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STATISTICAL MATHEMATICAL MODELLING OF THE MANUFACTURING PROCESS OF PARTS OBTAINED BY ELECTROMAGNETIC FORMING

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Abstract: *The paper describes a series of researches that observes the influence of some parameters (variables) that are specific to the electromagnetic forming process. The parameters chosen in this paper were: charging voltage of the capacitor bank and its capacity. The disk-shaped workpieces prepared were free formed (bulged), than the maximum forming depth obtained was measured (without cracking the material), which was considered to be the measure of formability for the parts processed by electromagnetic forming. The data obtained were statistically processed in order to select the significant parameters that will be part of the statistical mathematical model that is to be studied in the next researches*
Key words: *statistical mathematical modelling, electromagnetic forming*

1. INTRODUCTION

The improvement of the manufacturing processes performances requires finding the combination of optimal parameters value that operates in those processes (Hewidy et al., 2005; Kanagarajan et al., 2008).

The data obtained by preliminary experiments are subdued to some statistic processing such as: *variance analysis* and *correlation analysis*. For this, the obtained data are organised in table form and we calculate the sum, the average, and the dispersion on the *m* columns. Next, we calculate the Fischer criterion to establish the significant factors that are expressed by the rapport:

$$F_c = S^2 / S_a^2 \tag{1}$$

where S_a^2 is the variance caused by random factors, and S^2 is the variance given by the relationship,

$$S^2 = r\,S_x^2 + S_a^2 \tag{2}$$

with S_x^2 the variance caused by the analysed factor *X* and *r* the number of repeated tests.

Choosing the tabled values for Fischer criterion is based on the level of signification α and of the freedom degrees $\nu_1 = m-1$ and $\nu_2 = m(r-1)$. The signification level α (also called trustful level) has been chosen according to the special literature recommendations, with the value $\alpha = 0{,}05$ (5%), value that has been currently used for measurements in industry, laboratories, in control operations, in testing, expertise etc. (Banks & Tran, 2009).

In order to eliminate the variances that radically differ from other variances, we calculate the Cochran *criterion*, in order not to repeat the experiment, with the expression:

$$G_c = \frac{\max S_j^2}{S_1^2 + S_2^2 + \ldots + S_j^2 + \ldots + S_m^2} \quad ; \quad j = 1 \ldots m \tag{3}$$

where S_j^2 are the variances on the *m* columns of the organised data table.

The tabled values of Cochran criterion are taken based on the level of signification α, of the number of freedom degrees $\nu_3 = m-1$ and of the number of variances *m*.

Correlation analysis is used to estimate the connections between results and factors, and also for the selection of the significant connections that will be considered in the programmed experiment and will enter as variables in the mathematical model of the process. If it is to be found a certain connection, more or less tight, between the two variables *Y* and *X*, it is said that these are in *correlation* or that there is a *stochastic* relation between them.

In order to express the connection between the two variables *Y* and *X* an indicator was introduced, called *coefficient of simple correlation*, whose estimation r_{yx} is determined with the relationship:

$$r_{yx} = \frac{\sum_{i=1}^{n} x_i y_i - n\,\bar{x}\,\bar{y}}{(n-1)\,S_x\,S_y} \tag{4}$$

where S_x and S_y are estimated squared medium variances and *n* is the number of determinations.

Simple correlation coefficient square is respectively called *simple determination coefficient* ($R_{yx} = r_{yx}^2$) and it expresses that part from the variation of the result *Y* that can be attributed to factor *X*.

After calculating the correlation coefficients we checked up their significance. This way, in the case of the simple correlation coefficient the Student *criterion* is used, which is expressed by the relationship:

$$t_c = \frac{\left| r_{yx} \right| \sqrt{\nu_4}}{\sqrt{1 - r_{yx}^2}} \tag{5}$$

where $\nu_4 = n-2$ is the number of freedom degrees and *n* is the number of tests.

The research described in this paper is limited to applying statistical mathematical modelling in selecting the technological parameters specific to electromagnetic forming equipment.

2. EXPERIMENT AND STATISTICAL MODELLING

Charging voltage of the capacitor bank is an important factor (parameter) in the electromagnetic forming process, its influence was investigated by successive experiments (Luca, 2000; Mamalis et al., 2006). The result achieved in this case was the influence of the capacitor bank voltage on the forming depth of free deep-drawn (bulged) parts. In these tests the capacity of the capacitor bank remained constant (200 μF), changing each time the charging voltage from the control panel of the equipment. The workpieces used were 0.60-0.02 mm thick and were sampled as a disk from a FeP04 deep-drawn sheet. The experiment was repeated three times for three of the analysed factor levels, performing a total of 12 tests. After plastic deformation with increasing energies, formed parts were subjected to measurements of the forming depth obtained, resulting the values in Table 1.

Dispersion and correlation analysis were performed using data from the experiment, resulting the conclusions presented in Table 2.

