

Article

Optimization of Qualitative Indicators of the Machined Surface in Symmetrical Machining of TS by WEDM Technology

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Abstract: Current approaches in the process of evaluating the quality of the machined surface during wire electrical discharge machining (WEDM) generally do not include the assessment of micro- and macro-geometric indicators of both parts of the cut. In practice, however, there are specific cases when it is necessary to use both halves of the cut. In such cases, it is necessary to choose a special approach not only in the machining process but also when evaluating the quality indicators of the machined surface. Therefore, experimental measurements were aimed at the identification of these micro- and macro-geometrical indicators in symmetrical WEDM. Within them, qualitative indicators of flat and curved surfaces were assessed. The identification of individual characteristics was carried out using Suftes, Roundtest Mitutoyo, and a 3D coordinate measuring device. The design of the experiment followed the full DoE factorial design method, and the obtained results were processed using the Taguchi method. Based on the obtained results, the response of macro and micro-geometric parameters was characterized by means of multiple regression models (MRM) in symmetrically machined surfaces of tool steel EN X37CrMoV5-1 (Bohdan Bolzano, Kladno, ČR) by WEDM technology. They revealed the mutual dependence of the output qualitative indicators of the eroded area on the input variables' main technological parameters (MTP). Subsequent multi-parameter optimization resulted in a suitable level of setting of the MTP input variable parameters I , t_{on} , U , and t_{off} (9 A, 32 μ s, 15 μ s, and 70 V), through which the greatest agreement of macro and micro-geometric output indicators of symmetrically machined surfaces can be achieved. By applying the optimized levels of MTP settings for symmetrical WEDM of tool steel EN X37CrMoV5-1, their agreement was achieved at the level of 95%.

Keywords: optimization; surface quality; symmetry cut (SC); tool steel (TS); wire electrical discharge machining (WEDM)



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1. Introduction

In the wire electrical discharge machining (WEDM) process, it would be most appropriate for the cut to have zero width, the same dimensional parameters, the same quality of the machined surface, and no residual stress acting in the subsurface layers. Since it is not possible to achieve this 100%, it is necessary to try to at least minimize these shortcomings in the WEDM process. This is because any deviation of the actually achieved quality of the machined surface from the ideal state can cause serious problems. Another problem in the WEDM process is symmetrical machining. Although symmetrical machining in many classical machining technologies is well mastered, the situation is different in the WEDM process. This is due to the fact that with this technology, machining is carried

out by spark erosion during the mutual movement of the tool and the workpiece. At the same time, the electric potential of the spark can cause the instability of the electro-erosive process on the individual sides of the cut, which results in a different achieved quality of the machined surface.

Based on the analysis performed in the given area, it can be concluded that the potential of electrical discharge has a direct impact on the quality of the machined surface during WEDM. At the same time, on the basis of a wide range of experiments, it is evident that it depends on a large number of factors. The experiments carried out so far were partially focused on the identification of the influence of selected input factors on the evaluated output qualitative indicators of the machined area. A partial contribution to the issue was the result of experimental research conducted by Gong et al. [1]. As part of the conducted experimental research, they dealt with the accuracy and surface quality of the cut. They found that as the duration of the pause between discharges increased, the consistency of the notch width improved. They also observed that smaller craters, fragments, cracks, cavities, and spherical drops on the eroded surface can be achieved with a lower intensity of electrical discharges during offset cuts. At the same time, they observed that the size of the convex top of the machined surface decreases, and the peaks and valleys of the waves are more concentrated. Paulo et al. focused their research in even greater depth [2]. As part of their research, they dealt with the symmetry of the crater itself. They found that the aspect ratio of individual craters depends on the pulse energy. With low-energy pulses, rounder craters are created, while with high-energy pulses, elongated craters are formed. These craters then have an impact on the final quality of the eroded surface. A different approach to solving this problem was provided by Pradhan et al. [3], who, as part of their experimental research, chose the response method of selected input parameters on the output quality of the machined surface. They identified parameters that significantly contribute to the resulting quality of the machined surface. Researchers Rees et al. [4] performed a comparative study in which they described the effects of material microstructure refinement on the resulting surface quality of the machined surface during WEDM. They found that the choice of the electrode material used in the application of the electro-erosive process has a significant impact on the achievable aspect ratio of the machined surface and its roughness. In addition to the mentioned authors, many others have described the effects of various input factors and their levels on the output quality parameters of the machined surface. However, their research was limited to the selected type of machined material in connection with the selected parameters of the machined surface.

