EVALUATION OF DESTRUCTIVE TESTS ON DRAWN WIRES

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Abstract

The paper deals with the evaluation of experimental data on samples of steel wire. The main attention is aimed at the R&R study, which was a part of the experiment for studying effects of three factors on various mechanical properties of drawn wires. The experiment was performed in the wire drawing laboratory at VSB - Technical University of Ostrava. Samples of wire were tested for tensile, torsion and bending fatigue. Several operators took part in the experiment. Due to the destructive character of tests, a nested design was considered. The R&R study revealed that the mechanical properties along the wire length were not uniform and that the key assumption of the destructive-test analysis was not met. Since the employed scheme of assigning drawn wires to operators led to confounding of effects and made the further analysis dubious, another arrangement for this type of experiment is suggested in the paper. Apart from the R&R analysis, statistical methods of evaluation that take the real experimental pattern into account are discussed. The method based on means is applied and significant effects are identified.

Keywords: Destructive tests, nested design, R&R study, ANOVA

1. INTRODUCTION

Assessment of the quality of measured data is an important part of their evaluation and therefore the measurement system analysis should precede any data-based decision making. A measurement system is characterized by its stability, bias, linearity and precision [1]. To evaluate individual properties of the measurement system, special experiments are used [2]. The precision of a system is evaluated in terms of repeatability and reproducibility. Repeatability is the ability of an operator to consistently repeat the same measurement of the same part, using the same gage, under the same conditions, while reproducibility is the ability of a gage, used by multiple operators, to consistently reproduce the same measurement of the same part, under the same conditions. The aim of the R&R study is to assess the two sources influencing precision of experimental results [3]. Most commonly a cross study is used, when multiple operators measure several parts, each of them repeatedly. It is assumed that the parts do not undergo any changes during the experiment.

When destructive tests are used, repeated measurements cannot be realized. Two experimental designs are recommended to cope with the situation [4]. It is assumed that experimental units used in the experiment come from several batches and that the units from the same batch are very similar. Then tests carried out on the units from the same batch mimic repeated measurements on the same part.

The paper deals with tests for torsion. Drawn wires were produced under different conditions and effects of three factors on the number of cycles to failure were examined through a factorial experiment. The R&R study was a part of this experiment. Apart from the interpretation of results, some recommendations regarding both a suitable experimental design and correct methods of evaluation are suggested.

2. EXPERIMENTAL DESIGN FOR A DESTRUCTIVE R&R STUDY

Suppose experimental units come from batches, units from the same batch are very similar as compared with the units from different batches and several operators take part in the experiment.

Two scenarios are possible [4]:

- Batches are randomly assigned to each operator, there are several units in each batch (nested design).
- Batches are large enough so as each operator can measure units from all batches (crossed design).

Further only the nested design, according to which the experiment was carried out, is considered.
Usually three levels of variation are examined; variation between operators, between parts, and between repeated measurements on the same part taken by the same operator. In the nested R&R study, batches (factor B) are used instead of the parts, and measurements on samples from the same batch replace the repeated measures on the parts. Levels of B are nested within levels of factor O (operators). Both factors are considered random and the ANOVA model with random effects [5] is used for evaluation

$$y_{ijk} = \mu + o_i + b_{j(i)} + e_{ijk} \tag{1}$$

where y_{ijk} denotes the value on the *k*-th sample within the *j*-th batch obtained by the *i*-th operator, $i = 1, 2, ..., I$, $j = 1, 2, ..., J$, $k = 1, 2, ..., r$, μ is an unknown constant representing the grand mean, o_i, $b_{j(i)}$ and e_{ijk} are random variables with zero means and variances $\sigma_o^2, \sigma_b^2, \sigma^2$, respectively. Total variance $\mathrm{var}(y_{ijk}) = \sigma_T^2$ can be broken into three components due to

- batch-to-batch variation,
- operator variation (reproducibility),
- within-batch variation,

$$\mathrm{var}(y_{ijk}) = \sigma_T^2 = \sigma_o^2 + \sigma_b^2 + \sigma^2 \tag{2}$$

In the corresponding ANOVA table (**Table 1**) the expected values of mean squares are added to indicate how the variance components are determined.