Capacity of the capacitor bank is an important factor in the (visco)plastic deformation of the electromagnetic field, which is why many experiments were conducted aimed to determine the influence of this factor on the forming depth obtained for electromagnetically formed parts. To make this experiment the capacitor bank was constructed so that modules of 25 µF can be coupled or decoupled, achieving discrete values of the capacity between 0 and 200 µF. The materials used were EN AW-Al 99.0 aluminium sheet with 0.35-0.02 mm thickness and FeP04 steel sheet with 0.60-0.02 mm thickness. Aluminium specimens were subjected to free deep-drawing, maintaining constant the voltage charge of capacitor bank (4 kV) and gradually increasing its capacity. For three levels of the capacity the tests were repeated twice. Then the forming depth was measured and the results are presented in Table 3.

Data obtained from experiments were subjected to dispersion and correlation analysis, from which were obtained the results and conclusions presented in Table 4.

Further, specimens of steel were formed using a voltage of 6 kV and capacities with increasing values of up to 200 µF, resulting conclusions similar to those of aluminium.

No. of repeated tests	Factor levels (voltage *U*)					
	1 (3 kV)	2 (4 kV)	3 (5 kV)	4 (6 kV)	5 (7 kV)	6 (8 kV)
1	2,97	7,04	12,32	14,40	20,80	25,94
2	3,16	-	12,03	-	-	26,63
3	2,71	-	12,90	-	-	25,18
Sum	8,84	-	37,25	-	-	77,75
Average	2,947	-	12,417	-	-	25,917
Variance	0,051	-	0,196	-	-	0,526

Tab. 1. Influence of the capacitor bank voltage on forming depth

	Mode of decide	Value	r_{yx}= 0,99991	α =0,05
F_c	relationship (1)	1550,921	F_c>F_t : *U* is considered a technological parameter and will be inclused in the mathematical model	m= 3
F_t	from tables	5,14		r= 3
G_c	relationship (3)	0,68046	G_c<G_t : in conclusion the hypothesis regarding the homogeneousness of the variances is verified	$\nu_1 = 2$
G_t	from tables	0,8709		$\nu_2 = 6$
t_c	relationship (5)	72,8286	t_c>t_t : in conclusion there is a correlation between the *U* factor and the obtained result	$\nu_3 = 2$
t_t	from tables	12,706		$\nu_4 = 1$

Tab. 2. Results and conclusions of dispersion and correlation analysis for charging voltage *U* parameter

No. of repeated tests	Factor levels (capacity *C*)					
	1 (25 µF)	2 (50 µF)	3 (75 µF)	4 (100 µF)	5 (125 µF)	6 (150 µF)
1	5,28	12,25	17,41	23,56	32,26	41,18
2	5,04	-	17,74	-	-	41,27
3	5,45	-	16,97	-	-	40,36
Sum	15,77	-	52,12	-	-	122,81
Average	5,257	-	17,373	-	-	40,937
Variance	0,042	-	0,149	-	-	0,251

Tab. 3. Influence of capacity of the capacitor bank on forming depth

	Mode of decide	Value	r_{yx}= 0,99767	α =0,05
F_c	relationship (1)	4814,145	F_c>F_t : *C* is considered a technological parameter and will be inclused in the mathematical model	m= 3
F_t	from tables	5,14		r= 3
G_c	relationship (3)	0,56787	G_c<G_t : in conclusion the hypothesis regarding the homogeneousness of the variances is verified	$\nu_1 = 2$
G_t	from tables	0,8709		$\nu_2 = 6$
t_c	relationship (5)	14,6389	t_c>t_t : in conclusion there is a correlation between the *C* factor and the obtained result	$\nu_3 = 2$
t_t	from tables	12,706		$\nu_4 = 1$

Tab. 4. Results and conclusions of dispersion and correlation analysis for capacity *C* parameter

Future research will aim to apply the procedure described for selecting other technological parameters specific to the working tool (coil) and the workpiece in order to develop the mathematical model of electromagnetic forming process of the metal sheet.

3. CONCLUSION

Following the preliminary experiments regarding the parameters of the electromagnetic forming process of deep-drawn parts a series of conclusions resulted are presented next.

Charging voltage. The experimental results, presented in table 1, show that while the charging voltage grows, the obtained forming depth increases. Charging voltage *U* factor meets all required statistical criterions and can be selected as a technological parameter for the mathematical model of the electromagnetic forming process of the deep-drawn parts.

Capacity of the capacitor bank. The results lead to the conclusion that the capacity of the capacitor bank has a direct influence on the forming depth. In the case of the parts from EN AW-Al 99.0 aluminium sheet, the relative increase of the forming depth was of about 88% and in the case of the parts from FeP04 steel sheet, the relative increase of the forming depth was of about 90%. Capacity *C* factor satisfies all the required statistic criterions and may be selected as a technological parameter for the mathematical model of the viscoplastic process investigated.

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