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ESTABLISHING CONDITIONS FOR WIRE ELECTRICAL DISCHARGE CUTTING USING GREY RELATIONAL ANALYSIS

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ABSTRACT: The wire electrical discharge machining is a nonconventional machining method applied to machine ruled surfaces in plate type workpieces made of electroconductive materials. There are various methods to establish the optimal values for the process input factors in the case of the wire electrical discharge machining. One of these methods is the gray relational analysis that takes into consideration distinct weightings for some of the process output parameters. The method was applied considering the pulse on time, pulse off time and average current intensity as process input factors. The process output parameters were the surface roughness and the machining speed of penetration in the plate type workpiece. In this way, distinct combinations of the process input factors values were established for different weightings of the output parameters.

KEY WORDS: wire electrical discharge machining, pulse of time, pulse off time, peak current intensity, cutting speed, surface roughness, grey relational analysis.

1. INTRODUCTION

The electrical discharge machining (EDM) is one of the so-called nonconventional machining processes. It is based on the developing electrical discharges between the closest asperities that exist on the active surface of the tool electrode and workpiece, as a consequence of diminishing the distance between these surfaces by a work movement. Both the tool electrode and workpiece are connected in an electric circuit able to generate electrical pulses [3, 4, 5, 9, 10]. The electrical discharges determine the melting and vaporizing of small quantities of the tool electrode and workpiece material. The machining conditions must be selected so that a high volume of material is removed from the workpiece, in comparison with the quantity of materials removed from the tool electrode. The material detached from the two electrodes is removed from the work gap by means of the dielectric liquid circulation.

At present, the electrical discharge machining allows obtaining of complex shape surfaces in workpiece made of difficult-to-cut materials. At the same time, a high machining accuracy could be ensured, due to the use of computer numerical controlled EDM machines and to the use of low energy discharge pulses.

As limitations of the EDM processes, one could consider the low material removal rate and the fact that only workpieces made of electroconductive materials could be approached by this machining method.

There are two main EDM techniques: the ram machining, when massive tool electrodes are used, and the wire electrical discharge machining, which uses a wire tool electrode.

In the case of the last machining technique, in the work zone, the wire tool electrode performs a rectilinear motion along its axis, running from an initial roll and wrapping onto a second roll (fig. 1).

The wire electrical discharge machining allows the obtaining of ruled surfaces, as a consequence of the work movements achieved by the plate type workpiece and the wire tool electrode.

The values of the EDM process input factors are established by considering the type and the chemical composition of the workpiece material, the wire tool electrode material, the requested machining accuracy and surface roughness of the machined surfaces, the type and the way of dielectric liquid circulation in the work gap, etc.

One could mention that due to work conditions different in comparison with the ram electrical discharge machining, dielectric liquids characterized by a low viscosity are preferred and the deionized water is one of such work dielectric liquids.

The enlarging of using the wire electrical discharge machining determined an intensification of the

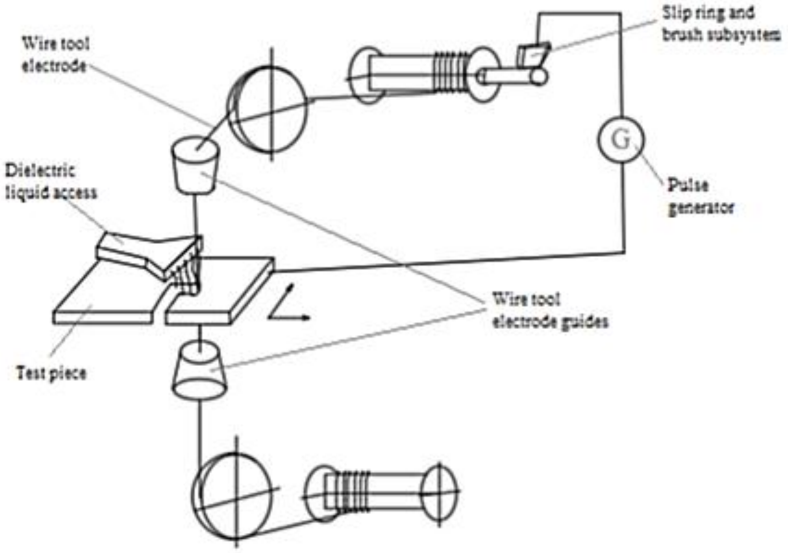

Figure 1. Machining scheme valid in the case of wire electrical discharge cutting of slots

researches aiming to improve the performances of this machining technique.

