OPTIMIZATION OF ELECTROCHEMICAL DISCHARGE DRILLING PROCESS BY MEANS OF GREY RELATIONAL ANALYSIS

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Abstract: *The electrochemical discharge drilling is a hybrid machining process applied to achieve holes in workpieces made of difficult-to-machine electroconductive materials and using not very complex machining equipment. On the other hand, the grey relational analysis facilitates obtaining the combination of process input factors able to ensure values for the process output parameters close to the optimum values, when certain weights are considered for the process output parameters. The grey relational analysis was applied to identify the combination of the electrochemical discharge drilling process input factors for distinct weights of material removal rate and tool electrode wear rate. By considering the experimental results of fulfil factorial experiment, the combinations of the process input factors (tool electrode diameter, electrolyte concentration, voltage applied to electrodes and the capacitance of capacitors included in the machining electric circuit) were determined.*

Keywords: *electrochemical discharge drilling, grey relational analysis, material removal rate, tool electrode wear rate, process optimization*

1. Introduction

The grey relational analysis is a method that could be applied in determining the optimal values of input factors corresponding to distinct machining processes.

The theory of grey systems was elaborated in the ’80 years of previous century by J.L. Deng, who published a paper concerning the control problems of grey systems [Deng, 1989].

The grey system could be defined as a system for which the available information is limited, incomplete and found under the hazard influence. One could consider that *a black situation* appears when there is not information about the situation evolution and *a white situation* when all the information is available, the grey situation is found between these limits. The researchers appreciate that in fact, many real problems are grey problems. The grey analysis does not ensure determining the best solution of a problem, but a good solution could be addressed.

Essentially, the grey analysis method takes into consideration the quantitative relation corresponding to the elements incorporated in two series. If the differences between elements are low, then the conclusion that the comparison result is better could be stated. In order to develop the comparison, the so-called grey relational coefficient is used. This coefficient is based on the level of similarity and variability.

Over the last decades, the grey analysis was applied in order to estimate optimal combinations of the values corresponding to certain process input factors, so that the output factors have a more convenient size.

Thus, the grey relational analysis could be used inclusively to optimize the so-called electrochemical discharge machining process. One defines *the electrochemical discharge machining* as a nonconventional machining method which uses simultaneous processes of electrical discharges and electrochemical dissolution, to ensure the material removal from workpieces made of difficult to cut materials.

There are many factors which could affect the parameters of technological interest in the case of electrochemical discharge drilling (material removal rate, tool electrode wear, roughness of obtained surface etc.).

As above mentioned, when the problem of optimizing the values of the input factors corresponding to electrochemical discharge machining process is stated, the grey relational analysis could be applied.

Over the years, the researchers had preoccupation in using the grey relational analysis to optimize electrochemical discharge processes of processes found in a certain correlation with such a machining process.

Sathisha et al. determined some of the significant factors (machining gap size, electrolyte concentration and voltage) able to affect the material removal rate and tool wear rate at the electrochemical spark machining. Subsequently, they used the grey relational analysis in order to estimate the values of the certain process input factors so that convenient values for the process output factors are obtained [Sathisha, 2013].

Lijo et al. took into consideration the electrochemical discharge machining process to machine conductive and non-conductive materials used in micro electro mechanical systems [Lijo, 2014]. They used the multi response analysis and grey relational analysis to optimize the values of output machining parameters (material removal rate, heat affected zone, diametral overcut). As process input factors, they considered the voltage, the electrolyte concentration, the duty factor.

Ravikumar developed an experimental research using the grey relational analysis and multiple regression model when applying the electrochemical machining [Ravikumar, 2011].

The objective of this paper was to present the results obtained by applying the grey relational analysis to estimate the combination of electrochemical discharge drilling process input factors able to ensure values for the process output parameters close to the optimal values, when certain weights are associated with each of process output parameters.

2. Experimental conditions

The electrochemical discharge drilling scheme presented in figure 1 was adopted within experimental research [Coteață, 2009]. A cylindrical bar of small diameter and made of high speed steel was used as tool electrode. The material for test pieces was the spring steel 60 CrMnSi 17A. The test pieces were oriented and clamped in a recipient where a passivating electrolyte (sodium silicate soluble in water, with distinct concentrations) was also introduced, so that the electrolyte practically covered the test piece. To obtain a uniform tool electrode wear and to intensify the electrolyte circulation in the drilling zone, the tool electrode was rotated by means of an electric motor of direct current. Both the tool electrode and test piece are connected in the electric circuit of a direct current source *S* (fig. 1). The capacitors *C* with distinct electric capacitances allowed the increase of the electrical discharges energy.

