COMPARISON OF FULL FACTORIAL EXPERIMENTS DESIGNED WITH DIFFERENT COMBINATIONS OF ONE FACTOR LEVELS DURING MULTIPASS WIRE DRAWING

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Abstract

The main goal of our paper is to compare the results obtained using full factorial experiments with different combinations of one factor levels. On the example of multipass wire drawing, we will show how the choice of levels of factors can affect the final result of the experiment, especially in view of the determination of the significant factors and their interactions. We will demonstrate how important the selection of each factor level is on the final result of the experiment. The experimental material was a drawn wire of 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 ways of descaling (mechanical and chemical) were used. A total of three uniform pass schedules were used with different single-pass reduction (23, 27 and 32.6 %). It gives us three individual experimental plans of design of experiments (DOE) in total with the following variations of one-pass strain levels: DOE1 23 - 27 %, DOE2 23 - 32.6 % and DOE3 27 - 32.6 %. The monitored depended variable is the number of bendings to fracture during the reverse bending test. All DOE were evaluated using graphical methods. The significant factors and their interactions were determined and compared for all DOE mutually.

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

1. INTRODUCTION

The principle of the experiment is the investigation of the cause - effect relation using the targeted changes of input values. This means that according to a certain plan we change the values of input factors and monitor the reaction of output factors. Experiments performed with the aim of improving quality are usually performed in operating or semi-operating conditions and their implementation may either endanger the fluency of production or cause a temporary deterioration of the process quality. Therefore, it is necessary to limit the number of tests to a minimum. Furthermore, compared to laboratory testing, we must also consider the impact of various disturbing effects which make the evaluation of the results more difficult. Therefore, the experiment must be thoroughly planned so that the evaluation of a relatively small number of experimental results is as efficient as possible [1 - 8].

The key moment of experiment preparation is the determination of factors and their levels. Professional literature uses DOE for solving certain operational problems in various industrial enterprises [9 - 12]. However, in the field of metallurgy using DOE we can meet infrequently [13], but the mutual comparison of numerous experiments, performed under similar conditions, is missing altogether. Therefore, the main goal of our paper is the comparison of the results obtained using full factorial experiments with different combinations of one factor levels. On the example of multipass wire drawing, we will show how the choice of the levels of factors can affect the final result of the experiment, especially in view of the determination of the significant factors and their interactions.

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 [14]. The total reduction was 79.3 %. Three pass schedules were used with a 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	4.5	3.7	3	2.5		
27.04	5.5	4.7	4	3.4	2.95	2.5	
32.57	5.5	4.7	4.1	3.6	3.1	2.8	2.5

We prepared a total of three mutually complementary experimental plans, where the aim of each experiment was to determine the factors which mostly impact the mechanical properties of the drawn wire, and set their ideal values. The main aim was the mutual comparison of results of respective plans with an emphasis on mutual factors and their interactions. The following factors were selected as the most significant ones:

A. Partial reduction Q_d - variable change in wire cross-section in one pass (%).We used the following factor levels A: 23.05 %, 27.04 % and 32.57 % which corresponds to drawing of wire in 6, 5 and 4 passes.

B. 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 (factor B levels: 8 and 12°).

C. Method of descaling - During cooling after hot-rolling, the surface of the wire becomes covered by a layer of iron oxides - scales, which must be removed prior to drawing. (qualitative levels of factor C: mechanical descaling by breaking in two planes and brushing with a spiral brush, chemical descaling by pickling in sulphuric acid with the subsequent application of borax as a lubricant carrier.

A total of three total factor planned experiments were designed so that there are 3 levels of factor A represented in all combinations. The respective experiments are called DOE1 (see **Table 3**), DOE2 (see **Table 4**), DOE3 (see **Table 5**).

Table 3 Selection of bottom and top limits of factors - DOE1

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

Table 4 Selection of bottom and top limits of factors - DOE2

Factor		Unit	Levels	
			-1	+1
A	Q_d (%)	%	23.05	32.57
B	Descaling method	-	Mechanical	Chemical
C	2α	°	8	12

Table 5 Selection of bottom and top limits of factors - DOE3

Factor		Unit	Levels	
			-1	+1
A	Q_d (%)	%	27.04	32.57
B	Descaling method	-	Mechanical	Chemical
C	2α	°	8	12

The following were used as output values for the planned experiment:

- Number of bends to fracture in reverse bend test (*NBF*).
- Number of revolutions to fracture in torsion test (*NRF*).
- Tensile strength (R_m).
- Proof stress ($R_{p0.2}$).
- Ductility (*A*).