Although assessing the quality of the machined surface in WEDM from the point of view of micro-geometry parameters is undeniably important, its assessment from the point of view of macro-geometry parameters is no less important. Errors in the macro geometry of the eroded surface affect its future functionality to the same extent. In this direction, new knowledge was brought by Naveed [5], who, as part of his research, devoted himself to deformations of the contour of the machined position. The aim of his research was to identify the extent, nature, and causes of the undesirable effects of the EDM process of EN3B steel and, at the same time, to identify important parameters that can be used to demonstrate the quality of the contour cut. He found that a thinner wire diameter provides a better surface layer quality in terms of its roughness but causes larger contour errors. In his article [6], he describes the findings regarding the WEDM cutting surfaces of samples on which the contour method of residual stress measurement was applied. The results of the research provided detailed information on the effects of the cutting process on the quality of the machined surface in terms of the contour profile at the beginning, in the middle, and at the end of the cut. Precise electrical discharge machining of profiles with a small radius

of rounding was dealt with by Abyar et al. [7]. They theoretically analyzed the causes of first and second finishing-stage machining errors on arc paths, developing a mathematical methodology to predict these errors with 78% to 83% accuracy. Authors Zahoor et al. [8] conducted an experimental study to investigate the effect of galvanized copper wire and main technological parameters (MTP) in the machining of a complex profile from an IN718 superalloy. They found that galvanized copper wire is suitable for machining complex curved geometric profiles such as convex, concave, straight, and inclined. At the same time, the best results in terms of geometric accuracy were recorded with concave geometric elements. The problem associated with the deviation of the wire guidance in the corner parts, which causes the profile error, was dealt with by Selvakumar et al. [9]. As part of their experimental research, they found a way to minimize the corner error by adjustment, which improved the geometric accuracy of the profile in the corners by 25%. The accuracy of machined convex and concave profiles through WEDM was addressed by Farooq et al. [10]. They comprehensively investigated the effect of MTP on the geometric accuracy of convex and concave profiles, including corner radii, during WEDM of a Ti6Al4V alloy. Through SEM, they found that the discharge energy significantly affects the profile accuracy and surface integrity. Researchers Firouzabadi et al. [11] focused on improving the accuracy of concave corners with a small radius in the finishing stage. They found that to achieve accurate corner radii, it was necessary to increase the length of the corner arc traveled by the wire in a concave corner with a small radius. Ahmad et al. [12] focused their research on identifying the influence of residual stress on the errors of the machined profile by WEDM technology. As part of the experimental research, they found that the duration of the spark pulse is a critical parameter in improving the quality of the machined profile. From the analysis carried out in the area of the influence of selected input factors on the macro geometry of the machined surface in WEDM, it can be concluded that their research, as in the case of micro geometry, was only carried out to a limited extent. At the same time, not one of the conducted research studies was concerned with assessing the quality of symmetrically machined surfaces during WEDM. Therefore, based on the analysis of the current state in the area of micro- and macro-geometry assessment in the symmetrical machining of materials by WEDM technology, a research gap was identified. These reasons led us to carry out experimental research, the aim of which was to optimize processes in symmetrical machining of materials using WEDM technology. At the same time, the conducted research contributes to the database of already existing knowledge in the given area. The inspiration for the multi-parametric optimization process was the method proposed by Wang et al. [13]. They proposed an optimization method through which it is possible to improve the accuracy of the machined surface in WEDM. Their system can also predict corner errors as well as recommend optimal machining parameters for smaller corner errors and higher machining speed. Optimization in the WEDM process was also addressed by researchers Divya et al. [14]. As part of the conducted research, they analyzed the possibilities of using multi-objective optimization in the WEDM process. To optimize the parameters of the electro-erosive process with one goal, they recommend applying the Taguchi method.

