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APPLICATION OF MODERN EXPERIMENTAL STRATEGY FOR PARAMETERS OF A RECONFIGURABLE DIE

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Abstract: *Flexible manufacturing systems are one of the main concerns for big companies, due to the fact that they bring the main advantage of quick reconfiguration of the tools used for manufacturing various products in short time-to-market. The paper presents the design of an experimental program for parameters of a reconfigurable die, based on principles of a modern strategy. By using an initial mathematical model and statistically testing it, the results showed that the applied regression equation was not adequate for experimental data. So, corrections have to be made for the initial model and repetition of the cycle, until optimal equation is found.*

Key words: *reconfigurable dies, discrete forming, experimental program, design of experimental research.*

1. Introduction

Reconfigurable tools are a topic of interest for researchers in the last years, as a response to market's demands for products of a large variety available in a short time [8]. Reconfigurable dies are tools for multipoint plastic deformation [3], which replace the traditional working area with a network of individual active punches, called pins.

This paper presents the design of an experimental program for a reconfigurable die, by mathematically modelling the action of the factors of influence upon the objective function of the system.

The objective function of the system consists of the edge fillet of the manufactured surface, where maximum deformations are concentrated.

For the mathematical model, we considered three factors of influence against objective function *y*. First factor considered is the friction coefficient between the sheet-metal and the actuation pin, which has the value $\mu = 0.16$ for a pair of materials OL/OL [9]. The admissible crushing stress in the actuation system of the die is the second parameter. The admissible stress for a pair of materials of type OL/OL are between $\sigma_s = 30…40$ MPa; we considered a nominal value of 35 MPa. The third factor of influence is the material used for deformation operations. In the experiment were used two types of material, aluminium and steel.

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2. Description of Experimental Strategy

Traditional method of experimental process, known as Gauss-Seidel strategy [4], has the property of reducing any experimental research to an uni-factorial process, meaning one factor is taken step by step, while all the other existing factors are being considered constant. This approach may lead to partially correct results, due to the fact that, on one hand, the factors of influence are not analysed in dependency one with the other, and on the other hand, because of increased number of factors, the experimental volume also increases significantly.

Box-Wilson strategy uses instead a factorial experiment, meaning at each run is modified the value of all existing factors, which leads to increased certainty of the results, also the volume of the experiment is reduced.

Figure 1 presents a modern strategy of experimental process, characterized by repetition of a number of experimental cycles, based on inadequacy of mathematical model set initially. Thereby, if in a previous experimental cycle was concluded that the initial mathematical model doesn't show a satisfying conformity and precision, the model is subject of a set of corrections for eliminating or adding new factors of influence, modification of variation interval of the factors or introduction of new response functions, based on the information gathered in previous cycle [5].

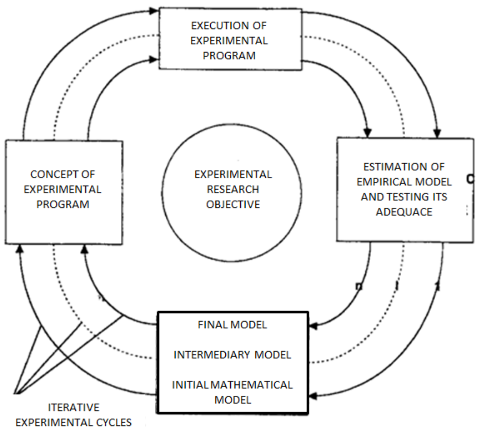

Fig. 1. *Modern strategy of experimental process* [5]

3. Defining the Mathematical Model

The objective function of the experiment defines and quantitatively evaluates the behaviour and evolution trends of the system which is subject of research, in certain conditions. So, the objective function represents the definition of existing relations set between the factors which influence the investigated process, by using a relation as the following:

$$y = f(x_1, x_2, x_3, ..., x_n), \quad (1)$$

where y is the dependent variable (output), and x_1, x_2, x_3, …, x_n are independent variables (input).

For the considered deep-drawing process, based on finite element analysis previously developed, in which the maximum deformations of the part were determined, the objective function of the experiment is set to be the edge fillet R, measured in mm.

