EXPERIMENTAL RESULTS CONCERNING THE WIRE ELECTRICAL DISCHARGE MACHINING OF HIGH-SPEED STEEL

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Abstract: *The wire electrical discharge cutting can be used to separate parts from plate-shaped workpieces or to make slots with various contours in electroconductive materials generally characterized by low machinability by conventional machining processes. The analysis of the wire electrical discharge machining process showed that there are many groups of factors able to affect the process results. The axiomatic design principles were used to define the conditions in which experimental research aiming to highlight the factors able to affect the sizes of technological interest in the case of wire electrical discharge machining. To evaluate the influence exerted by some input factors of the wire electrical discharge machining process, namely by the pulse on time, pulse off time, and by the average intensity of the discharge current, on some results of technological interest, an experimental research in accordance with the requirements of a full factorial experiment was designed and materialized. By processing the experimental results, it was possible to determine empirical mathematical models of power type function.*

Keywords: *wire electrical discharge machining, surface roughness, machining speed, empirical mathematical models.*

1. Introduction

The electrical discharge machining is based on the material removal from the workpiece as a result of developing electrical discharges between the closest asperities that exist on the surfaces of tool electrode and workpiece. This machining method is applied when the workpiece material is too hard or the surfaces are difficult to be obtained by classical machining methods. Such aspects are in fact the main advantages of the electrical discharge machining method. As a limitation of the above-mentioned machining method, one could take into consideration the relatively low material removal rate and the possibility to apply the electrical discharge machining only in the cases of the workpieces made of electroconductive materials.

Within the electrical discharge machining method, two main groups of techniques could be highlighted:

a) Electrical discharge machining techniques based on the use of massive tool electrodes or ram electrical discharge machining;

b) Wire electrical discharge machining (*WEDM*), when a wire tool electrode is used to separate parts generally from the plate or sheet type workpieces. During the machining process, the wire tool electrode achieves a continuous scrolling on a coil and winding on a second coil; in this way, the influence exerted by the normal wear of the tool electrode wire as a consequence of the electrical discharges on the machining accuracy could be significantly diminished. The wire electrical discharge machining process needs a continuous circulation of a dielectric fluid in the work gap, to remove the electroconductive particles detached from the workpiece and tool electrode as a consequence of the electrical discharges [Dodun et al., 2009; Slătineanu et al., 2004].

The machining scheme specific to the wire electrical discharge machining allows the obtaining of only ruled surfaces, as a result of the rectilinear shape of the wire tool electrode in the work zone; from the theoretical point of view, the machined surface is a consequence of moving the right line along the contour that corresponds to the surface to be obtained.

If initially, the guiding parts of the wire tool electrode have had a fixed position one to another, in the last decades a possibility of independently moving of the wire tool electrode guides have extended the technological possibilities of the machining method. In this way, for example, the conical surfaces or hyperbolical surfaces could be also obtained by using the wire electrical discharge machining method.

Over the years, many researchers investigated various aspects found in connection with the wire electrical discharge machining.

Thus, Balan and Giridharan have undertaken a large investigation concerning the factors able to affect the results of the wire electrical discharge machining [Balan and Giridharan, 2017]. They noticed that the attempts of optimizing the machining process were made, aiming to maximize the material removal rate and to improve the roughness of the machined surface and the kerf width.

Mandal and Dixit considered that the performances of the wire electrical discharge machining could be affected essentially by the properties of the workpiece material, characteristics of the electrical pulses, the wire tool electrode configuration and material, characteristics of the dielectric fluid and its circulation etc. [Mandal and Dixit, 2014].

Kumar showed that an important factor able to exert influence on the output parameters of the wire electrical discharge machining is the wire tool electrode [Kumar, 2016]. He noticed the trend of extending the use of zinc coated, diffusion annealed coated steel core wires tool electrodes.