We try to maximize all these values. An example of the evaluation of experiment DOE 1 can be found in the literature [15].

3. DISCUSSION OF THE RESULTS

3.1. General comparison of the significance of factors and their interactions

The main aim of this paper is the comparison and interpretation of the results of individual experiments. All the results of destructive tests are presented in **Table 6**, which summarizes how many times the factor effect, or interaction respectively, was evaluated in the respective experiments as statistically significant. In **Table 4** we see that the most frequent factor is B, i.e. the method of descaling. Factor B was evaluated as statistically significant most frequently in two out of three partial planned experiments. In total, factor B was evaluated as statistically significant nine times out of a total number of fifteen output values. Also, interactions in which factor B was involved, i.e. interactions AB and BC, were evaluated as statistically significant much more often than interaction AC, which was evaluated as significant only once.

Table 6 Number of statistically significant factors for all DOE

	DOE1	DOE2	DOE3	Total
A	0	2	3	5
B	3	1	5	9
C	2	1	2	5
AB	3	0	2	5
AC	0	0	1	1
BC	2	1	3	6

Changes in the mean output values during the transition from level -1 to level 1 are shown in the following **Tables 7** to **9**. Negative values show a decrease in the average output value during transition from level -1 to level 1. In the case of positive values the opposite applies. Red-highlighted values show a statistically significant factor.

Table 7 Changes in mean output values during the change in factor levels for DOE1

	DOE1				
	K	O	R_m	$R_{p0.2}$	A
A	-0.7	-0.325	1.02	-10.41	0.09167
B	2.3	0.975	27.59	49.75	-0.2195
C	0.95	0.675	-8.67	-3.3	0.003

Table 8 Changes in mean output values during the change in factor levels for DOE2

	DOE2				
	K	O	R_m	$R_{p0.2}$	A
A	2.15	-1.025	35.23	7.24	0.09819
B	1.45	0.375	3.93	30.92	-0.22035
C	0.7	0.775	-17.58	-17.44	0.27002

Table 9 Changes in mean output values during the change in factor levels for DOE3

	DOE3				
	K	O	R_m	$R_{p0.2}$	A
A	2.85	-0.7	34.21	17.65	0.00652
B	2.45	0.6	43.01	41.39	-0.47319
C	1.15	0.6	-7.19	-9.71	0.23935

3.2 Combined graphs of the main effects of partial reduction Q_d

Three levels were set for factor A - partial reduction Q_d. For a better understanding of the effect of this factor, graphs of the impact of this factor were drafted, showing the results from all three planned experiments, including their statistical significance.

Figure 1 shows a graph of the factor´s effect for all planned experiments for the torsion test. The graph shows that one experiment evaluated factor A as statistically insignificant (small line inclination), but the other two were evaluated as significant (large line inclination). The graph also shows the non-linearity of this factor, as well as the fact that at 27.57 % the Q_d. value is at its local minimum.

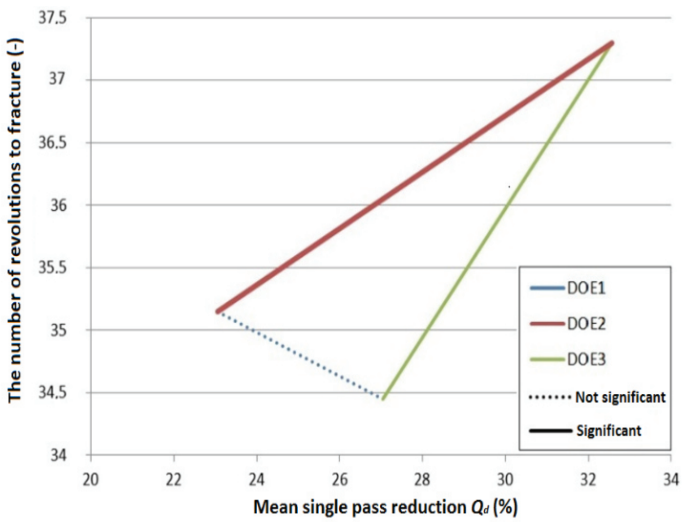

Figure 1 Combined main effects Q_d plot for torsion test, for all three experiments

Figure 2 shows a graph of the factor´s effect for all planned experiments for the reverse bend test. The situation is very similar to the previous test. The effect of factors is opposite but again one experiment evaluates the factor as insignificant and the remaining two as significant.