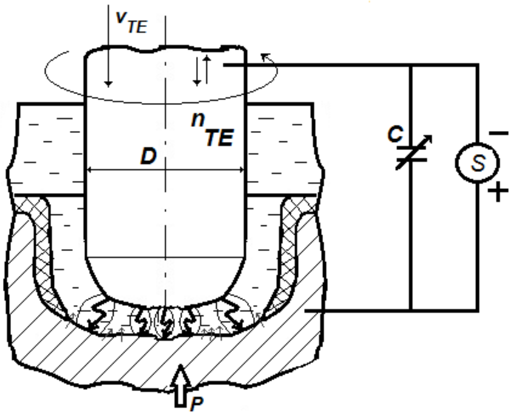

Figure 1: *Electrochemical discharge drilling of small diameter holes.*

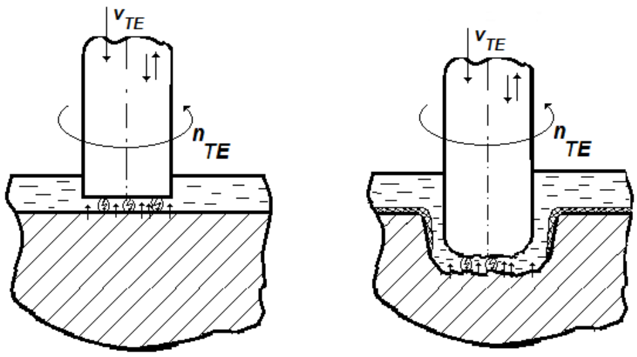

Figure 2: *Machining scheme corresponding to the electrochemical drilling of small diameter holes: a – at the beginning of drilling process; b - at the end of drilling process.*

Initial, a spring incorporated in the device for orienting and clamping the test piece was set to ensure a certain pressure between the frontal surface of tool electrode and the plane surface of the test piece. A rectilinear alternative movement achieved by the tool electrode facilitated the development of electrical discharge between the asperities existing on the tool electrode active surface and test piece surfaces, especially when the contact between electrodes is interrupted.

If the tool electrode and test piece are immersed in the electrolyte, electrochemical reactions are initiated between test piece material and electrolyte. As a result, a passivating layer is gradually generated on the test piece surfaces where the intensity of the electric field exceed certain values. The passivating film is partially destroyed by the electrical discharges developed between the electrodes asperities. As above mentioned, the tool electrode achieves a reciprocating movement and, in this way, the periodical contact between electrodes with the developing a certain pressure p contributes also to the breaking of the passivating layer. Small quantities of passivating layer are thrown in the work gap existing between tool electrode and test piece, from where they are removed as a consequence of the reciprocating movement achieved by tool electrode.

The process of material removal continues only on the zones found near the active surfaces of tool electrode, where electrical discharges develop. In the other zones of test piece, the electrochemical process of material removal practical stops, due to the presence of the passivating layer; in this way, the hole is gradually generated.

The electrical discharges have as effects not only the material desired removal from test piece, but also they contribute to the material removal from tool electrode, determining a wear process. If initially the frontal surface of tool electrode was plane, after a certain duration, as a consequence of the wear process, the tool electrode will present an approximately conical zone.

An experimental research in accordance with the principles specific to a full factorial experiment was designed and achieved in the above mentioned conditions.

As process input factors, the tool electrode diameter D, the voltage V applied to electrodes, the capacitance C of capacitors included in the relaxation circuit and the density δ of the work liquid were considered. Taking into consideration a set of four independent variables at two levels and a full factorial experiment, 16 experiments were achieved. The values of the process input factors (independent variables) were inscribed in the first lines of table 1.

The machining process results were appreciated by means of the material removal rate and tool electrode wear. Both test piece and tool electrode were weighted before and after each test using an analytical balance.