Thus, in the last decades, one could remark the use of computer numerical systems able to ensure not only coordinated work movements in a plane but also an independent movement of the upper and lower guides of the wire tool electrode, facilitating the obtaining of conical type surfaces.

Kumar and Ravikumar developed research directed to the optimization of the wire EDM process, taking into consideration the pulse on time, pulse off time, wire speed and wire feed as process input factors and the metallic material removal rate and surface roughness parameter Ra as process output parameters, respectively [3]. An L9 Taguchi array was applied to design the experimental program and to mathematically process the experimental results.

Mouralova et al. took into consideration a designed experiment in which they changed the values of the gap voltage, pulse on time, pulse off time, discharge current and wire feed when machining the aluminum alloy 7475-T7351 [4]. The analysis was focused on highlighting the topography and the subsurface layer of the machined surfaces.

Bisaria and Shandilya investigated the behavior of the Nimonic C-263 superalloy as a consequence of applying a wire electrical discharge machining process [1]. As process input factors, they considered the spark energy, spark frequency, peak current. They studied the influence exerted by the above mentioned process input factors on the surface roughness, average cutting rate and surface integrity aspects that correspond to the machines surface.

Reolon et al. used zinc-coated copper wire and uncoated brass wire to machine the Inconel alloy IN718 [7]. An optimization method allowed to them to obtain a 35 % increase in wire feed rate and a 40 % reduction in wire consumption, in the case of using the zinc-coated copper wire and an increase of 35 % in wire feed rate and a decrease of 80 % in wire consumption when using uncoated brass wire, respectively.

In this paper, the results of research aiming to optimize a wire EDM process by using the grey relational analysis were presented.

2. METHODS OF SELECTING THE OPTIMAL VALUES FOR THE WEDM PROCESS INPUT FACTORS

The concept of optimization means the selection of the most convenient solution from many versions of solving a problem.

Nowadays, the problem of optimization is usually connected with the concept of *system*: the concept refers to an assembly of material or ideal elements which are independent and constitute an organized entire; it could be applied to organize a field of theoretical thinking, the material included in a scientific field or to determine the development of the practical activities in accordance with the desired purpose [2].

There was a normal consequence to consider the machining process as a system.

To optimize the machining process means to identify the values of the process input factors so that one or more process output factors reach the most convenient values.

When only a single output parameter is necessary to be optimized, there is a problem of the so-called *monocriterial optimization*; when there are many output parameters to be optimized, *a multicriterial optimization problem* is practically formulated.

Over the years, many methods were proposed by the researchers to be applied in the case of the optimization problems.

Thus, in the case of necessity of adopting an optimal decision when there are certain conditions, for example, one could take into consideration [6] the global utility method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the group of ELECTRE methods (I, II, III, IV, IS, TRI) (the acronym ELECTRE has its origin in French language, where ELimination Et Choix Traduisent la Realité means the elimination and selection using a translation of the reality), the weighted sum model, WSM, analytic hierarchy process, AHP, multi-attribute utility theory, MAUT, dominance-based rough set approach, DRSA, aggregated indices randomization method, AIRM, nonstructural fuzzy decision support system, NSFDSS, grey relational analysis – GRA, superiority and inferiority ranking method, SIR method, potentially all pairwise rankings of all alternatives, PAPRIKA, value analysis, Onicescu method etc.

When the context of the problem involves risk conditions, some solving methods could be considered the method of the waited value, the three decision method, etc.

