

# MATRIX MODELING OF SURFACE ROUGHNESS OBTAINED BY WIRE ELECTRICAL DISCHARGING MACHINING

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**ABSTRACT:** It is known that the wire electrical discharge machining is a machining method which uses the electrical discharges developed between the workpiece and the wire tool electrode, in order to obtain distinct types of surfaces. This paper proposes a study concerning the influence exerted by some of the process input factors on the surface roughness parameter  $Ra$ , in case of a workpiece made of an alloyed steel. In order to develop an experimental research, a factorial experiment with six independent variables at two variation levels was used. As input factors, one took into consideration the workpiece thickness, current intensity average amplitude, wire axial tensile force, pulse on time, pulse off-time and wire electrode speed. Some empirical mathematical models were established and graphically represented, highlighting the influences of the input factors on the surface roughness parameter  $Ra$ . The matrix model of the process was made according to the Taguchi method requirements.

**KEY WORDS:** wire electrical discharge machining, roughness, Taguchi method, matrix modelling, wire tool electrode.

## 1. INTRODUCTION

The wire electrical discharge machining (EDM) is an electrical discharge machining process included in the category of non-traditional machining processes. This is a technological process in which the material is removed from the workpiece surfaces on the base of thermal effect of electrical discharges developed between the workpiece (WP) and active surface of tool electrode [1].

The process generates surfaces by thermal, chemical and mechanical phenomena applied to them. Thus, the workpiece passes through distinct structural changes, in solid state, thermal and chemical transformations, melting and vaporizing, also through breaks of interatomic bands.

The wire electrical discharge machining (WEDM) is performed using a machining tool found in a relative movement in relation to the surface which follows to be obtained by adequate work movements. The EDM effect represents the result of interaction between the workpiece and the erosive agent consisting of electrical discharges developed successively and which met certain conditions concerning the technological gap existing between the workpiece and the tool electrode. Otherwise, when the distance between tool electrode and workpiece is lower than a certain value, among the asperities peaks found in a dielectric liquid and on the workpiece surface and, respectively, on tool

electrode surface, electrical discharges in pulse are generated. As a result, at the zone where the plasma columns specific to the electrical discharge contacts the asperities peaks, the temperature becomes high and small quantities of materials are melted, even vaporized, and after that eliminated from the workpiece and tool electrode.

## 2. GENERAL CONSIDERATIONS

One of the parameters used for characterizing a processed surface of a part is its roughness. The roughness parameter  $Ra$  is considered the mean value between the ratio of the profile elements, widths and the depths of the geometrical errors [5]. The roughness parameter value  $Ra$  is very important because it can strongly affect the functionality of the parts in the whole assembly. Essentially, the machined surface represents the result of moving, with a certain speed, a cylindrical surface corresponding to the wire tool electrode along a curve line, which contributes to the material removal from workpiece, while two generators lines placed in positions diametric opposed have the role of finishing the plane surfaces thus generated.

Theoretically speaking, the processed surface must have small values for the surface roughness, but generation of electrical discharges between the close asperities peaks existing on the tool electrode and workpiece leads to small craters, each crater being the result of an electrical discharge.

**Table 1.** Design matrix of experiments

| Factors                           | Workpiece thickness $H$ [mm] | Pulse on time, $t_i$ [ $\mu$ s] | Pulse off time, $t_b$ [ $\mu$ s] | Current intensity, $i_a$ [positions] | Tensile force, $F_t$ [gf] | Wire tool electrode speed, $v_{rud}$ [mm/min] |
|-----------------------------------|------------------------------|---------------------------------|----------------------------------|--------------------------------------|---------------------------|---|
| Number of experimental levels     | 2                            | 2                               | 2                                | 2                                    | 2                         | 2   |
| Value corresponding to low level  | 60                           | 1                               | 7                                | 2                                    | 250                       | 1750  |
| Value corresponding to high level | 80                           | 8                               | 30                               | 9                                    | 550                       | 2500  |

It is well known that wire electrical discharge machining process is used in order to detach parts with various contours from plate workpieces [2].