Patel and Vaghmare emphasized the necessity of a better understanding of the relations among the various process input factors that could exert influence on the performances of the wire electrical discharge machining process [Patel and Vaghmare, 2013]. They noticed that adaptive monitoring and control systems could be the solutions to improve the development of the wire electrical discharge machining processes.

In this paper, the results of research concerning the wire electrical discharge machining of a test piece made of high-speed steel will be presented.

2. Systemic analysis of the wire electrical discharge machining process

It is known that equipment or a process could be analyzed considering it as a system that has input factors and output parameters. The systemic analysis could offer a better understanding of the investigated process and could highlight the distinct correlations that exist between the input factors and the output parameters.

In the case of the wire electrical discharge machining process, some main groups of process input factors could be taken into consideration:

1. The chemical composition and some physical properties of the workpiece material; one could notice that in this case, the mechanical properties practical do not exert influence on the machining process results. One must also notice that the presence in the workpiece material chemical composition of some elements with high melting and vaporizing temperatures could diminish the

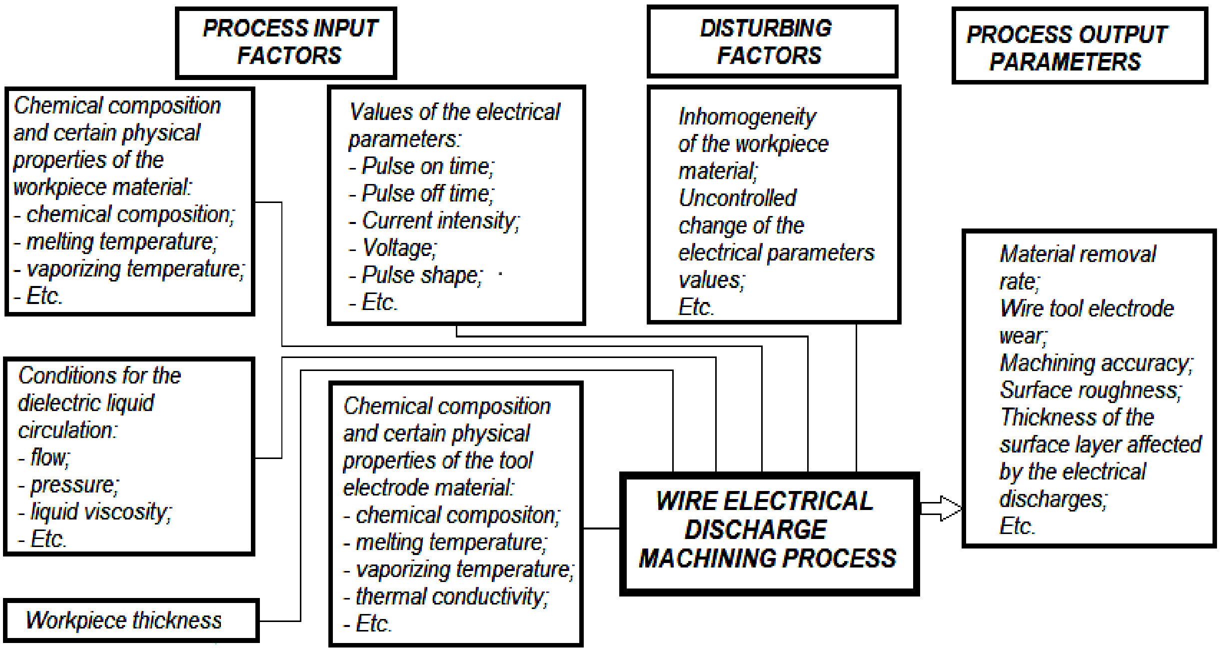

Figure 1: *Approaching the wire electrical discharge machining as a system.*

machinability by wire electrical discharge machining of the investigated material;

2. The values of the electrical parameters that are important for the developing of the electrical discharge machining process. It is known that the electrical discharge machining is really a consequence of the electrical pulses developed by an adequate pulse generator. As main factors that characterize the pulses and that could affect the results of the wire electrical discharge machining, one could consider the pulse on time, pulse off time, the average value of the current intensity, the voltage applied to the electrodes, the shape of the pulses etc.;

