INFLUENCE OF SINGLE-PASS REDUCTION ON PLASTIC PROPERTIESOF WIRE FOR STEEL ROPES

FABÍK Richard [1], VRUBLOVÁ Lucie [2], VYKYDAL David [1]

[1]VSB - Technical University of Ostrava, Ostrava, Czech Republic, EU, richard.fabik@vsb.cz, david.vykydal@vsb.cz,
[2]Trinec Steelworks, Trinec, Czech Republic, EU

Abstract

This paper deals with the evolution of plastic properties of steel wire for steel ropes during cold drawing. The evolution and final values of properties of drawn wire are dictated by the drawing process conditions. One of the most important factors among them is the amount of reduction per pass, and thus the total number of passes. The drawing process was performed using three types of pass schedules. The pass schedules varied in the amount of single-pass reduction and, naturally, in the number of passes. The first one was a standard schedule (7 passes) used in drawing mills, two others were experimental (6 and 5 passes). The principle was a decreasing in the number of passes and thus an increase in the single-pass reduction, while maintaining the total reduction. In this paper, we describe the influence of the amount of single-pass reduction on the final plastic properties (number of revolutions to fracture and number of bending cycles to fracture). Tensile test and metallographic analysis were also conducted. The impact of the pass schedule type on the numbers of bending cycles and revolutions to fracture was insignificant. The most profound impact was that of the pass schedule type on the maximum shear strain to fracture in torsion tests, where cementite lamellae began to bend due to the wire drawing.

Keywords: Wire drawing, wire for steel ropes, pass schedule, plastic properties, simple torsion test, reverse bend test.

1. INTRODUCTION

One of the crucial quality attributes of a steel rope is its life. It is influenced by the steel rope manufacturer as well as by its user. From the user's perspective, a proper design configuration of the rope and observation of operating conditions are the main aspects of importance. The rope manufacturer is responsible for choosing the right rope forming process and for the quality of the input feedstock, i.e. the drawn steel wire. The present paper is devoted to the quality of steel wire. The first difficulty arises even as the appropriate quality characteristics of the wire are to be defined. The typically defined quality characteristics of a steel wire for ropes are summarised in **Table 1**.

Table 1 Quality characteristics of drawn wire for wire ropes

Group of quality characteristics	Quality characteristics
Chemical composition	Contents of alloying elements (C, Mn, Si) and impurities (S, P)
Geometry	Diameter, ovality
Internal defects	Shape, type and size of non-metallic inclusions, segregation
Microstructure	Fractions of phases, pearlite grain size and interlamellar spacing, banding
Surface defects	Cracks, decarburization, abrasion, burning-in, impressions
Fundamental mechanical properties	Tensile strength, yield strength, elongation, reduction of area
Other mechanical properties • Low-cycle fatigue • High-cycle fatigue	 Number of bending cycles and revolutions to fracture Fatigue strength (rotating bending test)

The list of the quality indicators clearly shows that drawn wire for making wire ropes is a very complex product. In practice, one may encounter cases where a wire rope made of a wire which met all requirements has shorter life than a wire rope made of a wire whose quality characteristics were objectively poorer. In other words, it turns out that there is no definite correlation between the above-named quality characteristics of a wire and the life of the wire rope.

A very similar relationship is found between the wire drawing process parameters and the final properties of the wire. Although experience from industrial practice and previous investigations give us some picture of the link between, for instance, a single-pass reduction and the resulting tensile strength, it has been found that if all process factors at all conceivable levels (see **Table 2**) are taken into account, their effects become less definite even in regard to the tensile strength (let alone, for example, the number of bending cycles to fracture during reverse bending test).

Table 2 Overview of process parameters in wire drawing

Group of process parameters	Process parameters
Pass schedule	Total reduction, average single-pass reduction, pass schedule type (uniform, decreasing, increasing, etc.)
Drawing die geometry	Approach angle, friction angle, length of the cylindrical bearing area
Descaling method	Mechanical (bending, wire brushing, shot blasting) and chemical (H_2SO_4, HCl, and others)
Lubricant and lubricant carrier	Type and composition, method of application, purity, age
Wire-drawing machine setup and type	Speed, cooling, drawing block diameter, wire straightener setup (drawing die or 5, 7 or 9-roller straightener), type of die holder (rotating, water cooled), straight-through or accumulating-type wire-drawing machine, method of wire guiding (does the wire undergo twisting?)