If a decision must be adopted in the uncertainty conditions, some recommended methods to be used are the optimistic method, the pessimistic method, method of tempered optimism, method of equal probabilities, method of minimizing regret, etc.

In the last decades, one of the methods preferred to be used to optimize the machining processes was the grey relational analysis. It was proposed by the Chinese professor Julong Deng, in a paper published in 1982. One notices that the so-called *theory of grey systems* took into consideration some concepts from informatics when the black color suggests the total lack of information and the white color when there is all necessary information. In fact, in many real situations, there is a piece of certain information, even this information is not sufficient; thus, the concept of *the grey system* was introduced to define a useful tool for analyzing and abstract modeling of the systems for which the available information is limited, incomplete and characterized by random uncertainties.

3. GREY RELATIONAL ANALYSIS

The grey relational analysis evaluates the quantitative relation among the elements included in two series, one of these series being characterized by a piece of good quality information. When the differences between the elements included in the two series are low, one considers that the comparison results is convenient. The so-called *grey relational coefficient* is used to develop the comparison. The grey relational coefficient was defined by considering the similitude and variability level. Three distinct situations could be applied for the series elements:

- Higher the better;
- Lower the better;
- The nominal value is the best.

Some of the main stages used when applying the grey relational analysis are the following:

a) Selection of the situations;

b) Normalizing of individual entities;

c) Establishing the values of the differentiating coefficients;

d) Establishing values of the grey relational coefficients;

e) Establishing the values of the grey relational grades;

f) Selection of the version that has the maximum value of the grey relational grade.

4. APPLYING GREY RELATIONAL ANALYSIS IN OPTIMIZING A THE WIRE ELECTRICAL DISCHARGE MACHINING PROCESS

To apply the grey relational analysis, the experimental results included in table 1 were considered; these results were obtained within an experimental research concerning the influence exerted by the process input factors that correspond to the wire electrical discharge machining on some process output parameters (cutting speed *v*, surface roughness parameter *Ra*, width of slot, etc.).

As process input factors, one considered the pulse on time t_{on}, pulse off time t_{off}, and peak current intensity I_p. The proper values of the process input factors were mentioned in columns 2, 3 and 4 from table 1. In the columns nos. 6 and 7, the values of the cutting speed v and of surface roughness parameter Ra were highlighted.

The cutting speed v was determined by considering the initially established length of the slot (10 mm) and the determined duration of the cutting process. The values of the surface roughness parameter Ra represent the average value of three measurement results.

Table 1. Experimental conditions and results

Pulse on time: $t_{on\ min}$= 2 µs, $t_{on\ max}$=10 µs						
Pulse off time: $t_{off\ min}$= 12 µs, $t_{off\ max}$=60 µs						
Peak current intensity $I_{p\ min}$=2 A, $I_{p\ max}$=3 A						
Length of the slot: 10 mm						
Exp. no.	**Process input factors**			**Process output parameters**		
	Pulse on time, t_{on}, µs	**Pulse off time, t_{off}, µs**	**Peak current intensity, I_p, A**	**Process duration, *s***	**Cutting speed, *v*, mm/s**	**Surface roughness parameter *Ra*, µm**
Column no. 1	2	3	4	5	6	7
1	10	60	3	113	0.088	1.97
2	10	60	2	157	0.063	2.35
3	10	12	3	113	0.088	15.40
4	10	12	2	143	0.069	2.40
5	2	60	3	357	0.028	2.71
6	2	60	2	550	0.018	2.61
7	2	12	3	136	0.073	2.50
8	2	12	2	191	0.052	2.10

As a first stage in applying the grey relational analysis, a normalizing of the experimental results was applied, using one of the relations specific to the situations “larger the better”, and “smaller the better”. Such relations are the following:

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

when the larger is better (and this is the case of the cutting speed v, when we are interested to obtain a maximum value), and

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

when the smaller is better (the last relation is valid in the case of the surface roughness parameter *Ra*, which could have a minimum value).