3. The conditions of the dielectric liquid circulation in the work gap. Especially in the case of a necessary high machining accuracy, the dielectric liquid has to have a low viscosity to penetrate in the narrow spaces found between the tool electrode and workpiece, but one must take into consideration that a too low viscosity could not acceptably remove the particles detached from the workpiece and tool electrode and appeared as a result of the electrical discharges. If the dielectric liquid flow and pressure have higher values, better development of the wire electrical discharge machining process could be expected;

4. The chemical composition and certain physical properties of the wire tool electrode material. Generally, in the case of the electrical discharge machining, the establishing of the machining parameters values is achieved by considering the categories of the workpiece and tool electrode materials. The experimental research led to the recommendation of using certain tool electrode materials proposed by taking into consideration the workpiece material;

5. The thickness of the workpiece; due to the narrow spaces that correspond to the work gap and the difficult penetration of the dielectric liquid in such spaces, the workpiece thickness is an important process input factor in the case of the wire electrical discharge machining.

As process output parameters of the wire electrical discharge machining, one could consider the material removal rate, wire tool electrode wear, accuracy, and roughness of the obtained surfaces, the thickness of the surface layer affected by the electrical discharge machining process etc.

A graphical representation elaborated on the base of considering the wire electrical discharge machining as a system is presented in figure 1.

3. Use of some axiomatic design principles to develop experimental research concerning the WEDM

The axiomatic design was proposed by the professor Nam Pyo Suh in the ’70 years of the previous century, to improve the activities of designing production systems and processes. Even initially the axiomatic design was applied especially in solving the problems specific to the production systems and processes, gradually various applications in many other fields of human activity were investigated and applied, so that nowadays very distinct problems could be approached by means of this systems design methodology.

Two axioms are taken into consideration in the case of the axiomatic design. In accordance with the first axiom, the functional requirements specific to the wanted system must be independent. The second axiom mentions that among the possible problem solutions, one must prefer that solution that needs the minimum information [Suh, 2001].

Taking into consideration the objectives of the research whose results are presented in this paper, as the so-called customer need one could take into consideration the developing of an experimental research aiming to facilitate the establishment of some empirical mathematical models able to highlight the influence exerted by some process input factors of the wire electrical discharge machining on some of the process output parameters. In such a case, the functional requirement of zero order (*FR*0) could be: design and develop an experimental research aiming to determine some empirical mathematical models that could highlight the way in which some easier accessible process input factors exert influence on some of the process output parameters in the case of wire electrical discharge machining of test samples made of high-speed steel.

As functional requirements of the first order, one could consider:

*FR*1: Plan the experimental research;

*FR*2: Ensure the experimental equipment;

*FR*3: Perform the experiments and collect the experimental results;

*FR*4: Process the experimental results;

*FR*5: Analyze and explain the empirical mathematical models.

To these functional requirements of the first order, the design parameters (*DPs*) could be associated:

*DP*1: Experimental plan;

*DP*2: Experimental equipment;

*DP*3: Experiments and table including the experimental results;

*DP*4: Empirical mathematical models.

*DP*5: Explanations for the initial hypotheses and for the eventually contradictory results.

Coming back to the functional requirements within the so-called zigzagging activity, some functional requirements of the second order could be identified:

*FR*1.1: Clarify the objective of the experimental research;

*FR*1.2: Adopt the machining scheme;

*FR*1.3: Adopt the type of experiment;

*FR*1.4: Establish the values of the process input factors;

*FR*2.1: Ensure the electrical discharge machine;

*FR*2.2: Ensure the wire tool electrode;

*FR*2.3: Ensure the device for positioning and clamping the tool electrode;

*FR*2.4: Ensure the device for positioning and clamping the test piece;

*FR*2.5: Ensure the apparatuses for measuring the process output parameters;

*FR*3.1: Perform the experiments;

*FR*3.2: Record the experimental results;

*FR*4.1: Ensure software for mathematical processing of the experimental results;

*FR*4.2: Ensure the computer system for mathematical processing of the experimental results;

*FR*5.1: Highlight the values of the empirical mathematical models’ exponents;

Table 1: Matrix corresponding to the functional requirements and design parameters in the case of the experimental research concerning the influence of some process input factors on the values of the process output factors at wire electrical discharge machining.

