EVALUATION OF MECHANICAL PROPERTIES OF THE DRAWN WIRE USING THE DESIGN OF EXPERIMENTS

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Abstract

This paper deals with using the design of experiments (DOE) during the evaluation of mechanical properties of the wire for steel ropes. It was provided with a full factorial experiment with three factors at two levels. The factors are as follows: one-pass strain, the approaching angle and the method of the removing of the scales from the surface of hot rolled wire. The experimental material was a drawn wire with a 5.5 mm diameter of C78DP steel. The wire was drawn from the diameter of 5.5 mm to 2.5 mm using a straight-through single-block KOCH KGT 25 - E wire drawing machine. The total reduction was 79.3 %. The drawing dies of tungsten carbide had approach angles of 8° and 12°. Two uniform pass schedules were used with a different single-pass reduction. Two methods of descaling (mechanical and chemical) were used. Following each pass, an approx. 50 m sample was removed from the wire stock for subsequent testing. The following tests were carried out after each pass: tension test, torsion test to fracture and the reverse bend test to fracture. DOE was evaluated using both graphical and analytical methods. The significant factors and their interactions were determined and response surfaces were calculated.

Keywords: Design of experiments, wire drawing, patented wire, descaling, die geometry, pass reduction

1. INTRODUCTION

The planned experiment, abbreviated DOE (Design of Experiments), is based on the knowledgeable changes of the values of input factors (factors, dependent characteristics) of the process, or arbitrary activities, with the aim of determining the corresponding changes of these factors (dependent characteristics). In general, the experiment is used to study the process and the system to improve it and mainly to observe how inputs impact the outputs.

The process can be defined as a certain combination of equipment, materials, methods, people, environments and measuring, which transform inputs to outputs, which exhibit one or more visible reactions. Controllable variables (represented by the letter *X*) can change easily during an experiment and as a variable they play a key role in the process characteristics. Uncontrollable variables (represented by the letter *Z*) are difficult to monitor during the process. These variables or factors are responsible for the variability of the monitored process.

There are three basic DOE principles - randomization, replication and arrangement in blocks, which can be used in industrial design to improve the efficiency of experiments. These DOE principles are typically applied to reduce or even eliminate the systematic effect on experiments [1 - 5].

The utilization of DOE principles in practice is quite common [6 - 9]. However, the utilization particularly in the field of primary and secondary metallurgy is quite rare [10]. In this paper we will focus on the field of wire drawing. In particular, it involves the drawing of steel wires for the production of wire ropes, whose mechanical properties, internal structure and surface and internal quality are subject to stringent quality requirements [11]. The analysis of available literature sources shows that it is very difficult to find a relation between the final wire properties and the technological parameters of wire drawing. This provides an opportunity for the application of DOE, which could be used to determine the technological factors of drawing that most significantly impact the wire´s strength properties (tensile strength, yield strength), plastic properties (elongation to fracture, reduction of area) and fatigue properties (number of rotations to fracture and number of bends to fracture).

2. EXPERIMENT

The experimental material was a drawn wire with a 5.5 mm diameter of C78DP steel (the chemical composition is listed in **Table 1**). After hot rolling, the wire was cooled on a Stelmor conveyor, so its structure is formed by relatively fine-lamellar pearlite without the presence of any other phases, such as ferrite on one side or bainite on the other side. The wire was drawn from the diameter of 5.5 mm to 2.5 mm using a straight-through single-block KOCH KGT 25 - E wire drawing machine [12]. The total reduction was 79.3 %. Two uniform pass schedules were used with different single-pass reduction (see **Table 2**). The drawing dies of tungsten carbide had approach angles of 8° and 12°.

Table 1 Chemical composition of steel C78DP

Steel	Chemical composition (wt. %)				
	C	Si	Mn	S	P
C78DP	0.795	0.2	0.62	0.012	0.014

Table 2 Wire drawing schedule

Mean partial reduction Q_d (%)	Input	Die diameter *D* (mm)					
	d (mm)	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass
23.05	5.5	4.7	4.0	3.4	2.95	2.5	
27.04	5.5	4.7	4.1	3.6	3.1	2.8	2.5

The aim of the experiment was to determine the factors which most significantly impact the mechanical properties of the drawn wire and to determine their ideal values. A complete factor experiment was conducted for this purpose.

The following factors were selected as the most significant ones:

D. Partial reduction Q_d - a variable change in wire cross-section in one pass (%).

E. Angle of tapered section of drawing die 2α - basic geometric factor of the deformation zone which affects the distribution and character of deformation in the wire.