As already mentioned above, in the process of symmetrical machining by WEDM technology, a significant problem is the different achieved quality of the machined surface [15]. Since this problem has not yet been solved based on the analysis of the current state, an experiment was proposed. The proposed experiment to solve the given problem was oriented with the aim of minimizing micro- and macro-geometric deviations of symmetrically machined surfaces by WEDM technology. The experiment followed the method of full DoE factorial design [16–19]. Significant input variable parameters related to the MTP and their influence on the monitored output qualitative micro and macro indica-

tors of the machined surface were identified. In terms of input-independent parameters of the electro-erosive process, peak current I , pulse on-time duration t_{on} , pulse off-time duration t_{off} , and voltage of discharge U were assessed at three levels. From the point of view of the output-dependent qualitative micro- and macro-geometric indicators of the machined surface, the parameters of roughness R_a and R_z and deviations of flatness Δz_f and cylindricity Δy_C were assessed. The obtained results of experimental measurements were processed by the Taguchi method [20–23]. Subsequently, based on the processed results of the experimental measurements, the response of the input variable parameters of the electro-erosive process to the assessed output-dependent micro- and macro-geometric indicators during symmetrical WEDM was identified by means of multiple regression models (MRM) [24–26]. At the same time, the multi-parametric optimization was carried out to identify suitable levels of MTP input variable parameters of the electro-erosive process, through which the greatest agreement of macro- and micro-geometric output indicators of symmetrically machined surfaces can be achieved [27–31]. Experimental research was carried out on samples that were made by WEDM technology with a brass wire electrode. It is a type of wire tool electrode, which, based on previous experiments, demonstrates the achievement of the best qualitative results of the machined surface in terms of the assessed quality indicators of the machined surface. For that reason, it was assumed that even with symmetrical machining, this type of electrode would show the smallest deviations of the output micro- and macro-geometric indicators of the machined surfaces.

2. Materials and Methods

2.1. Theoretical Starting Points for the Research of Micro- and Macro-Geometric Indicators of the Machined Surface in the Process of Symmetrical WEDM

As is clear from the performed analysis, there has been only minimal interest in the dimensional accuracy of symmetrically machined surfaces by WEDM technology within the research community. At the same time, the reported studies regarding the quality of the machined surface during WEDM in terms of micro- and macro-geometric accuracy in most cases focused only on assessing the quality indicators of the machined surface of only one part of the section. In addition, in many cases, research has focused only on the characteristics of one qualitative indicator. In doing so, researchers did not take into account mutual combinations of the effects of several output qualitative indicators of the machined area. Therefore, the aim of the conducted experimental research was to investigate the mutual effects of the combination of four key qualitative indicators of the machined surface during symmetrical machining of surfaces by WEDM technology and, at the same time, find the optimal combination of the main controllable input-independent parameters for the four output-monitored quality indicators of the eroded area. This problem was solved in the form of mathematical modeling with subsequent optimization [32–35].

The task of modeling the quality of the machined surface in the WEDM process is to transform the mechanisms taking place on the machined surface into a mathematical formula. The latter should accordingly describe the achieved qualitative results of the machined surface based on a detailed definition of the input variables of the process parameters. Defining the mathematical function is the first step required in the optimization process. Its definition requires extensive knowledge of the interrelationships of input-independent MTP and output-dependent indicators of the machined surface in WEDM. After defining them, it is possible to select a suitable optimization criterion with subsequent implementation of the algorithm in a suitable software environment [36,37]. Based on the analysis of the current state in the field of process optimization in WEDM, it can be concluded that the optimization of the response of the machined surface, based on the analysis of the variability of input factors, is a suitable technique for finding optimal