Line no. 1	Design parameters			Design parameters of the zero order DP0														
2				Design parameters of the first order														
3				*DP*1				*DP*2					*DP*3		*DP*4		*DP*5	
4				Design parameters of the second order														
5	Functional requirements			*DP* 1.1	*DP* 1.2	*DP* 1.3	*DP* 1.4	*DP* 2.1	*DP* 2.2	*DP* 2.3	*DP* 2.4	*DP* 2.5	*DP* 3.1	*DP* 3.2	*DP* 4.1	*DP* 4.2	*DP* 5.1	*DP* 5.2
Column no. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
7	*FR* of the zero order	*FRs* of the first order	FRs of the second order	Design parameters that correspond to each functional requirement														
8			*FR*1.1	X														
9			*FR*1.2		X													
10		*FR*1	*FR*1.3			X												
11			*FR*1.4				X											
12			*FR*2.1					X										
13			*FR*2.2						X									
14		*FR*2	*FR*2.3							X								
15	FR0		*FR*2.4								X							
16			*FR*2.5									X						
17		*FR*3	*FR*3.1										X					
18			*FR*3.2											X				
19		*FR*4	*FR*4.1												X			
20			*FR*4.2													X		
21		*FR*5	*FR*5.1														X	
22			i5.2															X

*FR*5.2: Explain the values of the mathematical models exponents

The design parameters of the second order that correspond to the above mentioned functional requirements could be:

*DP*1.1: Objective of the experimental research;

*DP*1.2: Machining scheme;

*DP*1.3: Full factorial experiment;

*DP*1.4: Values for the pulse on time, pulse off time, current intensity;

*DP*2.1: Electrical discharge machine;

*DP*2.2: Wire tool electrode with a diameter of 0.15 mm;

*DP*2.3: Device of the machine;

*DP*2.4: Support for clamping the test piece;

*DP*2.5: Machine tool chronometer and roughness meter;

*DP*3.1: Experiments achieved;

*DP*3.2: Table including the experimental results;

*DP*4.1: Specialized software;

*DP*4.2: Computer system;

*DP*5.1: Mathematical models exponents;

*DP*5.2: Explanations for the empirical mathematical models' exponents.

Taking into consideration the functional requirements and design parameters, an adequate matrix was elaborated (Table 1). One could notice that in this simplified approach of the axiomatic design, the request of ensuring the independence of the functional requirements was met. The use of the axiomatic design could continue with establishing the process variables and optimizing the experimental research development.

4. Experimental conditions

Taking into consideration the results of using the axiomatic design to design and

Table 2: Experimental conditions and results.

Exp. no.	Process input factors			Process output parameters			
	Pulse on time, t_{on}, μs	Pulse off time, t_{off}, μs	Current intensity, *I*, A	Process duration, t, s	Cutting speed, *v*, mm/min	Surface roughness parameter *Ra*, μm	Surface roughness parameter *Rq*, μm
Column no. 1	2	3	4	5	6	7	8
1	10	60	3	113	0,0885	1,976	2,48
2	10	60	2	157	0,0637	2,353	2,973
3	10	12	3	113	0,0885	15,404	19,82
4	10	12	2	143	0,0699	2,406	3,07
5	2	60	3	357	0,0280	2,715	3,302
6	2	60	2	550	0,0182	2,616	3,19
7	2	12	3	136	0,0735	2,5	2,966
8	2	12	2	191	0,0524	2,106	2,74

develop the experimental research, one proposed the use of the wire electrical discharge machine. The wire tool electrode had a diameter of 0.15 mm and it was made of copper.