Table 1: *Experimental conditions and experimental results.*

Intended tool electrode diameter: D_{min}=0.5 mm, D_{max}=0.9 mm								
Electrolyte density: δ_{min}=1.05 g/cm^3, δ_{max}=1.20 g/cm^3								
Voltage applied to electrodes: U_{min}=35 V, U_{max}=45 V								
Capacitance: C_{min}=33 μF, C_{max}=840 μF								
Test duration: 6 min								
Exp. no.	Input process factors							
	Tool diameter *D*, mm	Electrolyte density, *δ*, g/cm^3	Voltage *U*, V	Capacity *C*, μF	Material removed from test piece, Δm_{TP} g	Material removal rate, Q_{TP}, mg/min	Massic tool electrode wear, Δm_{TE}, mg	Tool electrode massic wear rate, W_{TE}, mg/min
1	1/0.46	2/1.20	2/45	2/840	0.0135	2,250	0.0140	2,333
2	1/0.49	2/1.20	2/45	1/33	0.011	1,833	0.0057	0,950
3	1/0.51	2/1.20	1/35	2/840	0.0128	2,133	0.0081	1,350
4	1/0.48	2/1.20	1/35	1/33	0.01	1,667	0.0028	0,467
5	1/0.50	1/1.05	2/45	2/840	0.0113	1,883	0.0079	1,317
6	1/0.47	1/1.05	2/45	1/33	0.0086	1,433	0.0015	0,250
7	1/0.51	1/1.05	1/35	2/840	0.0093	1,550	0.0016	0,267
8	1/0.50	1/1.05	1/35	1/33	0.0086	1,433	0.0001	0,017
9	2/0.87	2/1.20	2/45	2/840	0.0176	2,933	0.0152	2,533
10	2/0.87	2/1.20	2/45	1/33	0.0123	2,050	0.0037	0,617
11	2/0.87	2/1.20	1/35	2/840	0.0143	2,383	0.0091	1,517
12	2/0.86	2/1.20	1/35	1/33	0.0101	1,683	0.0039	0,650
13	2/0.87	1/1.05	2/45	2/840	0.0117	1,950	0.0028	0,467
14	2/0.87	1/1.05	2/45	1/33	01.0092	1,533	0.0011	0,183
15	2/0.87	1/1.05	1/35	2/840	0.0102	1,700	0.0010	0,167
16	2/0.89	1/1.05	1/35	1/33	0.0086	1,433	0.0003	0,050

The experimental conditions and results were included in table 1.

3. Processing of the experimental results

The experimental results were firstly normalized, by using relations specific to the situations “larger the better” and “smaller the better, respectively. Subsequently, in successive stages, some indicators corresponding to the grey relational analysis (grey relational coefficient, grey relational grade) were determined, taking into consideration the experimental results.

Some stages specific to applying the grey relational analysis could be developed.

Thus, in a first stage corresponding to the normalization of the parameters, the following relation was used:

$$X_{ij} = \frac{Y_{ij} - \min Y_{ij}}{\max Y_{ij} - \min Y_{ij}}, \tag{1}$$

in the case of “larger the better” situation and, respectively:

$$X_{ij} = \frac{\max Y_{ij} - Y_{Yij}}{\max Y_{ij} - \min Y_{ij}}, \tag{2}$$

in the case of “smaller the better” situation. In the above mentioned relations, Y_{ij} is the size of the output the parameter *j* for the experiment *i*, min Y_{ij} and max Y_{ij} are the minimum and maximum size of the output parameter.

In the considered case, we are interested in maximization of the material removal rate *Q* and this means that the relation (1) will be applied for *Q*; on the other hand, it is necessary to minimize the tool electrode wear rate and the relation (2) will be applied for the output parameter *W*. The results of the output parameters normalization were included in the columns nos. 2 and 3 from table 2.

In the subsequent stage, *the grey relational coefficient* could be determined, by using the relation:

$$\xi_{ij} = \frac{\Delta_{\min} - \xi\Delta_{\max}}{\Delta_{0i} + \xi\Delta_{\max}}, \tag{3}$$

where ξ is considered as *a distinguish coefficient*, having values between 0 and 1, Δ_{0i} is the difference between the absolute value X^0_j of the ideal normalized result for the j^{th} performance characteristic and X_{ij}, $\Delta_{0i} = |X^0_j + -X_{ij}|$, Δ_{min} is the smallest value of Δ_{0i}, Δ_{max} is the largest value of Δ_{0i}.

In the first case, one could appreciate the two process out parameters (performance characteristics) as equal importance and this means that ξ=0.5. The results obtained when ξ=0.5 were included in the columns nos. 6 and 7 from tables 2.

The grey relational grade γ could be calculated by means of the relation:

$$\gamma = \frac{1}{n}\sum_{j=1}^{n} W_k \xi_{ij} \ , \qquad (4)$$

where n is the number of considered performance characteristics (in the analyzed case, there are two performance characteristics, material removal rate Q and the tool electrode wear rate W and this means n=2). The results of determining the grey relational grade γ were inscribed in column no. 8 from table 2. In the series of γ values, the maximum value (γ=0.6969) corresponds to the experiment no. 9 and this means that the values of the process input factors used in this experiment (D=0.87 mm, δ=1.20 g/cm^3, U=45 V, C=840 μF) could be appreciated as the most convenient; these values are close to those values able to ensure the maximum material removal rate Q and minimum tool electrode wear W, when the two output parameters are considered of equal importance.