Hence, the present paper only presents the first part of results obtained in dealing with the complex matter of life of steel ropes. The purpose of the paper is to describe the effect of a single-pass reduction on the evolution and final values of low-cycle fatigue characteristics of a drawn steel wire.

2. DESCRIPTION OF THE EXPERIMENT

2.1. Material

The experimental material was a drawn and patented wire of 3.4 mm diameter of C78DP steel, the composition of which is given in **Table 3**. Its microstructure consisted of pearlite with an average interlamellar spacing of 100 nm and small amount of upper bainite (see **Fig. 1**). The wire was pickled and its surface was coated with lubricant carrier.

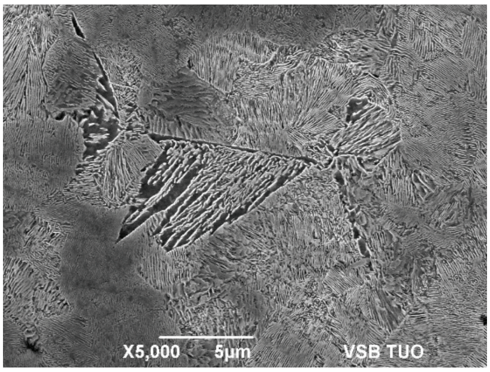


Fig. 1 Initial microstructure of the steel (scanning electron micrograph)

Table 3 Chemical composition of the steel examined (wg. %)

C	Mn	Si	P	S	Cu	Ni	Cr
0.79	0.63	0.20	0.010	0.014	0.04	0.02	0.05

2.2. Wire Drawing

The wire was drawn from the diameter of 3.4 mm to 1.5 mm using straight-through single-block KOCH KGT 25 - E wire drawing machine with a drawing block diameter of 600 mm and a water-cooled rotating drawing die holder. The total reduction was 80.5 %. The drawing speed was approximately 1 m/s. The WC drawing dies had an approach angle of 8°. The lubricant used was a commercial Condat 3T hard soap-based grade with an addition of lubricant carrier. A total of three pass schedules were used, as defined in **Table 4**.

Table 4 Overview of pass schedules

*Standard pass schedule: **7 passes** (average single-pass reduction = 20.8 %)*									
Pass number		0	1	2	3	4	5	6	7
Wire diameter	(mm)	3.4	3	2.7	2.4	2.15	1.9	1.7	1.5
Reduction	(%)		22.1	19.0	21.0	19.7	21.9	19.9	22.1
*Non-standard pass schedule No. 1: **6 passes** (average single-pass reduction = 23.9 %)*									
Pass number		0	1	2	3	4	5	6	
Wire diameter	(mm)	3.4	2.95	2.6	2.25	1.95	1.7	1.5	
Reduction	(%)		24.7	22.3	25.1	24.9	24.0	22.1	
*Non-standard pass schedule No. 2: **5 passes** (average single-pass reduction = 27.9 %)*									
Pass number		0	1	2	3	4	5		
Wire diameter	(mm)	3.4	2.9	2.45	2.1	1.75	1.5		
Reduction	(%)		27.2	28.6	26.5	30.6	26.5		

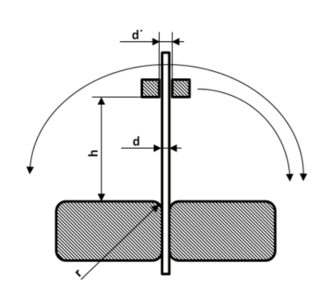
2.3. Wire Testing

Following each pass 10-kg sample of wire was removed from the stock for subsequent testing. Then, 10 test pieces of 60-cm length were made from this sample coil for a torsion test and 10 test pieces of 22-cm length were made for a reverse bending test. Prior to testing, the test pieces were straightened by hand.

