomenon. Numerous tests carried out in the drawing speed range of 1-5 m/s, [3-7] have shown explicitly that ageing processes are among the main factors responsible for the reduction in the ductility of wire and the increase in its yield strength and tensile strength. Aging also causes an increase in residual stresses. The above-mentioned properties of the wire have a direct impact on the forming process of wire products. During the production of springs, ropes and steel cord in extreme cases, wires may break during twisting and bending. This forces manufacturers to modify the production technology of the above-mentioned steel products.

Ageing processes in the drawing process take place as a function of time and wire temperature. In addition, these phenomena occur during wire storage at ambient temperature [8-11]. In view of the above, a very high temperature of wire drawn at high velocities, as well as a high degree of wire strain hardening, may cause a dynamic ageing phenomenon to occur, which impairs the plastic and engineering properties of the wire. Therefore, the effect of high drawing speeds on the aforementioned ageing phenomena will be determined in this study.

2. Drawing material and technology

The starting material for the drawing process was 5.5 mm diameter wire rod of C78D grade high-carbon steel (Table 1, Fig. 1), which was subjected to patenting, etching and phosphatizing processes. The wire drawing process was conducted in industry conduction based on machinery and technology typical for the drawing industry. C78D steel wires are commonly used in the production of such products as springs, ropes and steel cord.

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	rest.

On Fig. 1 was shown ferrite-pearlite structure typical after wire rod patenting process. 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, using conventional drawing dies of an angle of $2\alpha = 12°$.

In the multistage drawing process, due to the law of constant volume, there is an increase in the drawing speed in subsequent sequences (Fig. 2). The wires were drawn at the final speed: 5, 10, 15, 20, 25 m/s.

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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

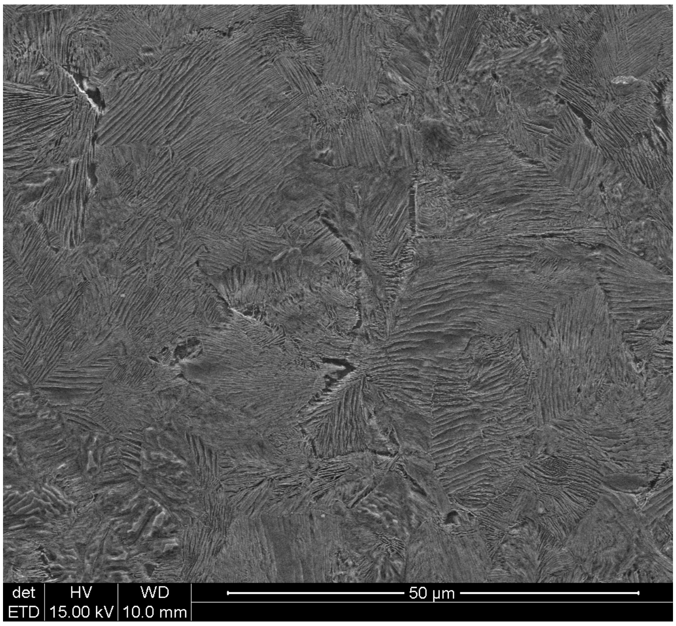

Fig. 1. The pearlitic structure of the wire rod after patenting

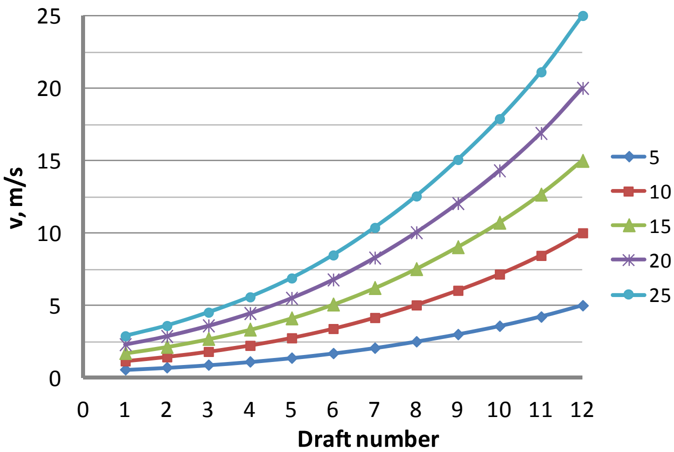

Fig. 2. Distribution of drawing speed in successive draws for individual drawing variants

3. The results and discussion

Tests for the mechanical and technological properties of the wire were performed in accordance with standard PN-EN 10218-1:2012 on a Zwick/Z100 testing machine, on a ZKZE 01/1 torsion test machine and on a ZOZP 01/04 bending type device. According to the standard, during the torsion test, specimens with dimensions of 100 × d (where d is a diameter of the wire) were loaded with an axial force being equal to 2% of the maximum breaking force. By contrast, in the test for the number of bends, the specimens were bent on rollers of a size of ϕ10 mm.