F. Method of descaling - During cooling after hot-rolling the surface of the wire becomes covered by a layer of iron oxides - scales. Scales are removed mechanically (usually by breaking or brushing) or chemically (usually by pickling in acids).

Table 3 defines the top and bottom limits of factors as they were set for the DOE. **Table 4** defines the plan of experiments.

From each experiment an approx. 50 m sample was taken to perform a tensile test to **Norm** [13], a reverse bend test to fracture to **Norm** [14] and a torsion test to fracture to **Norm** [15].

Table 3 Top and bottom limits of factors

Factor		Levels	
		-1	+1
A	Q_d (%)	23.05	27.04
B	Descaling method	Mechanical	Chemical
C	2α (°)	8	12

Table 4 Plan of experiments

Experiment	Factor		
	A	B	C
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1

3. DISCUSSION OF RESULTS

3.1. Torsion test

Statistically significant effects of the factors are shown in **Figure 1** and **2** respectively, where we can see a Paret chart of the effects of factors and a normal probability diagram.

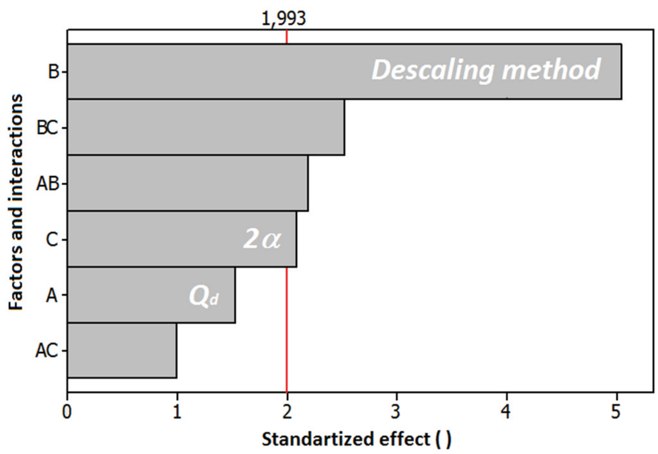

Figure 1 Pareto chart of the standardized effects for torsion test

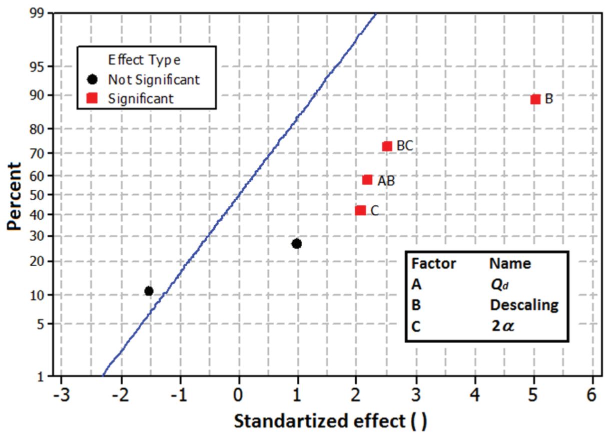

Figure 2 Normal plot of the standardized effects for a torsion test

Figure 1 and **Figure 2** show that factors B (descaling method) and C (approach angle) and interactions BC and AB were evaluated as statistically significant factors. From this experiment it followed that the most significant factor is factor B, i.e. the method of descaling. For factor B the optimal value is 1, i.e. descaling using the chemical method. For factor C the optimal angle value is 12°.

In **Figure 3** we see graphs of effects and in **Figure 4** graphs of individual interactions. We determined interactions BC and AB as statistically significant interactions. From the BC interaction graph (see **Figure 4**) it can be deduced that in the case of pickled wire a change in factor C from 8° to 12° lead to an increase in the output value, whereas in the case of mechanical descaling it was vice versa. In the case of interaction AB, the output value was higher for pickled wire in both pass schedules.