Torsion testing was carried out in ZKZE 02/5 machine according to ISO 7800 Metallic materials - Wire - Simple torsion test [1]. As the test pieces had diameters between 3.40 and 1.5 mm, the standard permitted a simplified method of setting the test piece length of 100 times its diameter. In line with the standard, the speed was 50 rpm. The bending test was carried out using ZOZP 02/5 machine according to ISO 7801 Metallic materials - Wire - Reverse bend test [2]. The setup of the test equipment is given in **Table 5**.

Table 5 Reverse bending test parameters

Nominal wire diameter **d**	The radius of the mandrel **r**	The tested length **h**	Diameter of the pinhole **d´**
(mm)	(mm)	(mm)	(mm)
1.0 < d ≤ 1.5	3.75	20	2.0
1.5 < d ≤ 2.0	5.00	20	2.0 - 2.5
2.0 < d ≤ 3.0	7.50	25	2.5 - 3.5
3.0 < d ≤ 4.0	10.00	35	3.5 - 4.5



3. DISCUSSION OF RESULTS

The processing of the results of both tests and, in particular, the comparison between the outcomes for individual pass schedules by means of mathematical statistics is complicated, as the data from these tests does not have the normal probability distribution [3]. This is why standards for steel wire for wire ropes typically specify the minimum number of bending cycles and revolutions to fracture. Such a value is robust enough for the wire user but it may lead to misinterpretation of results of analysis (not only in our case).

3.1. Simple Torsion Test to Fracture

The simple torsion test was conducted using test pieces of various diameters and thus of various lengths. Consequently, the resulting average numbers of revolutions to fracture N_t had to be converted according to the formula for shear strain to fracture [4]:

$$\gamma_t = \frac{\pi \cdot d \cdot N_t}{l} \quad [-] \tag{1}$$

This conversion yields the amount of shear strain in wires of individual diameters regardless of the test piece length L_z.

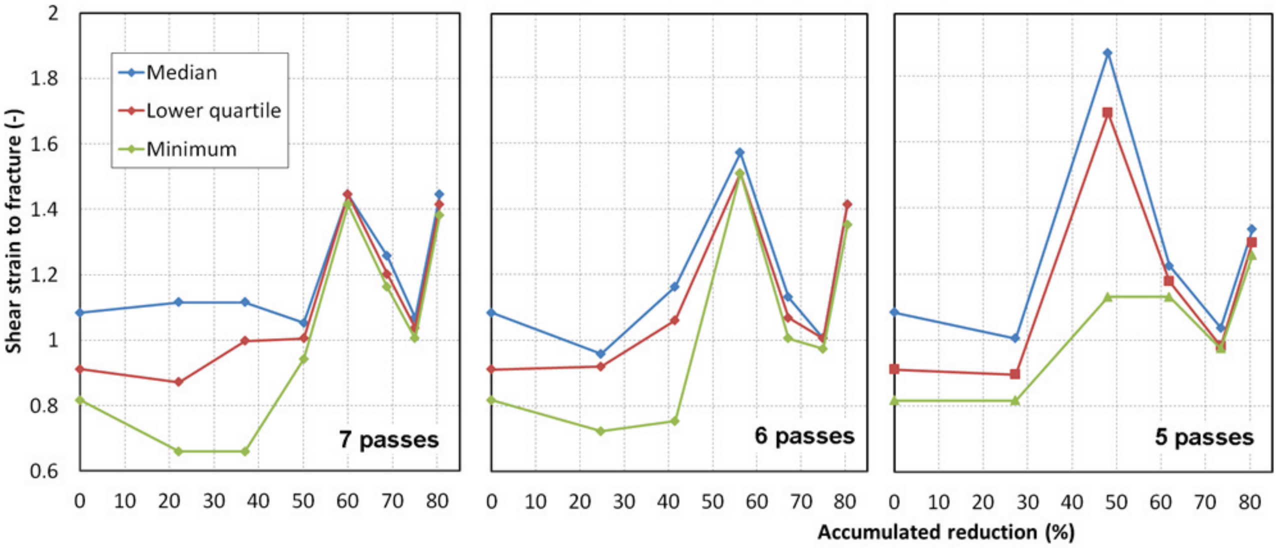


Fig. 2 Evolution of shear strain to fracture during drawing in various pass schedules