Table 1 ANOVA, nested design

Source	Sum of squares	Degrees of freedom	Mean square	Expected value of MS
Operator	*SSO*	*I* - 1	*SSO* / (*I* - 1)	$Jr\sigma_o^2 + r\sigma_b^2 + \sigma^2$
Batch (Operator)	*SSB*(*O*)	*I* (*J* - 1)	*SSB*(*O*)/ [*I* (*J* - 1)]	$r\sigma_b^2 + \sigma^2$
Residual	*SSE*	*IJ*(*r* - 1)	*SSE* / [*IJ*(*r* - 1)]	σ^2
Total	*SST*	*IJr* - 1		

Sum of squares are calculated according to known formulas, see e.g. [5]. Equating each of the expected value to the adjacent mean square, the estimates of variance components are obtained

$$\hat{\sigma}^2 = \frac{SSE}{IJ(r-1)} \qquad \hat{\sigma}_b^2 = \frac{1}{r}\left[\frac{SS_{B(O)}}{I(J-1)} - \hat{\sigma}^2\right] \qquad \hat{\sigma}_o^2 = \frac{1}{Jr}\left[\frac{SS_O}{I-1} - \frac{SS_{B(O)}}{I(J-1)}\right] \tag{3}$$

Based on the estimated within-batch variance σ^2, control charts for the batch means and ranges or standard deviations are constructed. The aim is to check the homogeneity of within-batch variation and to analyze possible differences between operators or batches. For the measurement system to be acceptable, all points in the *s* chart should fall within the control limits and most points in the $\bar{X}$ chart should lie outside the control limits. The construction of the centre line and control limits is described e.g. in [6] or [7].

3. R&R STUDY

Steel alloy wiredrawn products such as tyre cords, springs and ropes are widely used in industry. All these products are highly stress-exposed elements of mechanical systems and therefore the knowledge of their mechanical properties is extremely important. The R&R study was a part of the experiment conducted in collaboration with the laboratory of the Department of materials forming. The experiment was initiated by the introduction of a new wire drawing machine and the consequent effort to optimize its adjustment to achieve the best product from the mechanical point of view. The aim of the experiment was the examination of factors affecting mechanical properties of drawn wires. The effects of the size of partial reduction (factor A), the way of removing scales (factor B), and the angle of tapered section of drawing die (factor C) were studied. For this purpose, twelve samples (batches) of drawn wire with the final diameter of 2.5 mm were produced from 5.5 mm thick rolled rods by the straight-through single-block KOCH KGT 25 - E wire drawing machine under different experimental conditions (**Table 3**). Together with the study of stress and strain, the torsion and reverse bending tests were performed as the cyclic plasticity rupture tests and the number of loading cycles to the loss of material integrity (iniciation and growth of fatigue cracks) under different experimental conditions was examined.

The aim of the R&R study was to evaluate the accuracy and consistency of experimental results. In this paper only the torsion test results obtained by three operators are analysed. Twelve wires (batches) were divided between three operators according to the scheme in **Table 3** and ten samples from each wire, i.e. 120 samples in total, were tested. Details are given in [8].

Table 2 Factor levels

Factor		Levels		
		-1	0	1
A	Reduction	23.05 %	27.04 %	32.57 %
B	Descaling	Mechanical		Chemical
C	Angle	8 °		12 °

A) Partial reduction Qd (%) - the amount of cross-section reduction per pass.

B) Angle of the tapered section of a drawing die 2α - the basic shape parameter of the deformation zone which affects the distribution and character of deformation of the wire.

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.

Table 3 Experimental design

Operator	Batch	Factor levels		
		A	B	C
1	1	1	-1	-1
2	2	0	-1	-1
3	3	-1	-1	-1
1	4	1	1	-1
2	5	0	1	-1
3	6	-1	1	-1
1	7	1	-1	1
2	8	0	-1	1
3	9	-1	-1	1
1	10	1	1	1
2	11	0	1	1
3	12	-1	1	1

The results of ANOVA are shown in **Table 4**. Variances $\sigma_o^2, \sigma_b^2, \sigma^2$ estimated using formula (3) are displayed in **Table 5** together with their contribution to the total variance σ_T^2.

Apart from variances, standard deviations and their relative size in comparison with the total standard deviation are displayed.

Table 4 ANOVA, Statgraphics

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
Operators	176.467	2	88.2333	3.75	0.0654
Batches (O)	211.8	9	23.5333	3.19	0.0265
Residual	795.6	108	7.36667		
Total	1183.87	119			

The R&R variance of 8.98 (see **Table 6**) comprises a larger part of the total variance, which is 10.60. The major source of the R&R (82 %) is repeatability. Based on this value, the measurement system is found inadequate since the contribution of R&R is much greater than 30 %, which is the maximum acceptable value according to [1]. However, since the repeatability cannot be separated from the within-batch variation, it is more likely that the large variation results from nonuniform mechanical properties along the wire length due to an imperfect technology of the wire production.