In order to develop an electrical discharge machining process, it is necessary that the workpiece material be electro-conductive. Also, the technical literature presents some studies in which the researchers have applied the WEDM process in order to obtain parts made of certain ceramic and composite materials [3].

The surface conditions of the workpieces may be defined by their geometric and physical-chemical characteristics. The geometric condition of a surface can be defined as the geometric deviation of actual surface in relation with the surface recommended in the mechanical drawing of the part. The physical-chemical characteristics of the processed surface are characterized by the physical-chemical properties of the surface layers of the considered workpiece. For this reason, the machined surface roughness depends on the characteristics of processed material. Although, this study analyses especially the effect exerted on the obtained roughness by some of the electrical parameters, considering that the material properties allows to be processed in optimal conditions.

As advantages of this machining method, one can mention: the possibility to machine workpieces with thin walls, with very small corner radius, with high accuracy specific sometimes to the parts of complex geometry. In last case, after processing, one can mention that there are not burrs and this aspect could simplify the technological process.

Also, the WEDM process can be successfully applied to the conductive materials, without an influence possible to be exerted by the material hardness. It is important to mention that the WEDM is used when high dimensional tolerances and high accuracy are necessary to be obtained.

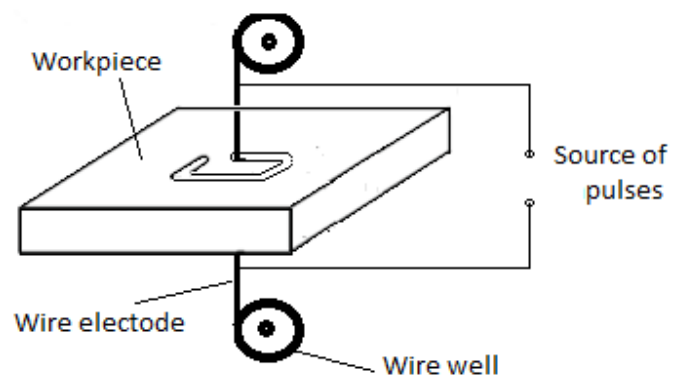
In order to describe the advances in the field of electrical discharge machining by means of wire tool electrode, in the last years, one can see that some researchers have studied in detail aspects concerning

how to obtain low roughness of the processed surfaces.

Thus, Silva et al. [4] have developed an investigation about the influence exerted by some machining parameters such as pulse peak current, servo gap voltage, wire feed rate, wire tension and servo feed rate on roughness of surfaces and surface topography obtained by finish cut wire electrical discharge machining. They concluded that the increase of the pulse on time, pulse peak current and servo feed rate determine the increase of the surface roughness. Also they mentioned that, at the extended of set voltage, both wire feed rate and wire tension increase and the craters and the density of global appendages will grow.

The researchers Lodhi and Agarwal [5] have succeeded to present an optimized model for surface roughness by taking into consideration the Taguchi method. They considered that the selection of optimum values for the input parameters is a significant step for the process automation and implementation into a computer integrated manufacturing system.

In order to identify just the most convenient combinations of some of the machining parameters, within our research, a Taguchi method was used. Generally, the Taguchi method aims a rigorous planning of the experiments which are made in order to determine the influence of some of input factors

