USING OF DESIGN OF EXPERIMENTS FOR DESCRIBING OF IMPACT OF COLD DRAWING PROCESS PARAMETERS ON PLASTIC PROPERTIES OF WIRE FOR STEEL ROPES

VYKYDAL David, FABÍK Richard, HALFAROVÁ Petra, NENADÁL Jaroslav

VSB - Technical University of Ostrava, Ostrava, Czech Republic, EU,
david.vykydal@vsb.cz, richard.fabik@vsb.cz, petra.halfarova@vsb.cz

Abstract

The present paper approaches the topic from two perspectives. The first one is a mathematical approach, using which various experimental designs will be compared. From the metallurgical perspective, the effects of various factors and their interactions on drawn wire properties will be explored. Shear deformation of subsurface layers in wire drawing leads to marked non-uniformity of strain across the wire cross section. In wires intended for products operating under dynamic loads, such as ropes and springs, the variance in work hardening level across the cross section may cause fatigue fractures. In this paper, we used physical modelling in an attempt to show how the non-uniformity of strain in drawing can be reduced by changing key process parameters. For this purpose, a full factorial experiment involving three factors was undertaken. (The factors included the approach angle 2α, single pass strain Qd or the number of passes n and type of scale removal (pickling or 2 axis bending + brushing.) The simulation involved drawing of 2.5 mm C78DP steel wire from 5.5 mm thick rolled rod. Koch single wire drawing block with a rotating die holder was used for the modelling. In this paper, we evaluate the influence of several factors on final plastic properties of the wire (number of torsion to fracture, number of bends to fracture). Tensile tests and metallographic analysis were also conducted.

Keywords: Design of experiments, wire drawing, steel ropes, strain, approach angle, simple torsion test

1. INTRODUCTION

Design of Experiments (DOE) is understood to mean systematic planning and arrangement of tests in a manner which yields as much statistical information as possible. The purpose of an experiment is to find ways to induce changes in and, subsequently, control the behaviour of an output quantity. We attempt to identify factors which affect the output quantity, seek the ideal configuration of input factors and strive to suppress process variation. The essence of an experiment is an exploration of causal relationships, wherein we purposefully alter the input quantities based on a certain design and monitor the response of the output quantities. Experiments must be conducted rigorously if effects of individual factors, their interactions, or noise factors are to be evaluated by statistical tools. Although noise factors are always present in experiment, they can be reduced to a minimum by thorough planning. Besides identifying influential factors, another objective of experiments is to determine optimum levels, i.e. values, at which the process has optimum properties. In this, multilevel experiments, robust plans and subsequent response surface modelling can prove useful.

Input parameters may be quantitative but also qualitative. The latter, however, require a special approach to the experimental design and evaluation. The output quantity must be a continuous quantity. Experiment may also reveal effects of quantities which have not been accounted for. Such effects may be random or systematic. Random effects can be encountered when tests are repeated under identical experimental conditions. The results are then affected by variation which is considered to manifest the random effect. Many statistical tests are available which can help us identify this during data processing. The systematic effect is reflected in trends in measured values [1 - 3].

We have applied DOE to wire drawing before. It involved mathematical modelling of the effect of drawing conditions on the non-uniformity of strain and the drawing force [4]. Here, we applied DOE principles to a real-world multiple-draft wire drawing process.

2. LABORATORY WIRE DRAWING

The physical experiment was carried out in collaboration with Regional Materials Science and Technology Centre (RMSTC), in particular with the Department of Forming Processes which comprises Wire Drawing Laboratory.

2.1. Wire drawing laboratory equipment

The single most important item of equipment installed in this laboratory is KOCH KGT 25 - E straight-through single-block wire-drawing machine with drawing blocks of 600 mm diameter (see **Fig. 1**). It is a conventional machine which is used in wire mills either as an autonomous station or as the last block in multiple-draft wire-drawing machines. The drawing block, as well as the rotating drawing die holder are water-cooled. The position of the drawing die holder can be adjusted in two axes to control the internal stress levels in the finished wire. Upstream of the drawing die holder, there is a lubricating box where soap powder, as well as emulsion may be used. The wire-drawing machine is provided with its own emulsion circulation, cleaning and cooling circuits. It has a Siemens control system which measures the drawing torque and thus the drawing force. If required, a thermal imaging system and two pyrometers can be installed for measuring the wire temperature downstream of the drawing die at the bottom of the drawing block and upstream of the straightening station. The machine has a pneumatic brake which stops its motion if the wire breaks or touches a safety cable.