In the above-mentioned relations, the symbols have the following explanations: Y_{ij} - the size of the output the parameter j for the experiment i, min Y_{ij} and max Y_{ij} - the minimum and maximum size of the output parameter.

The normalized results were included in the columns no. 2 and 3 from table 2.

The relation for determining the values of the grey relational coefficient ξ_{ij} is:

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

where ξ is the *distinguish coefficient*, that has values between 0 and 1, Δ_{0i} – 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}.

If one considers that the two considered output parameters (cutting speed v and surface roughness parameter *Ra*) are of equal importance, the distinguish coefficient ξ will have a value of 0.5. The differences Δt_{on} for the pulse on time t_{on} and Δt_{off} for the pulse off time t_{off} were included in the columns no. 4 and 5 from table 2. The results obtained for the grey relational coefficient when accepting the value established for ξ were presented in the columns no. 6 and 7 from table 2.

Taking into consideration the values of the grey relational coefficients, the grey relational grade γ_i could be determined, using the relation:

$$\gamma_i = \frac{1}{n}\sum_{j=1}^{n} W_k \xi_{ij}, \tag{4}$$

where n is the number of considered performance characteristics (two performance characteristics are considered, the cutting speed v and the surface roughness parameter *Ra* and this means n=2). As one can see, the grey relational grade must be determined for each experimental test and it is a weighted value of the grey relational coefficients established for each output parameter.

The values of the grey relational grades γ_i were mentioned in the columns no. 8 from table 2. Analyzing the series of the grey relational grade, one could notice that the maximum values correspond to the experiment no. 1; this means that the values of the process input factors that correspond to this experimental test (t_{on}=10 µs, t_{off}=60 µs, I_p=3 A) could be considered as close to values able to ensure a

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_v=0.5 and ξ_{Ra}=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_v=0.9 and ξ_{Ra}=0.1**	**Rank when ξ_v=0.9 and ξ_{Ra}=0.1**
	Cutting speed *v*, mm/s	**Surface roughness parameter *Ra*, μ**	**Pulse on time, $\Delta t_{on\ norm}$**	**Pulse off time, Δt_{off}**	**ξ_{ij} for v, when ξ=0.50**	**ξ_{ij} for *Ra*, when ξ=0.50**			**ξ_{ij} for *v*, when ξ_v=0.9**	**ξ_{ij} for *Ra*, when ξ_{Ra}=0.1**		
1	2	3	4	5	6	7	8	9	10	11	12	13
1	1.000	1.000	0.000	0.000	1.000	1.000	1.000	1	1.000	1.000	1.000	1
2	0.643	0.972	0.357	0.028	0.583	0.946	0.7649	4	0.716	0.779	0.7477	4
3	1.000	0.000	0.000	1.000	1.000	0.333	0.6667	6	1.000	0.091	0.5455	8
4	0.729	0.968	0.271	0.032	0.648	0.940	0.7940	3	0.768	0.757	0.7629	3
5	0.143	0.945	0.857	0.055	0.368	0.901	0.6346	7	0.512	0.645	0.5785	6
6	0.000	0.952	1.000	0.048	0.333	0.913	0.6232	8	0.474	0.677	0.5755	7
7	0.786	0.961	0.214	0.039	0.700	0.927	0.8134	2	0.808	0.717	0.7624	5
8	0.486	0.990	0.514	0.010	0.493	0.981	0.7370	5	0.636	0.912	0.7741	2

maximum cutting speed. Another situation could be that when the process output parameters are considered as being of unequal importance. For example, one could appreciate that the cutting speed *v* is more important than the surface roughness parameter *Ra* (as is the case of wire electrical discharge roughing). In such a case one could take into consideration, for example, ξ_v=0.7 and ξ_{Ra}=0.3. The new values of the grey relational coefficients ξ_{ij} that correspond to the last situations were included in the columns no. 10 and 11 from table 2. In this way, the values of the grey relational grades γ_i are those mentioned in column no. 12 from table 2. One could notice that the maximum value of the grey relational grade γ_i corresponds also to the experimental test no. 1.