**Figure 1.** Experiment set-up

**Table 2.** Experimental results obtained in case of studying the influence exerted by the process input factors on the size of the surface roughness parameter  $Ra$  (initiating voltage  $U=215$  V)

| Exp. no. | Input factors, codified value/real value |                                      |                                       |                                      |  |  | Values measured for the parameter $Ra$ , $\mu\text{m}$ |        |        | Average value for surface roughness parameter $Ra$ , $\mu\text{m}$ |
|----------|--|--------------------------------------|---------------------------------------|--------------------------------------|--|--|--|--------|--------|--|
|          | Test piece thickness, $h$ , mm           | Pulse on time, $t_i$ , $\mu\text{s}$ | Pulse off time, $t_b$ , $\mu\text{s}$ | Wire axial tensile force, $F_t$ , gf | Current intensity average amplitude, $i_a$ , (button position) | Traveling wire electrode speed, $v_{rnl}$ , mm/min | $Ra_1$   | $Ra_2$ | $Ra_3$ |  |
| 1.       | 1/60                                     | 1/1                                  | 1/7                                   | 1/250                                | 1/2  | 1/1750   | 1.74   | 1.88   | 1.78   | 1.80   |
| 2.       | 1/60                                     | 1/1                                  | 1/7                                   | 2/550                                | 2/9  | 2/2500   | 2.07   | 2.23   | 2.03   | 2.11   |
| 3.       | 1/60                                     | 1/1                                  | 2/30                                  | 1/250                                | 1/2  | 2/2500   | 1.93   | 1.76   | 1.77   | 1.82   |
| 4.       | 1/60                                     | 1/1                                  | 2/30                                  | 2/550                                | 2/9  | 1/1750   | 2.17   | 2.00   | 1.98   | 2.05   |
| 5.       | 1/60                                     | 2/8                                  | 1/7                                   | 1/250                                | 2/9  | 2/2500   | 2.08   | 2.19   | 2.12   | 2.13   |
| 6.       | 1/60                                     | 2/8                                  | 1/7                                   | 2/550                                | 1/2  | 1/1750   | 2.76   | 2.88   | 2.91   | 2.85   |
| 7.       | 1/60                                     | 2/8                                  | 2/30                                  | 1/250                                | 2/9  | 1/1750   | 2.12   | 2.04   | 2.08   | 2.08   |
| 8.       | 1/60                                     | 2/8                                  | 2/30                                  | 2/550                                | 1/2  | 2/2500   | 1.93   | 1.80   | 1.85   | 1.86   |
| 9.       | 2/80                                     | 1/1                                  | 1/7                                   | 1/250                                | 1/2  | 2/2500   | 2.17   | 2.31   | 2.18   | 2.22   |
| 10.      | 2/80                                     | 1/1                                  | 1/7                                   | 2/550                                | 2/9  | 1/1750   | 2.56   | 2.69   | 2.55   | 2.60   |
| 11.      | 2/80                                     | 1/1                                  | 2/30                                  | 1/250                                | 1/2  | 1/1750   | 2.39   | 2.26   | 2.25   | 2.30   |
| 12.      | 2/80                                     | 1/1                                  | 2/30                                  | 2/550                                | 2/9  | 2/2500   | 2.11   | 2.25   | 2.18   | 2.18   |
| 13.      | 2/80                                     | 2/8                                  | 1/7                                   | 1/250                                | 2/9  | 1/1750   | 2.68   | 2.60   | 2.67   | 2.65   |
| 14.      | 2/80                                     | 2/8                                  | 1/7                                   | 2/550                                | 1/2  | 2/2500   | 2.29   | 2.16   | 2.15   | 2.20   |
| 15.      | 2/80                                     | 2/8                                  | 2/30                                  | 1/250                                | 2/9  | 2/2500   | 2.89   | 2.78   | 2.73   | 2.80   |
| 16.      | 2/80                                     | 2/8                                  | 2/30                                  | 2/550                                | 1/2  | 1/1750   | 2.01   | 2.14   | 1.97   | 2.04   |

on the development of machining process. The method facilitates the minimizing the number of experiments made in order to maximize the obtained results [2]. In other words, one can mention that the Taguchi method can determine adoption of an optimal strategy for making experiments based on objective of the study.

Thus, the main objective of this research is to study the influence exerted by some input factors such are the workpiece thickness, current intensity average amplitude, wire axial tensile force, pulse on time, pulse off-time and wire tool electrode speed on the values of the roughness parameter  $Ra$  of the obtained surfaces.