machining conditions in WEDM [38–41]. For the given case, the minimal deviation of the assessed micro- and macro-geometric indicators of the eroded area appears to be a suitable optimization criterion. As part of the experimental measurements, deviations of the micro-geometric indicators of the eroded surface were assessed in terms of roughness R_a and R_z . The micro-geometric indicators of the machined surface R_a and R_z are defined by the standard [42]. The roughness of the machined surface after WEDM is comparable to the quality of finely ground surfaces. Although ground surfaces are generally characterized by a high gloss of the machined surface, in many cases, they show higher values of the mean arithmetic deviation of the roughness profile R_a , or the maximum height of the roughness profile R_z , than matte eroded surfaces. The parameter R_z characterizes the largest height of the unevenness of the profile without any averaged values, while the mean arithmetic deviation of the roughness profile R_a exceeds by 3 to 5 times (Figure 1).

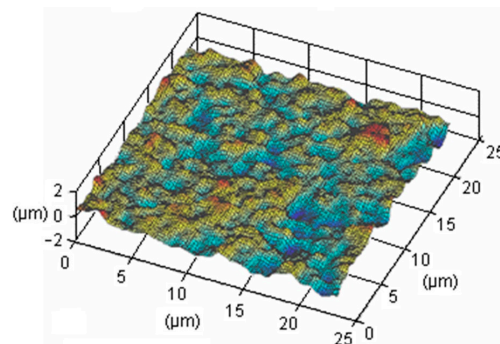


Figure 1. Micro geometry of the eroded surface.

From the performed analysis, it is clear that the macro-geometric indicators of the machined surface represent a separate group of significant geometric deviations of the machined surface after WEDM. Oniszczyk-Swiercz et al. [43], Narendranath et al. [44], and Kadam et al. [45] claim that in order to maintain the required quality of the machined surface after WEDM, deviations in the flatness and circularity of the eroded profile are significant. Therefore, within the assessment of the macro-geometric accuracy of the eroded surface, the deviations of the flatness indicator Δz_f were taken into account in accordance with the applicable standard [46]. In practice, these deviations are evaluated quantitatively as the largest distance between the points of the given profile in the normal direction or as the sum of the absolute values of the largest distances of the points of the given profile on both sides of the middle element. The real eroded surface is then represented by the surface that is separated from the surrounding environment by an ideal flat surface (Figure 2).

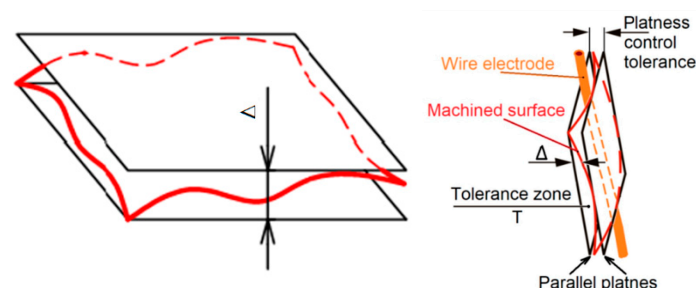


Figure 2. Macro geometry of the eroded surface.

In addition to flatness deviations Δz_f , the circularity deviations of the profile Δy_C were also taken into account when assessing the macro-geometric accuracy of the eroded surface. Their identification was carried out in accordance with the measurement method according to the standard [47]. The basic condition for the correct evaluation of the roundness

deviation was in compliance with the standard [48]. At the same time, for the correct evaluation of the roundness deviations of the profile Δy_C , data on the actual profile with the filtered-out roughness and waviness component were required on the nominal surface. The profile of the circular surface was obtained in the form of a polar diagram. It is about recording the values of the measured deviations so that it is possible to easily create a replacement element. The replacement element can be an envelope or a central circle, while the roundness deviation is evaluated using its center.