4. Concept of Experimental Program

The independent variables which influence the output variable were described in first chapter, and these are: x_1 = friction coefficient, a; x_2 = crushing stress from actuation system of the pins, b [MPa]; x_3 = material, c.

So, the 1st grade equation of the model which is planned to be found after processing the experimental results has the following form:

$$y = b_0 + \sum_{j=1}^{3} b_j \cdot x_j + \sum_{\substack{u,j=1 \\ u \neq j}}^{3} b_{ju} \cdot x_j \cdot x_u + \sum_{\substack{u,t,j=1 \\ u \neq t \neq j}}^{3} b_{jut} \cdot x_j \cdot x_u \cdot x_t \ . \tag{2}$$

The variation interval of a factor is a value, a number, which by adding or subtracting it from the basic level, determines the higher level and the lower level of the considered factor in an experiment [7]. That is how, by establishing the nominal values of the three variables, the variation interval of the factorial experiment was set and can be seen in Table 1. Due to simplification of the experimental matrix reasons, the basic level is encoded with zero, while higher level and lower level take +1 respectively −1.

Coordinates of central point and variation intervals of the factors Table 1

Parameter	**Encoded value**	**Physical value**		
		x_1 <=> a	x_2 <=> b [MPa]	x_3 <=> c
Central point x_{j0}	0	0.16	35	-
Variation interval D_j	Δ_j	0.02	5	-
Higher level $x_{j\,sup}$	+1	0.18	30	Al sheetmetal
Lower level $x_{j\,inf}$	−1	0.14	40	OL sheetmetal

The volume of the experiment is represented by the formula $N = p^k$ runs, where k is the number of factors, p is the number of variation levels of their factors [5]; in our case it results a volume of $N = 2^3$ run conditions, and for each condition are made five runs. This type of experiment is called factorial experiment [1, 2].

5. Development of Experimental Program

The program matrix of the experiment is shown in Table 2.

Program matrix of factorial experiment Table 2

Run number	Mean x_0	Levels of factors of influence			Values of output variables					
		x_1	x_2	x_3	y_1	y_2	y_3	y_4	y_5	y_{med}
1	+1	+1	+1	+1	15.6	16.9	17.1	18.8	18.3	17.34
2	+1	−1	+1	+1	17.8	17.5	18.3	19.1	17.6	18.06
3	+1	+1	−1	+1	17.4	17.5	18	17.9	19.5	18.06
4	+1	−1	−1	+1	18.6	18.3	18.9	19.2	19	18.8
5	+1	+1	+1	−1	17.5	18.2	17.7	18.4	19.4	18.24
6	+1	−1	+1	−1	18.5	17.4	18.2	18.4	19.1	18.32
7	+1	+1	−1	−1	17.4	18.5	18.4	17.9	18.7	18.18
8	+1	−1	−1	−1	18.5	19	18.8	18.7	18	18.6

The values of regression coefficients are calculated with formula (3), and the resulted values are shown in Table 3:

$$b_j = \frac{\sum_{i=1}^{N} x_{ij} y_i}{N}, \quad j = 1, 2, \ldots, k. \tag{3}$$

Values of regression coefficients Table 3

Coef.	Value	Coef.	Value	Coef.	Value	Coef.	Value
b_0	18.2	b_2	−0.21	b_{12}	0.045	b_{23}	−0.155
b_1	−0.245	b_3	−0.135	b_{13}	−0.12	b_{123}	−0.04

It results the definition of adopted mathematical model:

$$\begin{aligned} y &= 18.2 + x_1 \cdot (-0.245) + x_2 \cdot (-0.21) + x_3 \cdot (-0.135) + x_1 x_2 \cdot 0.045 \\ &\quad + x_1 x_3 \cdot (-0.12) + x_2 x_3 \cdot (-0.155) + x_1 x_2 x_3 \cdot (-0.04). \end{aligned} \tag{4}$$

6. Statistical Analysis of Obtained Experimental Results

6.1. Estimation of Experimental Error

Dispersion of response function for one measurement is the statistical estimator which characterizes the spread of results from a series of *n* measurements developed over the same measurement unit, and can be put under formula:

$$s_i^2 = \frac{1}{n-1} \sum_{q=1}^{n} (y_{qi} - \bar{y}_i)^2, \tag{5}$$

where y_i represents the result of the "i"th measurement, $\bar{y}_i$ is the mean of the *n* results considered.