The test piece had a thickness of 3 mm; the test piece material was the high-speed steel HS6-5-2, whose chemical composition includes 0.80 % C, 4.10 % Cr, 5.1 % Mo, 6.1 % W, 2.0 % V.

To establish the values of the process input factors, the principles that correspond to a full factorial experiment with three independent variables and two experimental levels were applied. One took into consideration a possible monotone variation of the process output parameters when the values of the process input factors have value in a pre-established experimental interval.

On the base of the recommendations valid in the case of the wire electrical discharge machining of alloyed steels, the first set of values corresponding to the pulse on time, pulse off time and current intensity were established. In this way, the following values were established for the process input parameters: $t_{on\,min}$ = 2 μs, $t_{on\,max}$ = 10 μs, $t_{off\,min}$=12 μs, $t_{off\,max}$=60 μs, I_{min}=2 A, I_{max}= 3 A.

Using the pre-established values of the process input factors, eight rectilinear slots with a length of 10 mm were achieved in the workpiece by wire electrical discharge machining. Knowing the duration of each experimental test, the cutting speed *v* was calculated.

To obtain an image concerning the roughness of the surfaces obtained by wire electrical discharge machining and taking into

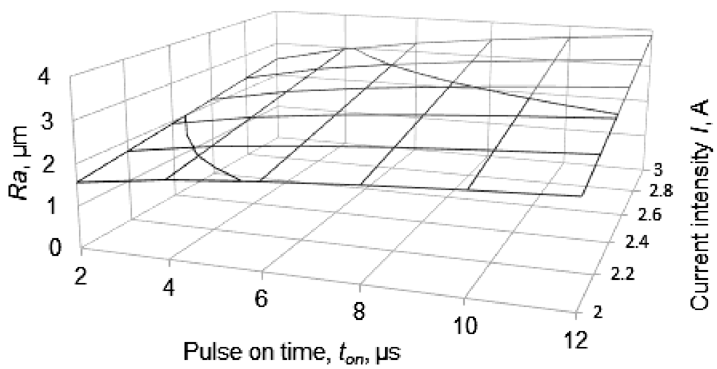

Figure 2: *Influence exerted by the pulse on time t_{on} and current intensity I on the size on the surface roughness parameter Ra (t_{off}=60μs).*

consideration the available roughness tester, the values of the surface roughness parameter *Ra* (arithmetic mean deviation of the assessed profile) and the root mean square deviation of the assessed profile *Rq* were determined using the Mitutoyo Surftest SJ 210 surface roughness tester.

The experimental conditions and results were included in table 2.

5. Processing of the experimental results

The experimental results were mathematically processed by means of a specialized software based on the method of least squares [Crețu, 1992].

One took into consideration the establishment of empirical mathematical models of power type functions since such functions offer a direct image concerning the change of the process output parameters when changing the values of the process input factors. In this way, the following empirical mathematical models were determined:

$$v=0.0387 t_{on}^{0.446} t_{off}^{-0.328} I^{0.822} \quad (1)$$

$$Ra=1.829 t_{on}^{0.237} t_{off}^{-0.275} I^{1.165} \quad (2)$$

$$Rq=2.428 t_{on}^{0.257} t_{off}^{-0.275} I^{1.108} \quad (3)$$

Taking into consideration the empirical mathematical models (1), (2) and (3), the graphical representations from figures 2, 3 and 4 were elaborated. The analysis of these graphical representations and of the empirical mathematical models facilitated the formulation of some general remarks. Thus, one noticed that in all three cases, the increase of the pulse on time t_{on} and of current intensity *I* determines an increase of the machining speed *v* and of the sizes that correspond to the surface roughness parameters *Ra* and *Rq*, while the increase of the pulse off time t_{off} has, as a result, the decrease of both the cutting speed and the pulse off time.