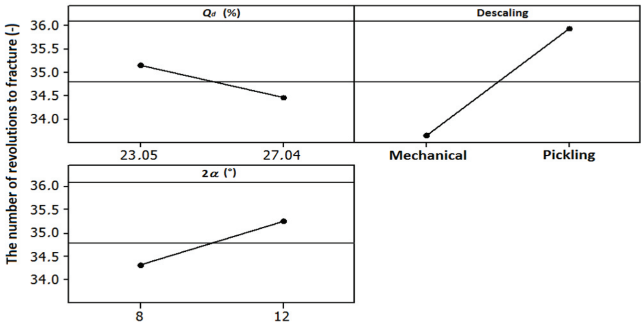

Figure 3 Main effects plot for torsion test

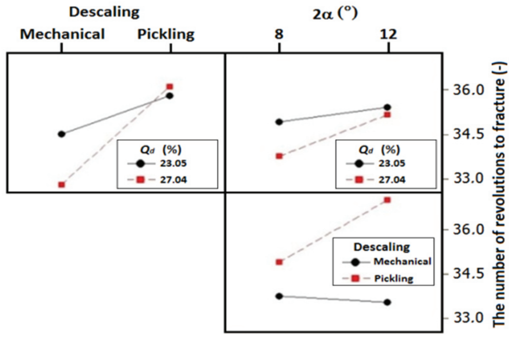

Figure 4 Interaction plot for torsion test

3.2. Reverse bend test

From the Pareto chart (**Figure 5**) and from the normal probability chart (**Figure 6**) we found that the most statistically significant factors were again factor B and factor C and interaction BC.

The results are the same as for the previous test. For factor B, i.e. the method of descaling, the optimal value is level 1, i.e. descaling by the chemical method. For factor C the optimal angle is 12° (**Figure 7**).

We determined interaction BC as a significant interaction. From the BC interaction graph it can be deduced that a change in factor C from 8° to 12° lead to an increase in the output value for pickled wire, as well as mechanically descaled wire (**Figure 8**).

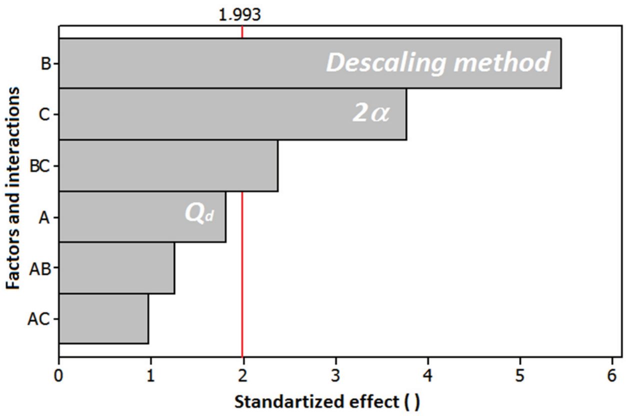

Figure 5 Pareto chart of the standardized effects for reverse bend test

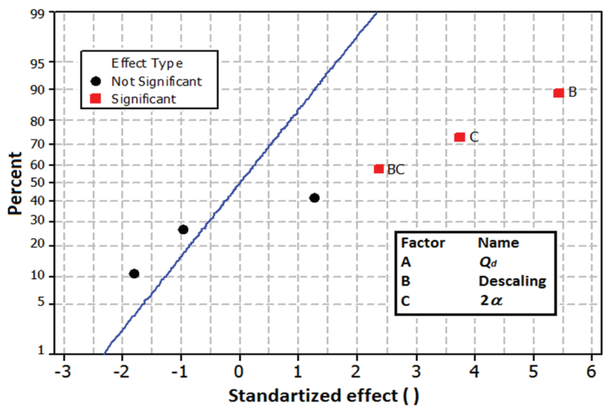

Figure 6 Normal plot of the standardized effects for a reverse bend test

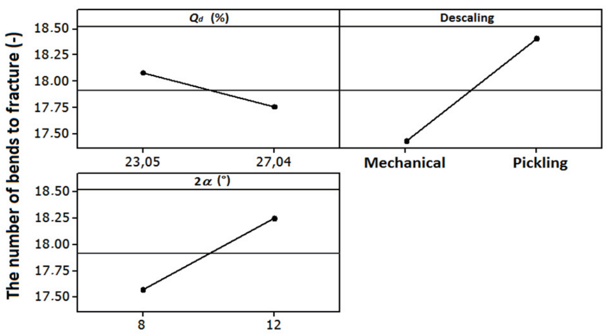

Figure 7 Main effects plot for reverse bend test

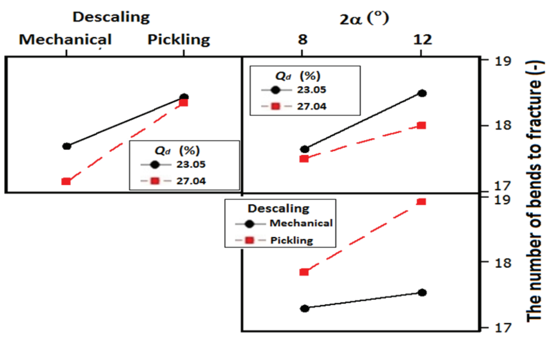

Figure 8 Interaction plot for reverse bend test

3.3. Tensile test - ductility

From the Pareto chart and from the normal probability chart we found that the most statistically significant factors were factor B and interaction AB (**Figure 9, 10**).