On the basis of the detailed identification of all four output qualitative indicators of the machined surface during symmetrical machining of surfaces by WEDM technology, it was possible to design mathematical regression models. Through them, using the optimization method, we subsequently determined a suitable combination of output-independent parameters of the WEDM process to the required level of combinations of output-dependent qualitative indicators of the machined surface [49–51]. Additionally, the optimization of the output-dependent qualitative indicators of the machined area R_a , R_z , Δz_f , and Δy_C must primarily respect their minimum deviation. At the same time, the experimental research carried out was designed with an emphasis on an organized approach to obtaining optimal output-dependent qualitative parameters of the machined surface during WEDM and suitable values of important MTP settings [52,53]. Thus, the optimization criterion was the minimization of the deviation of the parameters R_a , R_z , Δz_f , and Δy_C , while the predicted response was x , and the desired function was R_a , R_z , Δz_f , and Δy_C . The suitability value varied from 0 to 1. If the suitability value was 0, it meant that the predicted value was completely undesirable. If the suitability value was equal to 1, the predicted value was idle. The corresponding response requirement increased with the value of the parameters R_a , R_z , Δz_f , and Δy_C . Formula (1) describes the function of minimizing the one-sided transformation of the deviations of parameters R_a , R_z , Δz_f , and Δy_C .

$$R_a, R_z, \Delta z_f, \Delta y_C = \left\{ \left(\frac{x - x_{max}}{x_{min} - yx_{max}} \right)^{vol} \begin{cases} 0 \rightarrow x \leq x_{min} \\ x_{min} \leq x \leq x_{max} \\ 1 \rightarrow x \leq x_{max} \end{cases} \right. \quad (1)$$

R_a , R_z , Δz_f , and Δy_C are a function of the desired value of x , and the parameters x_{min}/x_{max} are the lower/upper limit values of the x response. Vol is a volume that can be varied from 0.01 to 10 to adjust the shape of the desired function. The overall desired function D ($0 \leq D \leq 1$) is then defined as the geometric mean of the individual desired functions. The multi-objective function is consequently the geometric mean of all the transformed responses of one objective problem shown in Equation (2). The higher the value of D , the better the response of the combined levels.

$$D = \left(R_a \times R_z \times \Delta z_f \times \Delta y_C \right)^{\frac{1}{n}} \quad (2)$$

Multi-parameter optimization with multi-response can be performed using a demand function in conjunction with WEDM symmetrically machined surface response methodology. The input-independent parameters of the electro-erosive process are then peak current I , pulse on-time duration t_{on} , pulse off-time duration t_{off} , and voltage of discharge U .

2.2. Material of Experimental Samples and Used Technological Devices

As part of the application experiment, low-alloy tool steel marked EN X37CrMoV5-1 (W.-Nr. 1.2343) was used to make the samples. It is a chromium–molybdenum–silicon–vanadium tool steel, which has a high hot strength of $R_m \geq 900 \text{ N}\cdot\text{mm}^{-2}$ and a high resistance to tempering. In a wide temperature range, it has good toughness and plastic properties, with good resistance to the formation of cracks. From the point of view of

chemical composition, the carbides in a given tool steel are very small and evenly distributed. This property gives this tool steel excellent cold and hot fatigue resistance and corrosion resistance. In terms of physical properties, it shows good oxidation resistance, as well as high toughness and wear resistance at medium temperature. These properties allow the given tool steel to maintain stable performance in various demanding environments. Table 1 shows selected chemical, mechanical, and physical properties of tool steel EN X37CrMoV5-1.

Table 1. Chemical, mechanical, and physical properties of tool steel EN X37CrMoV5-1.