Table 5 Gage Repeatability and Reproducibility Report, Statgraphics

Measurement	*Estimated*	*Percent*	*Estimated*	*Percent*	*Percent*
Unit	*Sigma*	*Total Variation*	*Variance*	*Contribution*	*of R&R*
Repeatability	2.71416	83.3615	7.36667	69.4914	82.00
Reproducibility	1.27181	39.0618	1.6175	15.2582	18.00
R & R	2.99736	92.0596	8.98417	84.7496	100.00
Parts	1.27148	39.0517	1.61667	15.2504	
Total Variation	3.25589	100.0	10.6008		

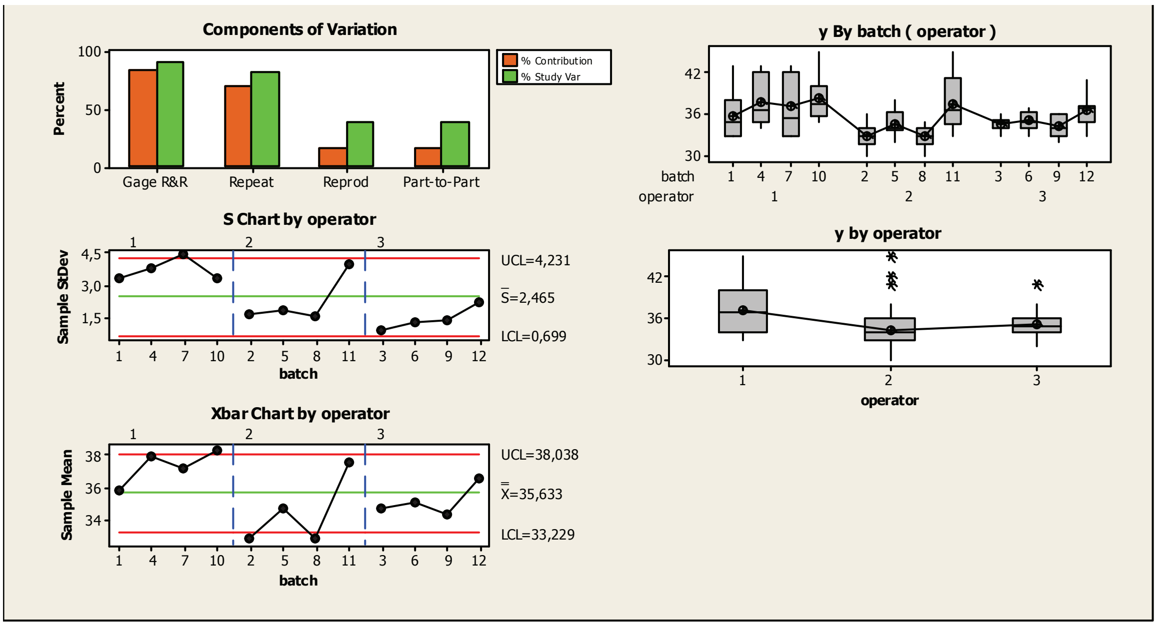

Figure 1 R&R plots, Minitab

Two components of variation can be further analyzed by means of plots in **Figure 1**. Not only that batch 7 is above the upper limit of the *s*-chart but all measurements taken by operator 1 lie above the centre line and indicate either poorer skills of this operator or a higher within-batch variation due to the production technology.

The control limits in the $\overline{X}$- chart are based on the repeatibility standard deviation and too many points falling within the limits mean that the batches cannot be properly distinguished. Both control charts and both box plots in **Figure 1** indicate that the measurements on batches 1, 4, 7, 10 taken by the first operator and the measurements on batch 11 taken by the second operator are higher and more scattered than the rest of observations and therefore the cause should be identified. Greater variation seems to be related to the higher level of measurements. Unfortunately, the different performance of the first operator cannot be explained unambiguously due to the experimental design which had been chosen (**Table 2**). The effect of factor A is confounded with the effect of operators; it cannot be decided whether the higher level and the higher variability of batches 1, 4, 7, and 10 results from the different operator skills or from the fact that factor A was at its lowest level.