Therefore, for factor B, i.e. the method of descaling, the optimal value is level 1, i.e. chemical descaling.

We determined interaction AB as a statistically significant interaction. From the graph of this interaction it can be seen that for the 23.05 % pass schedule the output value was higher for pickled wire, whereas for the 27.04 % pass schedule it was vice versa (**Figure 12**).

Ductility has an indirect correlation with tensile strength; the higher the strength the lower the ductility. But this is a value which we try to maximize, because high ductility means good plastic properties of the material.

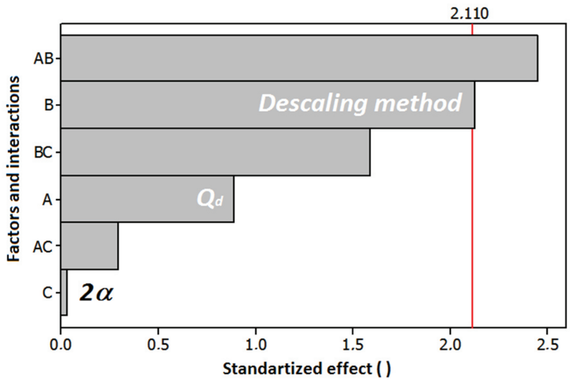

Figure 9 Pareto chart of the standardized effects for tensile test

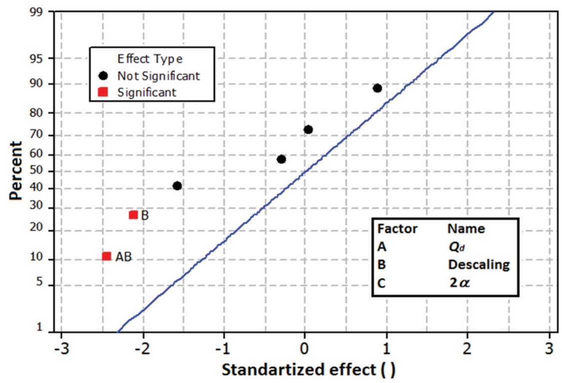

Figure 10 Normal plot of the standardized effects for tensile test

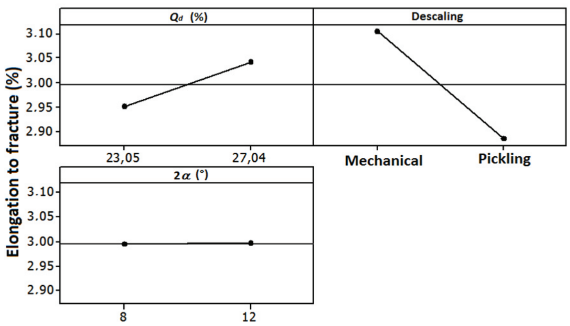

Figure 11 Main effects plot for tensile test

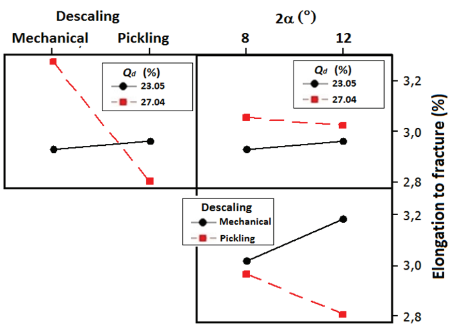

Figure 12 Interaction plot for tensile test

4. CONCLUSION

We performed and evaluated the planned experiment for drawing wire for steel ropes using the DOE principle. We selected factors and their levels based on studies of literature, whereas our main most significant factor favourite was the mean partial deformation value characterising the respective pass schedule. Quite surprisingly it emerged that the most significant factor is the method of descaling, where the best wire mechanical properties were achieved using pickling. The significance of this factor is even more interesting in that the method of descaling affects the mechanical properties indirectly through a change in contact conditions in the drawing die deformation zone, which are exhibited by an increased friction coefficient, which causes increased shearing strain in the subsurface layers of the wire, and which can also lead to greater heating of the wire during deformation, thus causing deformation fatigue, in turn causing the deteriorated plastic and fatigue behaviour of the wire.

The effect of the method of descaling on the friction coefficient is also supported by the significance of the BC interaction, where a combination of pickling and a large approach angle (and thus reduced contact surface between the wire and die) leads to an improvement of the monitored properties.

ACKNOWLEDGEMENTS

This paper was elaborated in the frame of the specific research project SP2016/91, which has been solved at the Faculty of Metallurgy and Materials Engineering, VŠB-TU Ostrava with the support of Ministry of Education, Youth and Sports, Czech Republic.

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