Fig. 1 KOCH KGT 25 - E wire-drawing machine: rotating die holder and drawing block during wire introduction by the wire pulling-in dog

Fig. 2 top: transfer pulley, **bottom:** laser measurement of dimensions and wire straightener

For the wire to be introduced, it must be wound around the bottom part of the block 4 to 6 times. Then, the wire runs over a pulley, through the laser dimension-measurement device and a 7-to-9-roller two-axis straightener (see **Fig. 2**) to be finally wound on the top part of the block which is provided with a coil holder (see **Fig. 3**). The coil holder capacity is up to 100 kg of wire. After drawing, the holder with the wire is retrieved using a gantry crane and transferred to a payoff stand or to finished product storage.

The payoff stand with an independent drive by the company VASPO Vamberk can handle coils of inner diameters up to 1.2 m and weights up to 200 kg. It is equipped with a pneumatic safety brake which protects the wire from breakage in the payoff stand (see **Fig. 4**).

Optionally, a descaler may be incorporated between the wire-drawing machine and the payoff reel. The descaler has pulleys with axes oriented in two directions, and spiral wire brushes for finish-cleaning of the wire surface after descaling (see **Fig. 5**). A universal frame with a wire feeder may be added. On the frame, wire roller straighteners for various wire diameters (for straightening the finished wire prior to mechanical testing) or a continuous resistance furnace for simulating wire annealing processes can be mounted.

In addition, the laboratory is equipped with testing equipment for low-cycle fatigue testing of drawn wire. Torsion testing was carried out in ZKZE 02/5 machine (see **Fig. 6**) according to ISO 7800 Metallic materials - Wire - Simple torsion test. The bending test was carried out using ZOZP 02/5 machine (see **Fig. 7**) according to ISO 7801 Metallic materials - Wire - Reverse bend test. In collaboration with other departments at RMSTC, tension tests can be conducted, as well as metallographic observation under an optical microscope and in SEM and TEM.