Graphs in **Fig. 2** show the evolution of shear strain to fracture during drawing in all pass schedules. The values shown are the median, lower quartile and the minimum value from the total of ten values measured for each pass and each pass schedule. It is clear to see that if just the minimum values for the 5-pass schedule were used, it would distort the results. From the mathematical-statistical viewpoint, it is interesting that the variance of the measured values considerably decreased in the last passes, regardless of the pass schedule. An interesting fact from the practical perspective is the maximum of the shear strain to fracture in the range of accumulated reduction of 48 to 60 %. It is clear at the first sight that with increasing single-pass reduction, the value of maximum shear strain to fracture increases. Another remarkable finding is the steep decrease in this value with increasing reduction and an equally steep rise upon the last pass.

To explain this peculiar behaviour, let us compare the median values of the maximum shear strain to fracture and the ultimate tensile strength values (UTS) (see **Fig. 3**). With the tensile strength evolution plotted for the drawing process, one can distinguish (thanks to different slopes of the curve) three distinct areas with different underlying physical principles of pearlite strengthening [6]. Up until approximately 40 %, the ferrite lamellae in pearlite strengthen. Then, between approx. 40 and 65 %, the cementite lamellae in pearlite undergo bending. Finally, when the reduction exceeds 65 %, cementite lamellae deform and break (to form cementite globules). Hence, it is obvious that the maximum shear strain to fracture in the torsion test is achieved at the point where the deformation resistance values of ferrite and cementite lamellae become equal, i.e. early in the second area. The subsequent decrease in shear strain is therefore due to the onset of cementite deformation. Nevertheless, this is not the way to explain the rise which occurs again after the last draft.

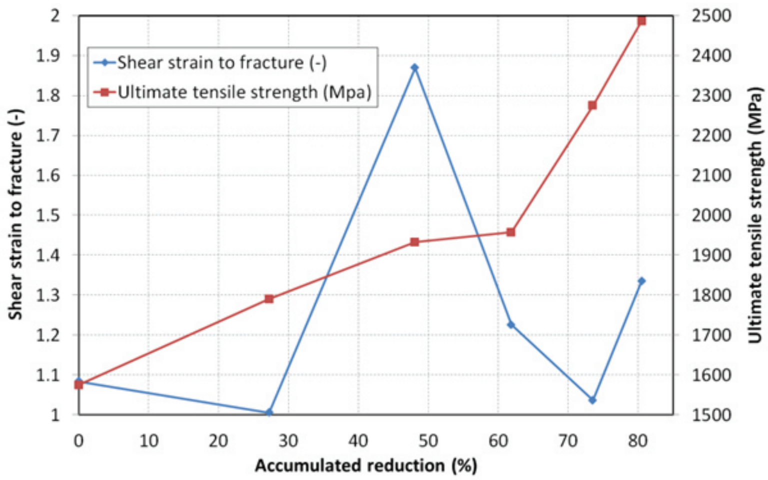


Fig. 3 Comparison between the evolution of UTS and shear strain to fracture for 5-pass schedule

Now, if the microstructures of the wire before and after the last draft are compared (see **Fig. 4**, the 5-pass schedule), it becomes clear that during the last pass, the pearlite colonies which were perpendicular to the drawing direction underwent extensive fracturing of cementite lamellae - which then tended to form globules. Their occurrence may be the cause of the increase in shear strain to fracture upon the last pass.