Finished 1.7 mm-diameter wires after, respectively, 1, 24, 720 and 8760 hours of the completion of the drawing process were subjected to testing to determine their mechanical and technological properties. The yield strength, *YS*; tensile strength, *UTS*; uniform elongation, A_r; total elongation, A_c; reduction of area, Z; number of twists, N_t; and the number of bends, N_b, have been determined. Figures 3-4 represent the variation in the strength properties of the wire as a function of ageing time.

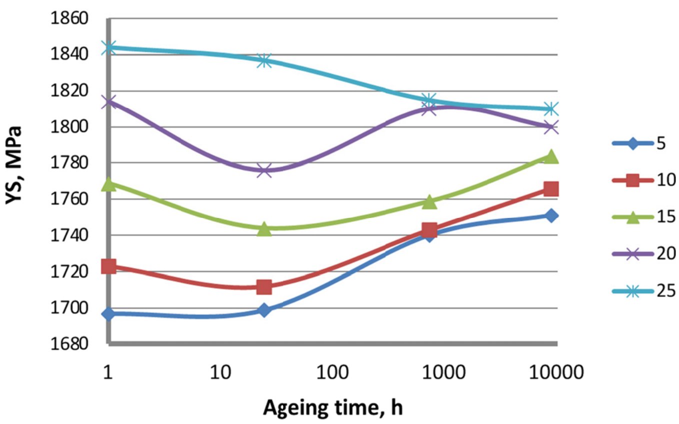

Fig. 3. Variation in the yield strength *YS* as a function of ageing time for wires drawn at a different drawing speed

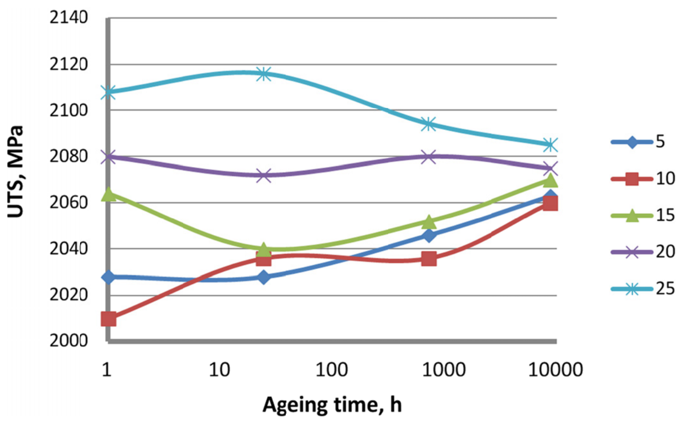

Fig. 4. Variation in the tensile strength *UTS* as a function of ageing time for wires drawn at a different drawing speed

The variations in the mechanical properties of wires shown in Figs. 3-4 indicate that an ageing phenomenon occurs after the multi-stage drawing process, with its nature being dependent on the drawing speed. For wires drawn at low speeds, i.e. 5 and 10 m/s, an increase in strength properties by 45 MPa, on average, was noted. By contrast, for wires drawn at a high speed of 25 m/s, the ageing phenomenon had a reverse behaviour, manifesting itself in a decrease in yield strength and tensile strength, on average, by 30 MPa. It was also demonstrated that differences in strength properties between wires drawn at speeds of 5 and 25 m/s decreased with the increase in ageing time. Immediately after drawing, differences in yield strength and tensile strength between wires drawn at speeds of 5 and 25 m/s were about 110 MPa, while after a year (8760 hours) of the drawing, these differences decreased to approx. 40 MPa. The obtained results are indicative of dynamic ageing phenomena in drawing at high speeds, above 15 m/s. Immediately after drawing, a very quick first ageing stage takes place, which is associated with the migration of carbon atoms dissolved interstitially in the ferrite phase to dislocations and then their fixing. The degree of those changes is dependent on the drawing speed; namely, the higher the drawing speed, the more dynamic the process becomes. High deformation speeds and a high wire temperature exceeding 1000°C [2] in the top layer may simultaneously accelerate the second ageing stage manifesting itself in the migration of carbon atoms from the cementite to dislocations in the ferrite. Whereas, the explanation of the causes of the decrease of strength properties in wires drawn at high speeds is complex. The decrease in tensile strength may suggest the occurrence of the third ageing stage, called over-ageing in the literature [8], which is responsible for the formation of carbon clusters, recovery and carbide precipitation. On the other hand, the third ageing stage occurs when heating up steel at high temperatures within longer time units. In drawing at high speeds, short-time heating of wire up to a temperature exceeding 1000°C takes place in the drawing die; after exiting the drawing die, a fast decrease in wire temperature occurs; and once on the drum, the wire has a temperature of around 200°C, which would contradict the occurrence of the third ageing stage. It is presumed that after a high-speed drawing process, so-called pseudo-ageing might occur. Nevertheless, to confirm this phenomenon, the author plans to carry out further metallographic examinations and investigation including differential scanning colorimetry (DSC) measurements.