Fig. 3 Lifting the coil holder from the drawing block

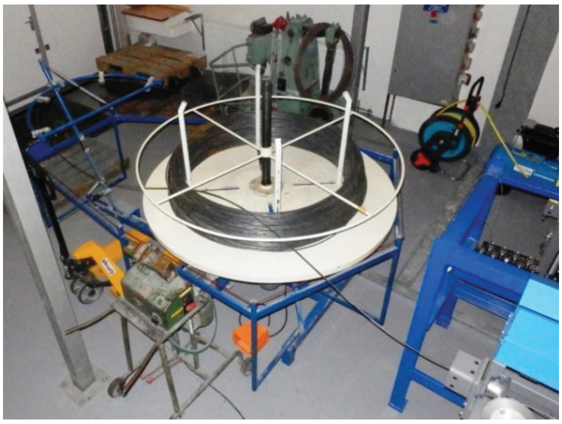

Fig. 4 Payoff stand

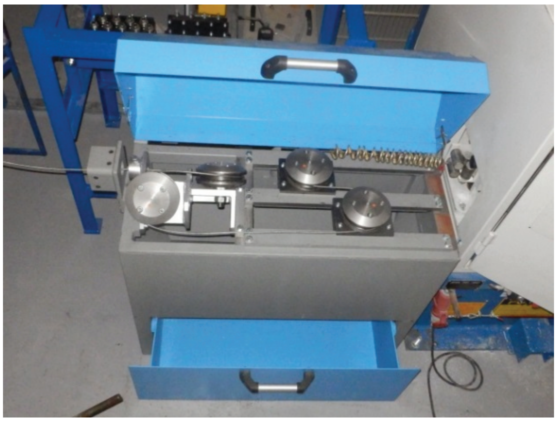

Fig. 5 Roller descaler with spiral wire brushes

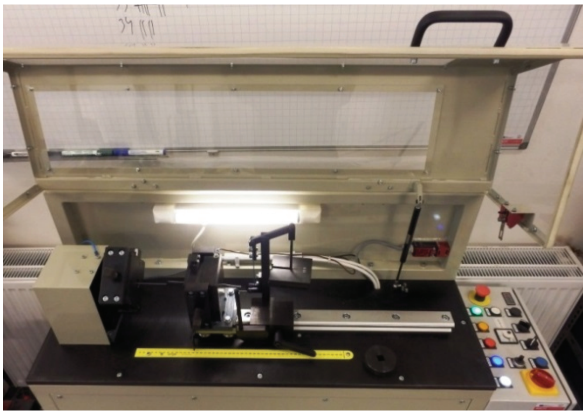

Fig. 6 Simple torsion test, ZKZE 02/5 machine

Fig. 7 Reverse bend test of wire, ZOZP 02/5 machine

2.2. Experimental

The experimental material was a rolled and controlled cooled wire of 5.5 mm diameter of C78DP steel which is intended for making steel ropes. Its microstructure consisted of pearlite with an average interlamellar spacing of 215 nm. The first coil of wire was pickled and its surface was coated with lubricant carrier Sale Tri 56. The other coil was kept in its initial condition (scaled surface) and was mechanically descaled prior to drawing. It was assumed that the descaling method would impact the friction coefficient during drawing because breaking scales by rollers can only remove approximately 95 % of scale. The characteristics of the material used are given in **Table 1**.

Table 1 Experimental material data

Steel Grade	Wire Rod Diameter	State	Chemical composition (wt. %)					Surface condition	
			C	Si	Mn	S	P	a)	b)
C78DP	5.5 mm	Hot Rolled and Controlled-Cooled	0.795	0.20	0.62	0.012	0.014	Pickled + lubricant carrier	Scale

The wire was drawn from a diameter of 5.5 mm to 2.5 mm. The total reduction was 79.3 % (see eq. 2). The drawing speed was approximately 1 m/s. The drawing dies of tungsten carbide had approach angles of 8° and 12°. The lubricant used was a commercial hard soap-based grade with an addition of Condat 3T lubricant carrier. A total of three uniform pass schedules were used, as defined in **Table 2**. The difference between the pass schedules is in the average one-pass strain magnitude $Q_{d,i}$ determined using the following equation:

$$Q_{d,i} = \frac{d_{i+1}^2 - d_i^2}{d_{i+1}^2} \cdot 100 \qquad [\%] \qquad (1)$$

Where d denotes the wire diameter and i is the sequential number of a pass between 1 and n, while n is the total number of passes. The total reduction is calculated from the following equation:

Table 2 Drawing schedule

Factor A	Level	Drawing schedule									
Average one-pass strain magnitude Q_d (%)	32.57	pass number	(-)	0	1	2	3	4			
		die diameter	(mm)	5.5	4.5	3.7	3	2.5			
		relative strain	(%)		33.06	32.40	34.26	30.56			
		wire velocity	(m/s)	1							
	27.04	pass number	(-)	0	1	2	3	4	5		
		die diameter	(mm)	5.5	4.7	4	3.4	2.95	2.5		
		relative strain	(%)		26.98	27.57	27.75	24.72	28.18		
		wire velocity	(m/s)	1							
	23.05	pass number	(-)	0	1	2	3	4	5	6	
		die diameter	(mm)	5.5	4.7	4.1	3.6	3.1	2.8	2.5	
		relative strain	(%)		26.98	23.90	22.90	25.85	18.42	20.28	
		wire velocity	(m/s)	1							

$$Q_c = \frac{d_0^2 - d_n^2}{d_0^2} \cdot 100 \qquad [\%] \qquad (2)$$

One-pass reduction $Q_{d,i}$ and approach angle 2α, the variables in this experiment, have a profound effect on the geometry of the deformation zone. It may be defined, for instance, by means of delta-factor, a ratio between the average height of the deformation zone in the direction perpendicular to the drawing axis and the length of the deformation zone along the drawing axis [5]:

$$\Delta = \frac{\alpha}{Q_{d,i}} \cdot \ [1 + (1 - \ Q_{d,i})^{\frac{1}{2}}]^2 \ \approx \ \frac{4 \cdot \tan\alpha}{\ln[\frac{1}{(1 - Q_{d,i})}]} \quad [-] \qquad (3)$$

Previous experience indicates that, provided adequate lubrication can be maintained, die designs involving low Δ values (i.e., low approach angles and/or large reductions) should offer superior performance in terms of reduced wear, reduced requirements for intermediate annealing, reduced cuppy core breakage, improved final product ductility, and minimization of thinning beyond the die exit. Our experiment is intended to verify this experience. Δ values for our experiment are given in **Table 3**.