There is also situation when the two process output factors are not of equal importance. For example, one could consider the parameter Q more important than the parameter W, associating the value γ=0.9 for the parameter Q and the value γ=0.1 for the parameter W. The values of the grey relational coefficients corresponding to the new values of the distinguish coefficients (γ=0.9 and γ=0.1, respectively) were included in the columns nos. 10 and 11 from table 2. On the base of the new values for the distinguish coefficients γ, the new values for the grey relational grade were determined (column no. 12 in table 2).

Determining the new rank of the grey relational grades, one noticed that the maximum value for this grade corresponds to the experiment no. 6, for the combination of the process input factors D=0.50 mm, δ=1.05 g/cm^2, U=35 V and C=33 μF. This combination could be considered as being close to the optimal combination, when to the material removal rate Q, the value of the distinguish coefficient ξ=0.9 was associated, while the value ξ=0.1 was considered as corresponding to the tool electrode massic wear rate W.

4. Conclusions

One of the methods that could be applied in order to solve certain problems of multicriterial analysis is the grey relational analysis. In some precedent experimental researches, full factorial experiments were designed and developed in order to investigate the influence exerted by the tool electrode diameter D, electrolyte density δ, voltage V applied to the tool electrode and workpiece and the capacitance C of capacitors included in the electric circuit on the values of some parameters of technological interest at the electrochemical discharge drilling of small diameter holes. Being interested in determining the combination of the process input factors able to ensure certain conditions for the results of the electrochemical discharge drilling of small diameter holes, the grey relational analysis was applied. In this way, some combinations of values corresponding to the process input factors were determined and one could consider that these values are close to the optimal combinations, taking into consideration the imposed weights for the material removal rate and the tool electrode massic wear rate. In the future, there is the intention to correlate the results obtained by means of the grey relational analysis with the values of the signal/noise ratio applicable in the case of the Taguchi method.

Table 2: *Mathematical processing of the experimental results.*

Exp. no.	Normalized values for		Differences Δ for		Grey relational coefficients ξ_{ij} for ξ=0.5		Grey relational grade, γ, when ξ_Q=0.5 and ξ_W=0.5	Rank when ξ_Q=0.5 and ξ_W=0.5	Grey relational coefficients ξ_{ij} for ξ=0.9;01		Grey relational grade, γ, for ξ_Q=0.9 and ξ_W=0.1	Rank when ξ_Q=0.9 and ξ_W=0.1
	Material removal rate normalized, Q_{WPnorm}	Toole electrode wear rate normalized, W_{TEnorm}	Material removal rate normaized, ΔQ_{WPnorm}	Toole electrode wear normalized, ΔW_{TEnorm}	ξ_{ij} for Q, when ξ=0.50	ξ_{ij} for W, when ξ=0.50			ξ_{ij} for Q, when ξ_Q=0.9	ξ_{ij} for W, when ξ_W=0.1		
1	2	3	4	5	6	7	8	9	10	11	12	13
1	0,545	0,079	0,455	0,921	0,523	0,352	0,4377	16	0,664	0,098	0,3810	15
2	0,267	0,629	0,733	0,371	0,405	0,574	0,4898	13	0,551	0,212	0,3817	14
3	0,467	0,470	0,533	0,530	0,484	0,486	0,4848	14	0,628	0,159	0,3934	13
4	0,156	0,821	0,844	0,179	0,372	0,737	0,5543	10	0,516	0,359	0,4374	10
5	0,300	0,483	0,700	0,517	0,417	0,492	0,4543	15	0,563	0,162	0,3624	16
6	0,000	0,907	1,000	0,093	0,333	0,844	0,5886	7	0,474	0,519	0,4965	7
7	0,078	0,901	0,922	0,099	0,352	0,834	0,5930	6	0,494	0,502	0,4979	6
8	0,000	1,000	1,000	0,000	0,333	1,000	0,6668	2	0,474	1,001	0,7375	1
9	1,000	0	0,000	1,000	1,000	0,333	0,6669	1	1,000	0,091	0,5456	5
10	0,411	0,762	0,589	0,238	0,459	0,677	0,5682	9	0,605	0,296	0,4501	9
11	0,634	0,404	0,366	0,596	0,577	0,456	0,5166	12	0,711	0,144	0,4272	11
12	0,167	0,748	0,833	0,252	0,375	0,665	0,5202	11	0,519	0,284	0,4019	12
13	0,345	0,821	0,655	0,179	0,433	0,737	0,5847	8	0,579	0,359	0,4687	8
14	0,067	0,934	0,933	0,066	0,349	0,883	0,6161	5	0,491	0,602	0,5465	4
15	0,178	0,941	0,822	0,059	0,378	0,894	0,6359	4	0,523	0,627	0,5748	3
16	0,000	0,987	1,000	0,013	0,333	0,974	0,6539	3	0,474	0,884	0,6789	2

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