Chemical Composition (wt %)	Mechanical Properties	Physical Properties
0.32–0.42 C	Tensile strength R_m 950 MPa	Specific heat capacity $460 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
0.20–0.50 Mn	Yield strength $R_{p0.2}$ 600 MPa	Thermal expansion coefficient $11.5 \times 10^{-6} \text{ m}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
0.80–1.20 Si	Hardness in the annealed state 225 HB _{max}	Thermal conductivity $25 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
4.50–5.50 Cr	Achievable hardness after refining 56 HRC	Electrical conductivity $1.92 \text{ Siemens}\cdot\text{m}\cdot\text{mm}^{-2}$
1.10–1.50 Mo	Machinability 75.0–80.0%	Specific electrical resistance $0.52 \Omega\cdot\text{mm}^2\cdot\text{m}^{-1}$
0.30–0.50 V	Poisson's ratio 0.27–0.30	Density $7.8 \text{ kg}\cdot\text{dm}^{-3}$
0.030 P _{max}	Elongation 6–16%	Hot forming temperature 900–1100 °C
0.030 S _{max}	Reduction area 42–58%	Exposure temperature 540 °C

The experimental samples were made on an AgieCharmilles CUT E 350 electrical discharge machine. It is a compact electro-erosive device of the Swiss manufacturer GF that enables the cutting of metallic electrically conductive materials. The AgieCharmilles CUT E 350 electrical discharge machine has an ergonomic AC CUT HMI interface with a 19" touch screen, a wire preparation system using the Thermocut module, automatic wire threading, the possibility of bevel cutting, and other progressive functions.

Demineralized water treated with deionization resin to an electrical conductivity of about $10 \mu\text{S}\cdot\text{cm}^{-1}$ was used as a dielectric.

The experimental samples were made with a wire tool electrode $\varnothing 0.25 \text{ mm}$ labeled AC Brass LP 1000. It is a standard brass wire electrode in the ratio 63%Cu/37%Zn. It is designed for a wide range of operations performed on modern electrical discharge machines. It is particularly suitable for precise machining with acceptable performance, which puts it in the category of universal wire electrodes.

As already mentioned in the introduction, the output indicators of micro- and macro-geometric accuracy of the machined surface during symmetrical machining of tool steels by WEDM technology are largely dependent on the combination of input-independent MTP settings. At the same time, on the basis of the performed analysis, it can be assumed that peak current $I(A)$, pulse on-time duration $t_{on}(\mu\text{s})$, pulse off-time duration $t_{off}(\mu\text{s})$, and voltage of discharge $U(V)$ have a significant influence on the assessed output-dependent indicators of the eroded area R_a , R_z , Δz_f , and Δy_C . Table 2 shows the lower, middle, and upper values of the MTP settings during symmetrical machining of tool steel EN X37CrMoV5-1 by WEDM technology with a $\varnothing 0.25 \text{ mm}$ wire tool electrode marked AC Brass LP 1000.

Mitutoyo SurfTest SJ 400 (Mitutoyo, Kawasaki, Japan) contact roughness meter with automatic radius and slope compensation with an accuracy of $0.001 \mu\text{m}$ was used to measure the micro-geometric indicators R_a and R_z of symmetrically machined surfaces using WEDM technology. Figure 3 shows the measurement of the micro-geometric indicators R_a and R_z of symmetrically machined surfaces from tool steel EN X37CrMoV5-1 by WEDM technology.

Table 2. Lower, middle, and upper values of MTP settings for symmetrical machining of tool steel with WEDM technology.

Setting Value	MTP			
	Peak Current I (A)	Pulse On-Time Duration t_{on} (μ s)	Pulse Off-Time Duration t_{off} (μ s)	Voltage of Discharge U (V)
Low	9	20	10	70
Middle	14	26	15	80
High	19	32	20	90

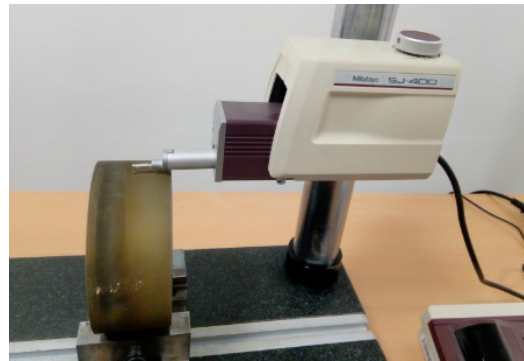


Figure 3. Measurement of micro-geometric indicators of the eroded surface R_a and R_z of symmetrically machined surfaces of experimental samples with the Mitutoyo Surftest SJ 400 device (Mitutoyo, Kawasaki, Japan).