Table 3 Δ values

Δ values	**Average Q_d (%)**		
approach angle (°)	32.57	27.04	23.05
8	1.48	1.90	2.36
12	2.35	3.13	4.11

Following each pass, an approx. 50-m sample was removed from the wire stock for subsequent testing. Prior to testing, this wire was straightened in a nine-roller two-axis straightener. The following tests were carried out after each pass: tension test, torsion test to fracture and reverse bend test to fracture.

3. DESIGN OF EXPERIMENT - FULL FACTORIAL EXPERIMENT

The development of individual designs of our experiment builds on the basic plan. In this case, there are 3 factors, one with three levels and two others with two levels in each. Their levels are summarized in **Table 4**. Additional plans also include three factors but each of those has only two levels. Consequently, it is possible to compare the results. The plans of the experiments are outlined in **Table 5** to **Table 8**. The experiment is conducted with repeat treatments.

Another issue we faced was the use of a qualitative factor representing the descaling method (B). An another factor, the one-pass reduction (A) is not free from difficulties either. As the amount of the one-pass reduction depends on the number of drafts (passes) and the total reduction was constant, only certain one-pass reduction magnitudes were available. Consequently, the A factor levels are not symmetric. The difference between the -1 and 0 levels is 3.99 % but that between the 0 and 1 levels is as high as 5.53 %. This calls for a final correction of the results.

Key quality indicators in this experiment may be divided into material and process indicators. The material indicators include the following: number of bending cycles to fracture and number of revolutions to fracture (characterising low-cycle fatigue), fatigue strength (measured by rotating bending test), tensile strength, yield strength and elongation. We have described the issues associated with the evaluation of torsion and bending tests earlier [6]. The process indicators include: total drawing force, torque and wire temperature downstream of the drawing die.

The results obtained using DOE procedure will be correlated with the outcomes of the conventional regression analysis. We will be seeking a relationship between the above-named key quality indicators and the value of the Δ parameter.

Table 4 Factor levels

	Factor	Unit	Factor levels		
			-1	0	1
A	**One-pass strain magnitude Q_d**	%	23.05	27.04	32.57
B	**Descaling method**	-	Mechanical		Pickling
C	**Approach angle 2*α***	°	8		12

Table 5 Experimental design - option 1

Treatment no.	Factor levels		
	A	B	C
1.1	1	-1	-1
1.2	0	-1	-1
2.1	-1	-1	-1
3.1	1	1	-1
3.2	0	1	-1
4.1	-1	1	-1
5.1	1	-1	1
5.2	0	-1	1
6.1	-1	-1	1
7.1	1	1	1
7.2	0	1	1
8.1	-1	1	1

Table 6 Experimental design - option 2

Treatment no.	Factor levels		
	A	B	C
1.1	1	-1	-1
2.1	-1	-1	-1
3.1	1	1	-1
4.1	-1	1	-1
5.1	1	-1	1
6.1	-1	-1	1
7.1	1	1	1
8.1	-1	1	1

Table 7 Experimental design - option 3

Treatment no.	Factor levels		
	A	B	C
1.2	0	-1	-1
2.1	-1	-1	-1
3.2	0	1	-1
4.1	-1	1	-1
5.2	0	-1	1
6.1	-1	-1	1
7.2	0	1	1
8.1	-1	1	1

Table 8 Experimental design - option 4

Treatment no.	Factor levels		
	A	B	C
1.1	1	-1	-1
1.2	0	-1	-1
3.1	1	1	-1
3.2	0	1	-1
5.1	1	-1	1
5.2	0	-1	1
7.1	1	1	1
7.2	0	1	1

4. CONCLUSION

Due to the scale of the experiment, the present papers only discusses its preparation and theoretical background. We have drawn on our previous experience to identify the most important factors and set up their levels. Now the entire experiment must be evaluated for all 4 proposed experimental designs. It will be followed by the key stage of the mathematical portion of the experiment: cross-comparison among the results of all 4 designs. Only after that can we draw conclusions regarding the process itself and its impact on the mechanical properties of the drawn wire. We will inform about the outcomes of the experiment at the next Metal conference.

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