Figure 3 shows a graph of the effect of the factor for all planned experiments for the tensile test - tensile strength. The situation is very similar to the results for the torsion test, only experiment DOE2 evaluates the factor as insignificant, but according to the inclination of the red line in **Figure 3** it can be deduced that this result is relatively close.

Figure 4 shows a graph of the effect of the factor for all planned experiments for the tensile test - proof stress. IN the graph we can see a very strong non-linearity and, as for the torsion test, Q_d is at its local minimum at 27.57 %. However, all factors for this output value were evaluated as statistically insignificant.

Figure 5 shows a graph of the effect of the factor for all planned experiments for the tensile test - ductility. Once again, we see the non-linearity of the effect of the factor and there is also no statistically significant effect of factor A.

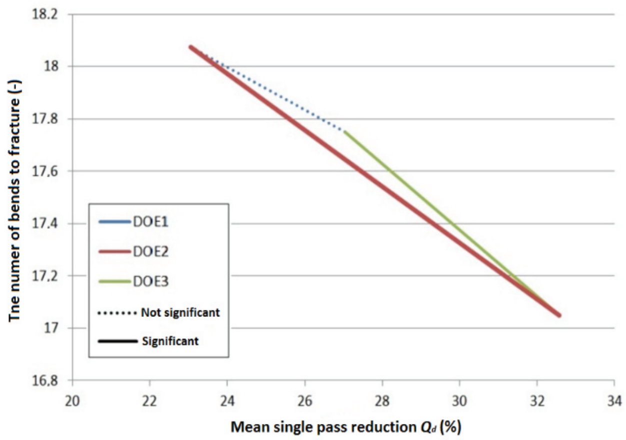

Figure 2 Combined main effects Qd plot for reverse bending test, for all three experiments

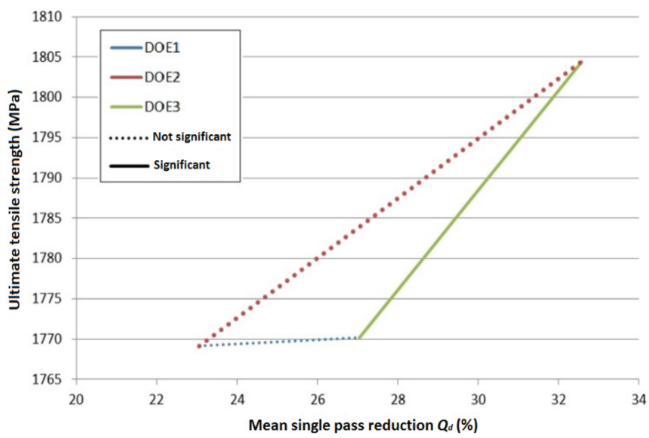

Figure 3 Combined main effects Q_d plot for tensile strength obtained from the tensile test, for all three experiments

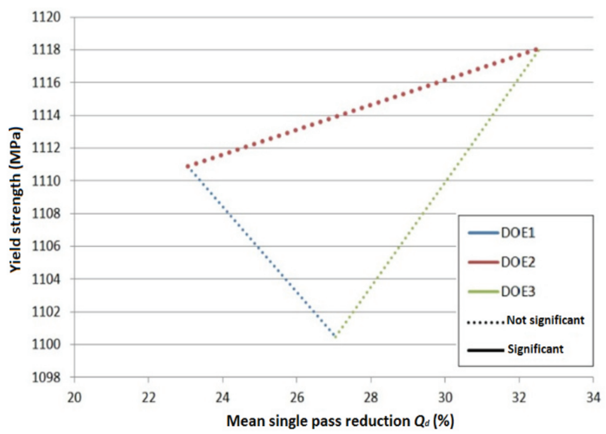

Figure 4 Combined main effects Q_d plot for yield strength obtained from the tensile test, for all three experiments