One considers that essentially, the variation of the pulse on time determines the existence of a maximum corresponding to the material removal rate and a possible explanation of the experimental results for *v* could be based on the developing the experimental tests in the ascendant zone for the factor t_{on}.

The increase of the cutting speed and of the values of the surface roughness parameters when the current intensity *I* increases could be explained by the developing of more intense electrical discharges and this fact could lead both to the increase of the material removal rate and of the heights of the generated asperities.

Among the three considered process input factors, the highest influence is exerted by the current intensity *I*, since to this size the exponent with the maximum absolute value is associated in all the three empirical mathematical models.

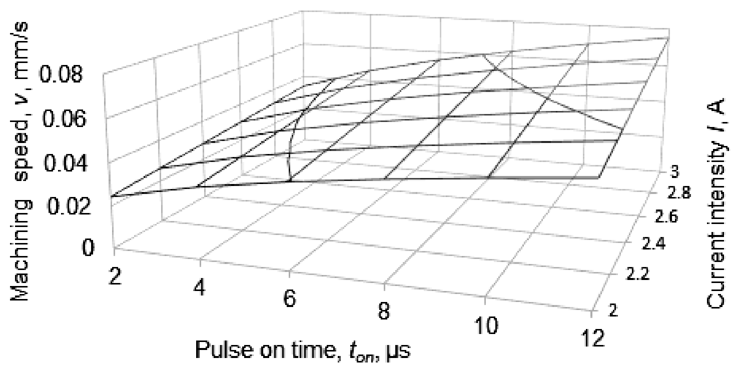

Figure 3: *Influence exerted by the pulse on time ton and current intensity I on the cutting speed v (t_{off}=60µs).*

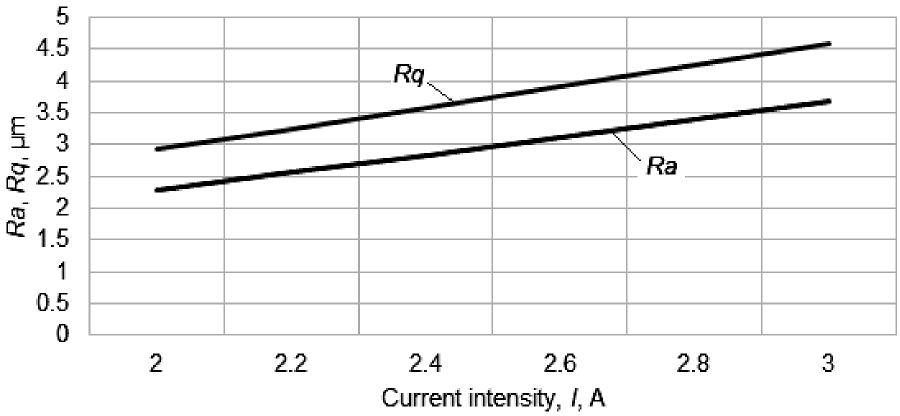

Figure 4: *Influence exerted by the pulse on time ton and current intensity I on the size of the surface roughness parameter Ra (t_{off}=60µs).*

6. Conclusions

To develop an investigation concerning the influence of some process input factors on the values of the cutting speed and of the surface roughness parameter *Ra* and *Rq* at the wire electrical discharge machining of high-speed steel, experimental research corresponding to a full factorial experiment was designed and performed. In establishing the conditions of the experimental research, some principles of the axiomatic design were applied. By mathematical processing of the experimental results, mathematical empirical models of power type functions were determined. These empirical models showed that the maximum influence on the cutting speed and on the surface roughness parameters *Ra* and *Rq* is exerted by the electrical pulses current intensity. The empirical mathematical models highlighted also that the increase of the pulse on time and current intensity determine an increase of the cutting speed and of the surface roughness parameters, while the increase of the pulse off time leads to a decrease of the considered process output parameters.

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