In order to have a correct evaluation of the estimator s, it is necessary that possible aberrant values to be taken out from the individual results series. The presence of aberrant results can be done through two tests, Grubbs-Smirnov test and Student test.

Grubbs-Smirnov test. If after measurements we have obtained the series of n data with y_i values, which have the mean $\overline{y}$ and empirical dispersion s, and y^* is the suspicious value, then we can calculate:

$$GS_{calc} = \frac{\left|y^* - \overline{y}\right|}{s}. \tag{6}$$

For all sets of trials the data string was composed of five values, and the reliability level P was considered 0.95. So, value GS_{tab} = 2.08 was selected according to tabular data consulted [7]. The results of Grubbs-Smirnov test can be found in Table 4.

Grubbs-Smirnov test results Table 4

Considered value	GS_{tab}	GS_{calc}	Result
GS_1	2.08	1.83	not aberrant
GS_2	2.08	2.12	aberrant
GS_3	2.08	2.28	aberrant
GS_4	2.08	1.53	not aberrant
GS_5	2.08	1.56	not aberrant
GS_6	2.08	1.69	not aberrant
GS_7	2.08	1.33	not aberrant
GS_8	2.08	1.42	not aberrant

Student test. If after measurements we have obtained the series of n data with y_i values, y^* is the suspicious value and we calculate the mean $\overline{y}$ and dispersion s of the other $n-1$ values, then we can calculate:

$$t_{calc} = \frac{\left|y^* - \overline{y}\right|}{s}. \tag{7}$$

For all sets of trials the data string was composed of five values, and the reliability level P was considered 0.95. So, value t_{tab} = 2.776 was selected according to tabular data consulted [7]. The results of Student test can be found in Table 5.

Student test results Table 5

Considered value	t_{tab}	t_{calc}	Result
t_1	2.776	2.65	not aberrant
t_2	2.776	4.33	aberrant
t_3	2.776	7.2	aberrant
t_4	2.776	1.85	not aberrant
t_5	2.776	4.02	aberrant
t_6	2.776	2.27	not aberrant
t_7	2.776	1.51	not aberrant
t_8	2.776	1.66	not aberrant

After the aberrant values have been eliminated from the data string, the values of the response function dispersion were calculated for each run; the results are presented in Table 6.

Values of response function dispersion Table 6

Dispersion	Value	Dispersion	Value	Dispersion	Value	Dispersion	Value
s_1^2	0.826	s_3^2	0.194	s_5^2	0.216	s_7^2	0.277
s_2^2	0.162	s_4^2	0.125	s_6^2	0.377	s_8^2	0.145

In order to check the homogeneity of dispersions, Cochran criterion is used, based on the following formula:

$$G_{calc} = \frac{\max s_i^2}{\sum_{i=1}^{N} s_i^2}. \quad (8)$$

If $G_{calc} < G_{tab\ \alpha,v1,v2}$, then the dispersions are homogeneous, $\alpha = 0.05$, $v_1 = n - 1$, $v_2 = N$

From calculations resulted $G_{calc} = 0.355$, and the tabular value of Cochran criterion, for $\alpha = 0.05$, $v_1 = 4$, $v_2 = 8$ was selected $G_{tab} = 0.391$ [6]. $G_{calc} < G_{tab\ \alpha,v1,v2}$, so the dispersions are homogeneous.

Calculation of reproducibility dispersion is calculated based on the formula:

$$s_0^2 = \frac{1}{Q(n-1)} \sum_{i=1}^{Q} s_i^2. \quad (9)$$

where Q - number of replicated points, n - number of replications/point.