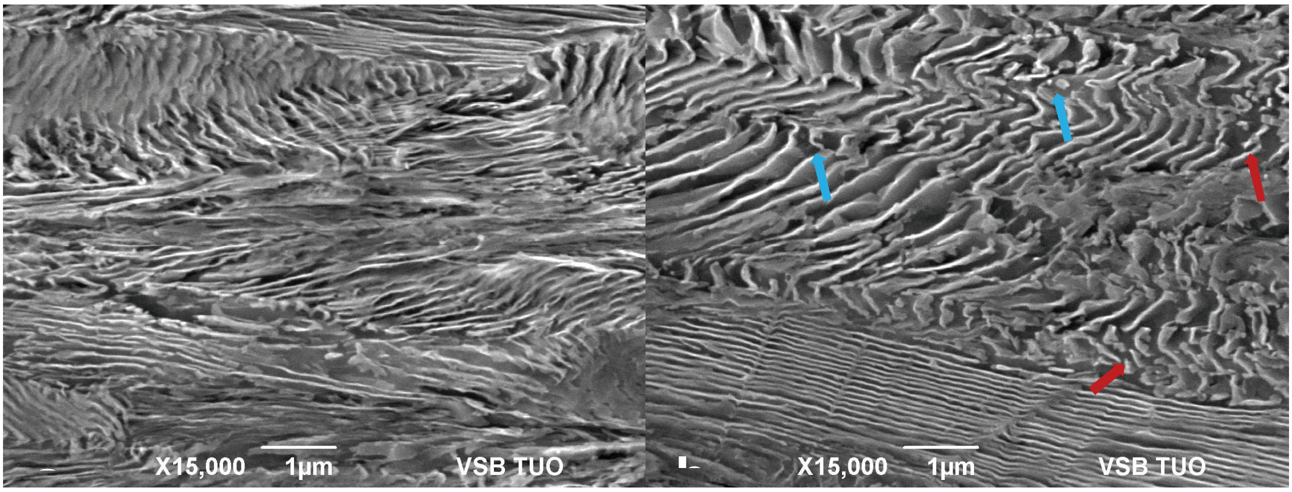


Fig. 4 Comparison between wire microstructures before (a) and after (b) the last draft (the red arrows identify the locations of fractures in cementite lamellae and the blue ones show the forming cementite globules). The drawing direction is from left to right. 5-pass schedule

In order to assess the statistical significance of the differences between the final values of shear strain to fracture in individual pass schedules, the non-parametric Kruskal-Wallis test was used [7]. Its results suggest that the differences between the median values were statistically insignificant.

3.2. Reverse Bend Test to Fracture

In this test, too, drawn steel wires of various diameter were used. In addition, the setup of the test equipment was different here (see **Table 5**). As a consequence, the number of bending cycles to fracture N_B had to be converted using Burggeller formula [3]:

$$B_f = 10 \cdot \frac{N_B}{\left(2 \cdot \frac{r}{d} + 1{,}65 + 0{,}05 \cdot d\right)^2} \quad [mm^{-2}] \tag{2}$$

Graphs in **Fig. 5** show the evolution of B_f during drawing in all pass schedules. The values shown are the median, lower quartile and the minimum value from the total of ten values measured for each pass and each pass schedule. With increasing reduction, the Burggeller value increases (and so does the number of bending cycles to fracture). The wild swings on individual curves may be attributed to the configuration of the test. The portion of the test piece that is actually tested is relatively small. As a result, the test is rather sensitive to the presence of inclusions or surface defects (scratches and others) in the section being bent. Given the nature of the data, the comparison between various pass schedules is difficult. In simple terms, it may be concluded that there are no major differences between the schedules. The median B_F even appears the same for the 7-pass and 5-pass schedules. The difference between the 6-pass schedule and the others is statistically insignificant, as shown by the non-parametric Kruskal-Wallis test [7].