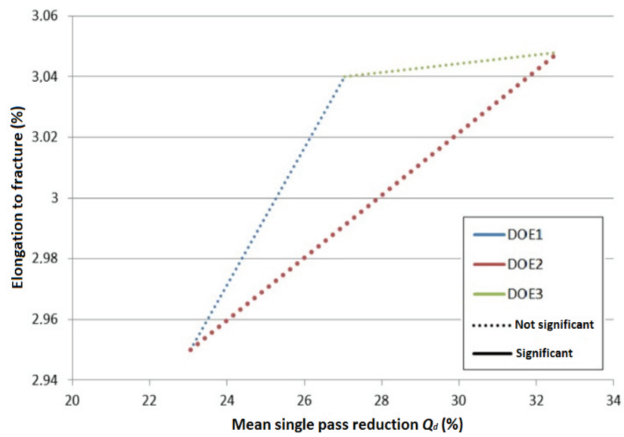

Figure 5 Combined main effects Q_d plot for elongation to fracture obtained from the tensile test, for all three experiments

3.3. Combined graphs of interactions of factor B with factor A (partial reduction Q_d)

The effect of interactions of factors is also best evaluated by graph. **Figures 6** and **7** show the combined graphs of the interactions of the effects of factor B with factor A. To evaluate the significance of the interaction of factors, it is necessary to compare the inclination of lines of the same colour. If the inclination differs significantly, the interaction of both factors is significant. For greater clarity, the area between two corresponding lines is coloured in the same colour. **Figure 6** shows the effect of interaction AB on the number of turns to fracture, obtained from the respective experiments. This interaction is evaluated as significant only by DOE1, where we can see that the combination of mechanical descaling and the average reduction 27.04 % gives a local ductility minimum expressed by the number of turns to fracture. An even better picture is provided by the effect of the selection of factor A level (mean reduction) on the evaluation of significance of interaction factors in the graph shown in **Figure 7**. The interaction of factors AB is quite evidently significant (as was deduced from the evaluation of experiments DOE1 and DOE2), but if the experiment is set with factor A levels, as in the case of DOE2, this fact will remain hidden to us.

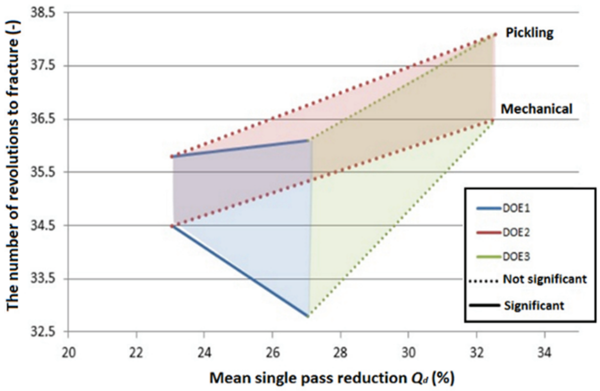

Figure 6 Combined interaction AB plot for the torsion test, for all three experiments

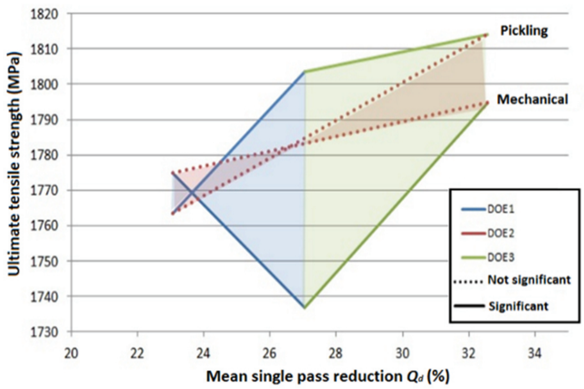

Figure 7 Combined interaction AB plot for tensile strength obtained from the tensile test, for all three experiments

4. CONCLUSION

The mutual comparison of the factor experiments differing in the set level of factor A (mean partial deformation) showed how important the selection of suitable factor levels is for the impact on determining factor significance and their interactions. In our case, it is evident that the effect of factor A is highly non-linear (i.e. the dependence of respective input values on this factor cannot be described as a linear dependence in the entire scope of used values of partial deformation). Due to this fact, various levels of factor A render different results. Therefore, it is always necessary to carefully consider this possible non-linearity of the evaluated factors and to potentially use the planned experiment with the factor at various levels.

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