Calculated value for s_0^2 is:

$$s_0^2 = \frac{1}{8 \cdot 4} \cdot 2.323 = 0.072. \quad (10)$$

Calculation of regression coefficients dispersion is based on the following formula:

$$s_{bj}^2 = \frac{s_0^2}{N \cdot n}, \quad (11)$$

where N - number of trials, n - number of replications for each trial.

Calculated value for coefficients dispersion is $s_{bj}^2 = 0.0018$.

6.2. Inspection of Statistical Meaning of Regression Coefficients

Testing the statistical meaning of coefficients is based on Student test calculation:

$$t_{calc} = \frac{|b_{j\min}|}{s_{bj}}. \quad (12)$$

For all eight coefficients from Table 3, the comparison $t_{calc} > t_{tab\ \alpha,v(n-1)}$ was made (for $t_{tab\ \alpha = 0.05,\ v = 4} = 2.776$); resulted values are shown in Table 7.

Student test values Table 7

Coef.	t_{calc}	Coef.	t_{calc}	Coef.	t_{calc}	Coef.	t_{calc}
b_0	433.33	b_2	5	b_{12}	1.07	b_{23}	3.69
b_1	5.83	b_3	3.21	b_{13}	2.85	b_{123}	0.95

It can be concluded that, from statistical point of view, coefficients b_{12} and b_{123} are not significant, so the 1st grade mathematical model resulted is the following:

$$\tilde{y} = 18.2 - 0.245 \cdot x_1 - 0.21 \cdot x_2 - 0.135 \cdot x_3 + 0.045 \cdot x_1 \cdot x_2 - 0.155 \cdot x_2 \cdot x_3 . \quad (13)$$

6.3. Inspection of Adequance (Conformity) between Objective Function Values Based on Empirical Model with Real Values (Measured) of Objective Function

The conformity dispersion is calculated with the following formula:

$$s^2_{adecv} = \frac{n}{N - I} \cdot \sum_{i=1}^{N} (\overline{y_i} - \tilde{y}_i)^2 = \frac{5}{8 - 6} \cdot 0.3382 = 0.845 , \quad (14)$$

where I is the number of significant coefficients from regression equation and $\tilde{y}$ is the value estimated based on determined regressive model.

Fisher criterion is calculated with the following formula:

$$F_{calc} = \frac{s^2_{adecv}}{s_0^2} = 11.743 . \quad (15)$$

From tables, for $\alpha = 0.05$, $v_1 = 5$ and $v_2 = 8$ the value of $F_{tab} = 3.69$ is selected.

$F_{calc} > F_{tab\ \alpha,v1,v2}$, thereby the obtained regression equation is not adequate with the experimental data and new cycle with revised parameters has to be considered.

7. Conclusions and Further Directions

The main information trackers are the regression coefficients, shown by their numerical value and their sign. Analysis of regression coefficients permits the judgement of the amplitude and the direction of influence of the factors.

As it was resulted from the statistical inspection of the coefficients, two of them were insignificant. This can happen because of, on one hand, the experimental conditions, considering that the variation intervals of the factors were too small, or it can be because the experimental error was too big. There is though the possibility that these two insignificant factors to indicate the retaining of some factors truly not relevant inside the experiment, or it can also indicate that some other significant factors were not included at all into the experiment.

Another aspect of obtained results interpretation is the comparative analysis of the information calculated with empirical model with the information resulted from measurements. As it was concluded with Equation (15), the linear model adopted as first cycle of experiment is not adequate. Thereby, it is demanding that the experimental research to be resumed based on revised conditions, which can be, on one hand, reducing the variation intervals of the factors, or by eliminating some factors or adding others new inside the experiment, which were not considered in the first cycle. Changing the central point of the experiment can be another direction to follow in next cycle, by using other materials for the sheet-metal, or by finding new design solutions for the pins actuation system, which should lead to an acceptable crushing stress.

The paper presented the modern strategy of an experimental process, by describing the initial mathematical model and the obtained results; based on them, it was concluded that a new experimental cycle is needed, while the iterative cycles will finish when the final adequate model is found and can be used in the experimental research.

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