As regards the plastic properties of wire, the tests have shown explicitly that the ageing phenomenon, regardless of the drawing speed, causes a decrease in wire plastic properties, as confirmed by the results illustrated in Figs. 5-7. Depending on the drawing speed, wires examined after 1 year, compared to wires examined immediately after drawing, exhibit uniform elongation and total elongation values smaller, on average, by 9%, and a reduction of area smaller by 2%.

Figures 8-9 depict the effect of ageing on the technological properties of wire.

The obtained results do not confirm some literature data [12] that show a significant effect of ageing on the obtained numbers of wire twists and bends. No significant influence of ageing on the increase in wire susceptibility to delamination in the torsion test has been demonstrated, either. The tests carried out within this study have confirmed that, depending on the drawing speed and ageing time, either a slight increase or decrease in technological properties may occur, with these differences ranging from 0.2 to 4%, maximum.

According to the author, in the process of multi-stage drawing, due to the high degree of strengthening (usually wires from high-carbon steel are drawn with a total draft exceeding 90%) and much higher strain rates than those occurring during drawing

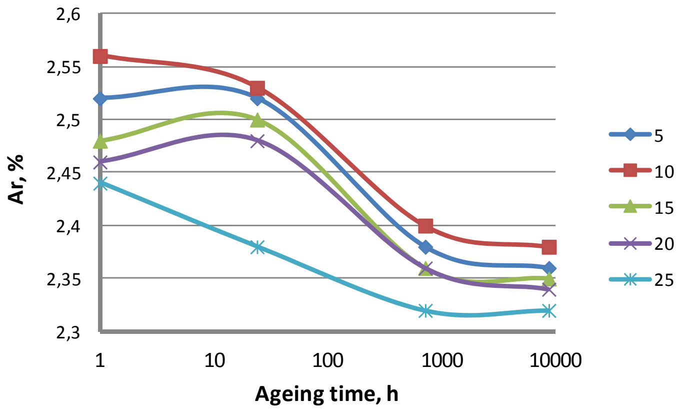

Fig. 5. Variation in uniform elongation A_r as a function of ageing time for wires drawn at a different drawing speed

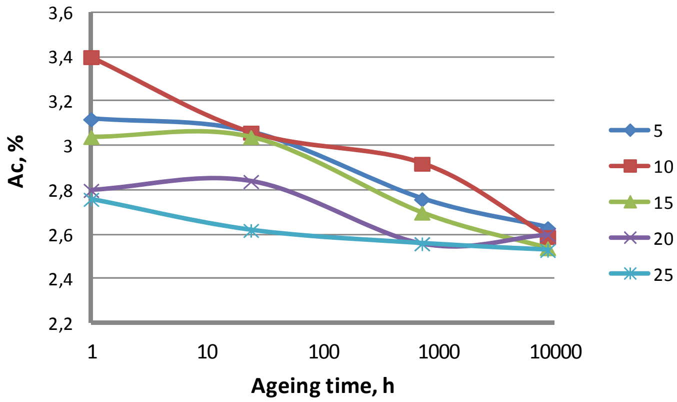

Fig. 6. Variation in total elongation A_c as a function of ageing time for wires drawn at a different drawing speed

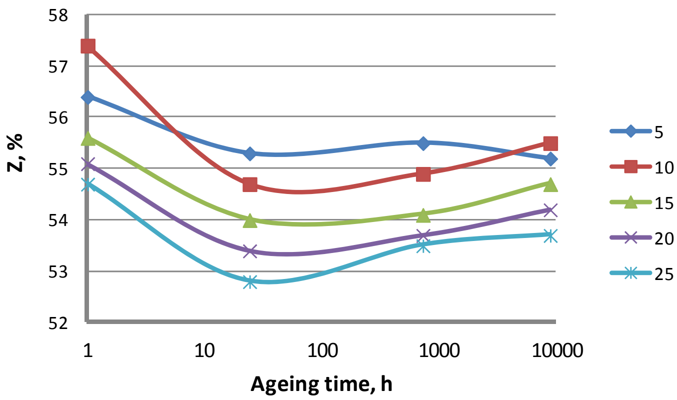

Fig. 7. Variation in the reduction of area Z as a function of ageing time for wires drawn at a different drawing speed