4. ANALYSIS OF THE FACTORIAL EXPERIMENT

It should be noted that the experiment was unreplicated; ten samples from each batch do not represent true replications since they were obtained during a single treatment. In this case either the mixed-effect model [9] or the solution based on batch averages should be used [10]. The latter method was chosen since it does not require software with implemented mixed-effect models. The disadvantage of this method is a small number of degrees of freedom. If all interaction effects are included, no degrees of freedom remain for the experimental error estimation. To be able to test hypotheses about factor effects, some interactions must be pooled with the experimental error, i.e. excluded from the ANOVA model. Based on the stepwise method, insignificant interaction terms were excluded and from the main effects only those of factors A and B appear to be significant (**Table 6**).

Table 6 ANOVA, unreplicated design

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A: Partial reduction	17.6467	2	8.82333	8.44	0.0107
B: Removing scales	12.8133	1	12.8133	12.25	0.0081
RESIDUAL	8.36667	8	1.04583		
TOTAL (CORRECTED)	38.8267	11			

5. CONCLUSION

Differently from the common R&R study where the same parts are measured repeatedly, repeatibility variation cannot be separated from the within-batch variation in destructive tests. The small value of R&R variation confirms the appropriatness of a measurement system, but in the case of an unacceptably great repeatibility no conclusion related to the measurement system capability can be made.

Commonly, batches are considered random levels of factor B and they are divided between operators randomly. In the presented study the batches were defined by different treatments corresponding to the factorial design. In this case, operators must be included as another factor, which means that their shifts must be planned conscientiously so that their effects are not confounded with effects of the examined factors. Instead of matching operators and levels of factor A, all operators should test several samples of wire from the same batch. For example, in the case of 9 samples taken from each batch, every operator would test 12·3 = 36 samples in total and the design could be considered a crossed design.

The great within-batch variation may not be a problem in data evaluation if the number of samples from each batch is sufficient. To analyse experimental results correctly, data from each batch are represented by the batch average. In replicated experiments, sufficient degrees of freedom are left to test factor effects. In unreplicated experiments either high-order interactions are excluded from the model or, in the case of two-level factors, the Lenth's method based on pseudo standard error can be used. Another possibility is the use of a mixed-effect model, where batches are included as a random-effect factor, but the analysis requires a suitable software. Consequently, to make the analysis easier, two levels of experimental factors should be set and the experiment should be replicated, which means that at least two batches should be produced by the same treatment. The factorial design in randomized blocks would be suitable; all possible treatments would be comprised in each block and the blocks could correspond to different operators. The number of samples in each batch could be smaller. In this way, using roughly the same number of experimental units, the evaluation efficiency would significantly increase.

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REFERENCES

[1] Measurement Systems Analysis. Reference Manual. 4th ed. Chrysler Group LLC, Ford Company, General Motors corporation, 2010.

[2] MONTGOMERY, D.C., RUNGER, G.C. Gauge Capability and Designed Experiments: Part I: Basic Methods. *Quality Engineering*, 1993, vol. 6, no. 1, pp. 115-135.

[3] PAN, J.N. Evaluating the Gauge Repeatability and Reproducibility for Different Industries. *Quality & Quantity*, 2006, vol. 40, no. 4, pp. 499-518.

[4] Gorman, D., Bower, K.M. Measurement System Analysis And Destructive Testing. *Six Sigma Forum Magazine*, 2002, vol. 1, no. 4, pp. 16-19.

[5] MONTGOMERY, D.C. *Design and Analysis of Experiments*, 8th ed. New York: John Wiley & Sons, 2013. 752 p.

[6] ISO 7870-2:2013 Control charts -- Part 2: Shewhart control charts. Geneva: International Organization for Standardization, 2013. 44 p.

[7] MONTGOMERY, D.C. Statistical Quality Control: A Modern Introduction, 7th ed. New York: John Wiley & Sons, 2013. 768 p.

[8] KLAPUT, P., FABÍK, R., HALFAROVÁ, P. Analysis of the Measurement of Interlamellar Spacing of Pearlite in Eutectoid Steel. In *METAL 2016*: 25th International Conference on Metallurgy and Materials. Brno: Tanger Ltd., 2016, pp 409-414.

[9] WEST, B.T., WELCH, K.B., GALECKI, A.T. *Linear mixed models: A practical guide using statistical software*. New York: Chapman & Hall/CRC, 2007. 348 p.

[10] JAROŠOVÁ, E. Analysis of the Central Composite Experiment with Pseudoreplications. In Aplimat 2013: *12th International Conference on Applied Mathematics*. Bratislava: Institute of Mathematics and Physics, Faculty of Mechanical Engineering, 2013, pp. 335-345.