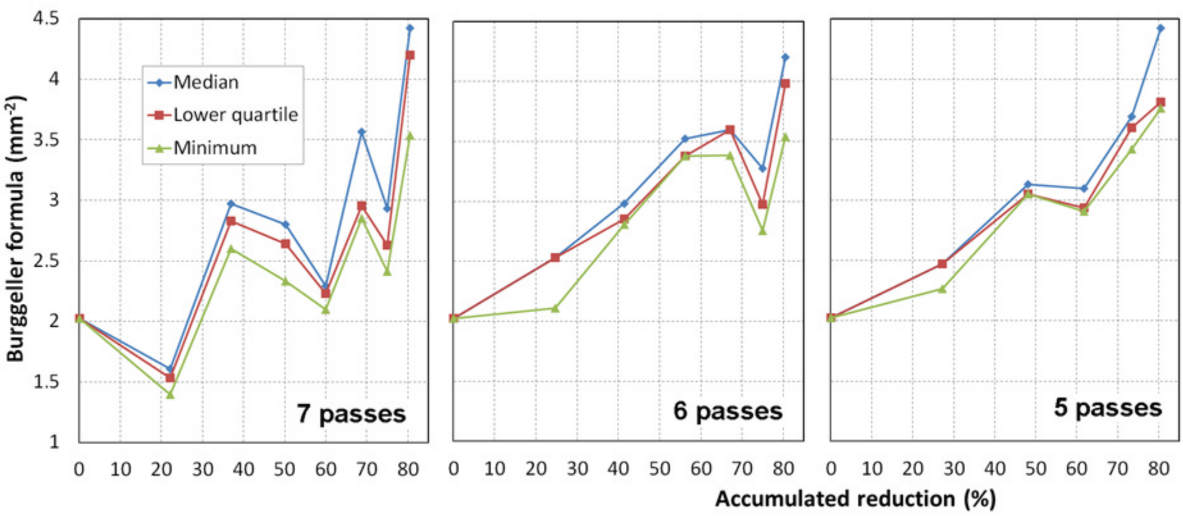


Fig. 5 Evolution of Burggeller value during drawing for individual pass schedules

4. CONCLUSION

In the experiment described in the present paper, we have proven that drawing of a steel wire may substantially influence its resistance to low-cycle fatigue. The differences between results for individual schedules are not major. The non-uniform distribution of deformation across the cross-section of the wire, as shown previously, strongly depends on the amount of single-pass reduction [7], i.e. it does not strongly affect the number of bending cycles and revolutions to fracture. The largest effect was that of the type of the pass schedule of the maximum shear strain to fracture during torsion testing in the 48 - 60 % region of accumulated reduction. There, the use of the 5-pass schedule led to an increase in the maximum value by almost 30 %, when compared to the 7-pass schedule.

ACKNOWLEDGEMENTS

This paper was created in the Project No. LO1203 "Regional Materials Science and Technology Centre - Feasibility Program" funded by Ministry of Education Youth and Sports of the Czech Republic. and the specific research project SP2015/91. which has been solved at the FMME VSB-TU Ostrava with the support of Ministry of Education Youth and Sports. Czech Republic.

REFERENCES

[1] ISO 7800. Metallic materials: Wire - Simple torsion test. 2012.

[2] ISO 7801. Metallic materials -- Wire -- Reverse bend test. 1984.

[3] FABÍK R., HALFAROVÁ P., VYKYDAL D., LEZHNEV S., KLIMEŠ A. Analysis of Results of Testing of Wire by Reverse Bending from the Viewpoint of Normality of the measured Data In METAL 2014: 23th International Conference on Metallurgy and Materials. Ostrava: TANGER, 2014, pp. 341-346.

[4] FABÍK R., Selected Chapters from Metal Forming - drawing (study support): Ostrava, VSB-TU Ostrava, 2008. Available from: www.fmmi.vsb.cz/modin/cs/studijni-opory (in Czech)

[5] FABÍK R., HALFAROVÁ P. Impact of drawing process parameters on uniformity of strain in spring wire, In METAL 2011: 20th International Conference on Metallurgy and Materials. Ostrava: TANGER. 2011. pp. 234-240.

[6] FABÍK R. Influence of technological conditions of drawing on inhomogeneity of deformation under condition of hydrodynamic lubrication. In METAL 2013: 22nd International Conference on Metallurgy and Materials. Ostrava: TANGER. 2013. pp. 358-363.

[7] KRISHNAIAH P. R., SEN P. K. Nonparametric methods. New York, N.Y., U.S.A.: Sole distributors for the U.S.A. and Canada, Elsevier Science Pub. Co., c1984, 968 p. ISBN 0444868712.