### 3. EXPERIMENTAL SET-UP

The experimental studies were performed on a Japax L250 wire electrical discharge machine.

The material used for the considered workpiece was an alloyed steel 205Cr115, containing 2.05 % carbon and 11.5 % chromium.

As a tool electrode, a wire made of electrotechnic copper with a diameter of  $d=0.2$  mm was used.

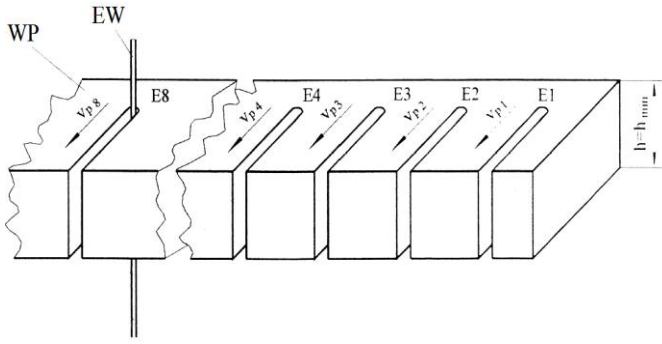
Figure 1 presents a schematic representation of the WEDM process. One can see that a profiled kerf is gradually generated as a controlled movement developed by the workpiece in a plan coordinates system to the travelling wire tool electrode.

The process input factors which have been chosen were the following: workpiece thickness  $h$ , current intensity average amplitude  $i_a$ , wire axial tensile force  $F_t$ , pulse on time  $t_i$ , pulse off-time  $t_b$  and wire electrode speed  $v_t$ . (Table 1).

In order to measure the surface roughness parameter  $Ra$  of the processed surface, a Surtronic 3 device was used.

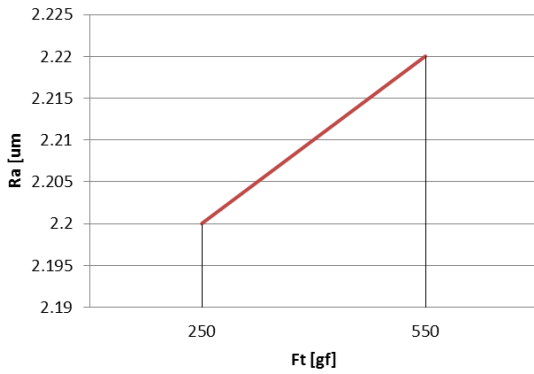
To evaluate the effects of the selected process input factors on the value of the surface roughness parameter  $Ra$ , one can apply the Taguchi method, by taking into consideration a possibility to minimize the number of experiments that must be made [3]. With this aim in view, one used the Taguchi method in order to model the WEDM process. According to the Taguchi method principles, within the experimental plan, one took into consideration the study of the influence exerted by the input factors (the six independent variables) on the response variable, namely the values of the roughness parameter  $Ra$  of the machined surface. For each factor, 2 levels of variation were taken into consideration.

In order to study the influence of the above mentioned input factors on the size of the roughness parameter  $Ra$  of the machined surface of the workpiece, one considered the achievement by wire electrical discharge machining of eight slots in



**Figure 3.** Schematic of obtaining the 8 slots in test piece having the minimum thickness ( $h=h_{min}$ )

prismatic test pieces having distinct thicknesses, as one can see in figure 2; in this figure, E1, E2...E8 correspond to the eight slots obtained in test piece by eight successive experiment.