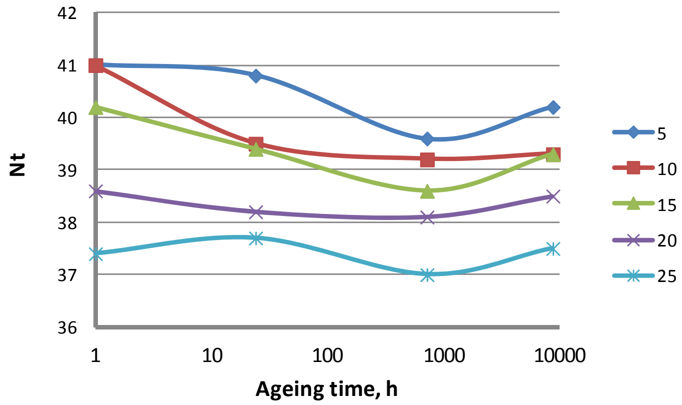

Fig. 8. Variation in the number of twists N_t as a function of ageing time for wires drawn at a different drawing speed

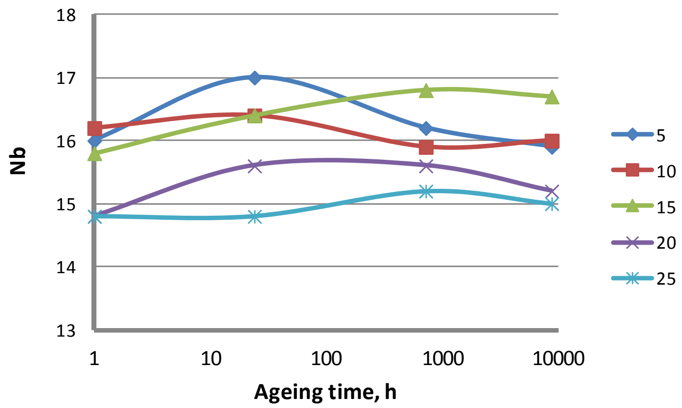

Fig. 9. Variation in the number of bends N_b as a function of ageing time for wires drawn at a different drawing speed

on bull block, dynamic structural formation of wire properties occurs. Immediately after the drawing process, the technological properties of the wire are already pre-stabilized, thus the differences in the number of twists and bends are so small.

5. Conclusions

1. The investigation carried out within the study has demonstrated that an ageing phenomenon occurs after the drawing process, and that its behaviour depends on the drawing speed.
2. For wires drawn at speeds of 5-10 m/s, an increase in strength properties was noted, while for wires drawn at high speeds above 25 m/s, the ageing phenomenon shows a reverse behaviour and manifests itself in a decrease in yield strength and tensile strength.
3. It has been found that the ageing phenomenon, regardless of the drawing speed, causes a decrease in the plastic properties of the wire, as confirmed by smaller values of uniform elongation, total elongation and reduction of area.
4. The tests carried out within this study have confirmed that, depending on the drawing speed and ageing time, either a slight increase or decrease in technological properties may occur, with these differences ranging from 0.2 to 4%, maximum. No significant influence of ageing on the increase in wire susceptibility to delamination in the torsion test has been demonstrated, either.
5. Immediately after drawing, differences in yield strength and tensile strength between wires drawn at speeds of 5 and 25 m/s were about 110 MPa, while after a year (8760 hours) of the drawing, these differences decreased to approx. 40 MPa. The obtained results for strength properties show dynamic ageing phenomena to occur in the high-speed drawing process. Immediately after drawing, very quick first and second ageing stages take place, which are associated with the migration of carbon atoms to dislocations and their fixing. The degree of those changes is dependent on the drawing speed; namely, the higher the drawing speed, the more dynamic the process becomes.
6. The investigation has demonstrated that the ageing phenomena in wire after the high-speed multi-stage drawing process are much more complex than those occurring in wire drawn at a speed of around 1-5 m/s. Hence, ageing phenomena will be the subject of the author's further studies, in which the author plans to extend the analysis based on scanning microscopy examination, differential scanning colorimetry (DSC) measurements and the examination of the magnetic field and force of magnetic coercion of steel wire.
7. The effect of drawing on the aging of high-carbon steel wire is important only for times smaller than a year. Because after this period most of the determined parameters (YS, UTS, Ar, Ac, Z) are at a similar level.
8. The results reported in the 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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