The combination of the process input factors values used within this experimental test could be considered also as close to the optimal combination, when a distinguish coefficient ξ_v=0.7 was attributed to the cutting speed v and a distinguish coefficient ξ_{Ra}=0.3 was taken into consideration for the surface roughness parameter *Ra*. The application of the grey relational analysis could be continued using some principles specific to the Taguchi method, by taking into consideration the ratio signal/noise S/N. To calculate the so-called function of quality loss, the following relations could be used:

- When there is an evaluation type "higher the better:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{Y_{ijk}^{2}}, \tag{5}$$

- When there is an evaluation type "lower the better:

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}Y_{ijk}^{2}, \tag{6}$$

where *n* is the number of the repeated tests for the same values of the input factors, *k* – number of the experimental test, Y_{ijk} – the value of the output parameter for the test i, in the experiment no. *j* and test no. *k*.

The ratio *S*/*N* could be calculated for the two above-mentioned situations using the relation [8]:

$$\eta_{ij} = -10\log(L_{ij}) \tag{7}$$

In the case of the obtained experimental results, the relation (5) could be used to determine the value of the function of quality loss. These values were used to elaborate the graphical representation from figure 2, where three values of differentiating coefficient were used (first situation: ξ_v=0.5 and ξ_{Ra}=0.5; second situation: ξ_v=0.7 and ξ_{Ra}=0.3; the third situation corresponds to the values ξ_v=0.9 ξ_v=0.7 and ξ_{Ra}=0.1). One could notice that for all the three situations, the most convenient combination of the process input factors corresponds also to the experiment no. 1, for which the proper values of the input factors were above-mentioned. This situation generates a certain contradiction: usually, when the cutting speed is high (due to higher energy of the electrical discharges), the height of the asperities should be lower; a possible explanation of this contradiction could consider the higher dispersion that corresponds to the measured values of the surface roughness parameter *Ra*.

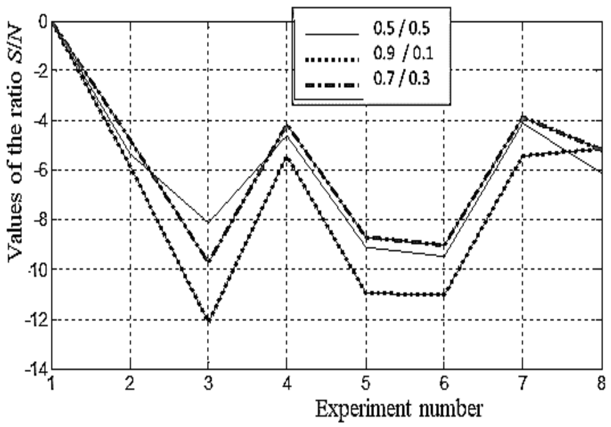

Figure 2. Graphical representation of the ratio *S*/*N*

5. CONCLUSIONS

The last decades highlighted a clear extension of using the wire electrical discharge machining to detach parts characterized by ruled surfaces generally from plate type workpieces. One of the current research preoccupations in this field is considered to be the optimization of the wire electrical discharge machining. This means to find that combination of the process input factors able to ensure optimal values or values close to the optimal values for one or more process output parameters. In order to establish such a combination in the case of a wire electrical discharge machining, as process input factors the pulse on time, pulse off time and peak current intensity were selected, while the cutting speed v and surface parameter *Ra* were taken into consideration as process output parameters. The Grey relational analysis was applied to find the optimal combination of the process output parameters. One noticed that both in the case when considering the process output parameters as being of equal importance (characterized by a value of the distinguish coefficient equal to 0.50) and of unequal importance (situation when the distinguish coefficient had a value of 0.7 for the cutting speed and 0.3 for the surface roughness), the same combination of the process input factors values seems to ensure the most convenient developing of the wire electrical discharge machining process. In the future, there is the intention to extend the experimental research, to better clarify the aspects concerning the optimal selection of the working conditions for the wire electrical discharge machining.

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