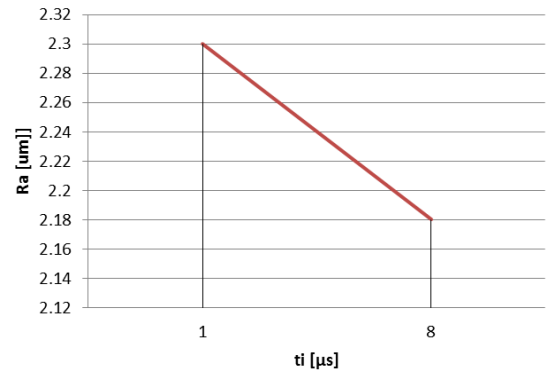
**Figure 2.** Effect of the wire tensile axial force  $F_t$  on the value of the surface roughness parameter  $Ra$

For the experimental program, from the total number of experiments,  $N=16$ , half of them corresponded to the minimum thickness  $h_{min}$  of the test piece and the other 8 experiments were made on using the test piece of maximum thickness  $h_{max}$ . All the experiments were developed on test pieces made of the same metallic material. One used the symbol  $v_{rul}$  for the wire tool electrode travelling speed.

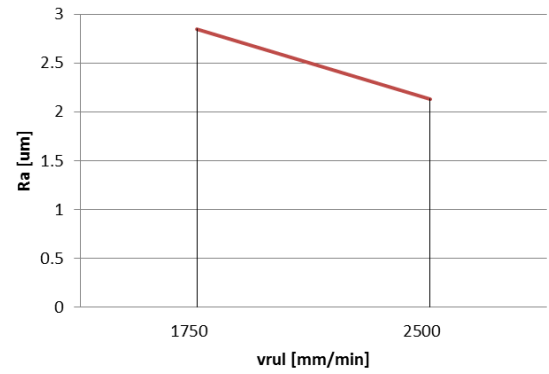
#### 4. EXPERIMENTAL RESULTS

Three measurements were made for each set of experimental conditions and the results of these measurements were displayed in table 2. Also, table 2 contains the average values of the surface roughness parameter  $Ra$  for each of the 16 experiments made on two test pieces having distinct thicknesses.

The experimental results were mathematically processed in order to determine the matrix model in accordance with the requests specific to the Taguchi method (equation (1)). The model facilitates the highlighting the influences exerted by each of the considered process input factors and also by the influence exerted by the interactions between two



**Figure 5.** Effect of the pulse on time  $t_i$  on the value of the surface roughness parameter  $Ra$



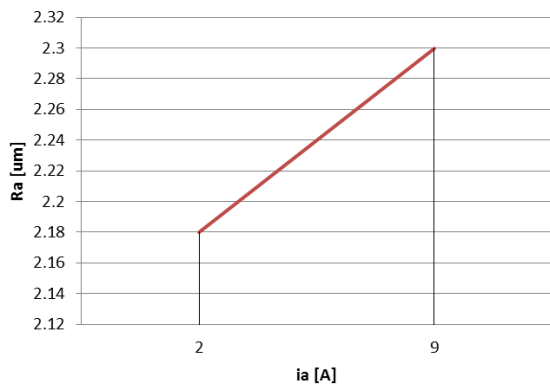
**Figure 4.** Effect of the travelling wire electrode speed  $v_{rul}$  on the value of the surface roughness parameter  $Ra$

independent variables (process input factors) on the size of the surface roughness parameter  $Ra$ . In this way, one can obtain an image concerning the intensity of the influence exerted by the process input variables and by the interactions between two such independent variables on the value of the surface roughness parameter  $Ra$ .

The matrix model determined, based on the values from the tables 1 and 2, has the following form:

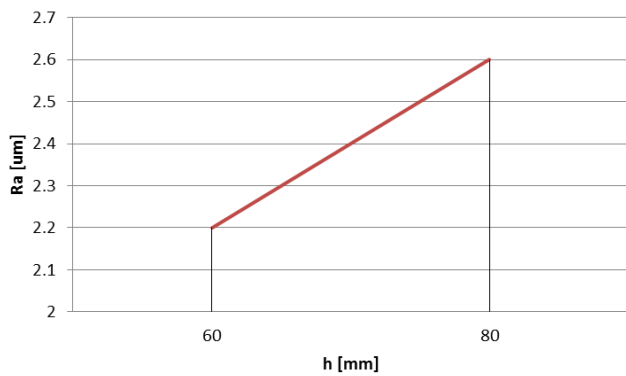
$$\begin{aligned}
 Ra = & 2.2306 + (0.1431 + 0.1431) * (h) + \\
 & (0.0956 + 0.0956) * (t_i) + \\
 & (0.0894 \quad 0.0894) * (t_p) + (0.0944 \quad 0.0944) * (i_a) + \\
 & (0.0656 + 0.0656) * (v_{rul}) + \\
 & {}^t(h) * \begin{bmatrix} -0.0469 & 0.0469 \\ 0.0469 & -0.0469 \end{bmatrix} * (t_i) \\
 & {}^t(h) * \begin{bmatrix} -0.1244 & 0.1244 \\ 0.1244 & -0.1244 \end{bmatrix} * (F_t) + \\
 & {}^t(h) * \begin{bmatrix} 0.0894 & -0.0894 \\ -0.0894 & 0.0894 \end{bmatrix} * (i_a) \\
 & {}^t(T) * \begin{bmatrix} -0.0831 & 0.0831 \\ 0.0831 & -0.0831 \end{bmatrix} * (v_{rul})
 \end{aligned}$$

On the base of the results obtained by means of the Taguchi method, the diagrams from Figures 3, 4, 5, 6, 7, 8 and 9 were also elaborated. These diagrams highlight the effects exerted by each input factor on

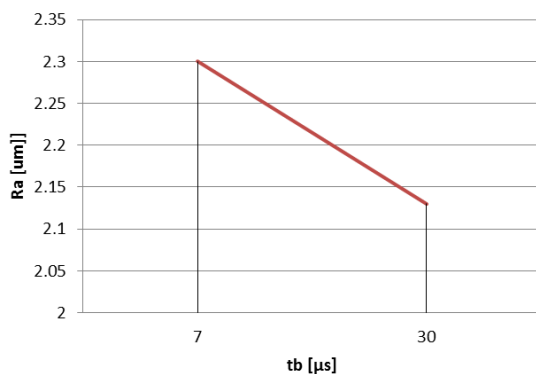


**Figure 6.** Effect of the current intensity average  $i_a$  amplitude on the value of the surface roughness parameter  $Ra$

the value of the surface roughness parameter  $Ra$ . One knows that if the slope of such a graphical representation is bigger, the influence exerted by the analyzed factor is higher.



**Figure 7.** Effect of the test piece thickness  $h$  on the value of the surface roughness parameter  $Ra$



**Figure 8.** Effect of the pulse off time  $t_b$  on the value of the surface roughness parameter  $Ra$

## 5. CONCLUSIONS

The wire electrical discharge machining is a machining method based on the material removal from workpiece as a consequence of the electrical discharges developed between the workpiece and the wire tool electrode found in a travelling motion along its axis. As one can see, the research presented

in this paper refers to a study concerning the influences exerted by some factors, considered as process input factors, on the size of the surface roughness parameter  $Ra$ , appreciated as an output parameter, in the case of wire electrical discharge machining. It is important to ensure for the size of the roughness parameter  $Ra$  values lower than the values prescribed in the mechanical drawing of the part and, as a consequence, the machining parameters must be adequately established, in order to obtain the desired values for the surface roughness parameters. In order to obtain an image concerning the effects of the process input factors on the size of the surface roughness parameter  $Ra$ , a factorial experiment with six independent variables at two levels was designed and applied. The Taguchi method was also used in order to establish a matrix model able to highlight the above mentioned effects. Within experimental research, as process input factors, one considered workpiece thickness  $h$ , current intensity average amplitude  $i_a$ , wire axial tensile force  $F_t$ , pulse on time  $t_i$ , pulse off-time  $t_b$  and wire electrode speed  $v_t$ . One can mention that the matrix model offers information concerning the influence exerted by the interactions of two considered process input factors on the size of the surface roughness parameter  $Ra$ .

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