Contact 3D CNC coordinate machine Rapid-Plus (Thome Präzision, GmbH, Messel, Germany) with a measuring range of $1500 \text{ mm} \times 800 \text{ mm} \times 700 \text{ mm}$ and a measurement accuracy of $0.01 \text{ }\mu\text{m}$ was used to measure the macro-geometric indicator of the eroded surface Δz_f of symmetrically machined surfaces using WEDM technology. Figure 4 shows the measurement of macro-geometric deviations of the flatness of the eroded surface Δz_f of symmetrically machined surfaces made of tool steel EN X37CrMoV5-1 by WEDM technology.



Figure 4. Measurement of macro-geometric deviations of the flatness of the eroded surface Δz_f of symmetrically machined surfaces of experimental samples by a 3D CNC coordinate machine Rapid-Plus.

A compact measuring device, Roundtest RA-120 (Mitutoyo, Kawasaki, Japan), was used to measure the macro-geometric indicator of the eroded surface Δy_C of symmetrically machined surfaces by WEDM technology in accordance with the valid standards [46,47]. Figure 5 shows the measurement of the macro-geometric deviations of the circularity of the

eroded surface Δy_C of symmetrically machined surfaces from tool steel EN X37CrMoV5-1 by WEDM technology.



Figure 5. Measurement of macro-geometric deviations of circularity Δy_C of the eroded surface of symmetrically machined surfaces of experimental samples by the Roundtest RA-120 measuring device.

2.3. Design of Experiment Plan

Based on the analysis of methods suitable for the design of the plan of experiments in the production of samples through WEDM technology, the Taguchi method was chosen. It is a very effective tool for investigating the response of the output-dependent quality indicator of the machined area to several input-independent variables of the MTP. In addition, it allows us to summarize the condition of minimizing the influence of the causes of variations with relatively little sensitivity to uncontrollable factors. The advantage of applying this method compared to traditional fully factorial designs of experiments is that it allows for reducing the scale of the set of experiments. This is particularly beneficial in the production of experimental samples by WEDM technology, which is characterized by an extremely time-consuming nature.

As part of the design of the experiment, the application of a two-level setting of specific MTPs was considered, while the set would represent 64 samples. However, there was a risk that in the case of a non-linear dependence of input/output values, the measured results would be burdened with a disproportionately large error. In the case of the application of a 4-level setting of specific MTP, the recorded results would be somewhat more accurate, but the set would represent 128 experimental samples, which is twice the number of samples. Therefore, due to the effectiveness of the conducted research, the design of the experiment was based on a four-factor analysis of 3 levels of setting the input-independent variables of the MTP in WEDM, namely peak current $I(A)$, pulse on-time duration $t_{on}(\mu s)$, pulse off-time duration $t_{off}(\mu s)$, and voltage of discharge $U(V)$. This represents a set of 9 levels (L9) of combinations of MTP settings for each type of cut and height of the material being machined. In doing so, 2 types of cuts were applied with a material thickness of 30.0 mm and 130.0 mm. At the same time, with each symmetrical cut, 2 machined surfaces of the samples were created, which represents a total of 72 experimental samples. The results of experimental measurements of output qualitative indicators of the machined surface Ra and Rz after WEDM of tool steel EN X37CrMoV5-1 with brass wire electrode AC Brass LP 1000 are shown in Tables 3 and 4.

From the results of experimental measurements listed in Table 3, it can be observed that the lowest value of the quality indicator of the micro geometry of the machined surface Ra was recorded for the sample with a material thickness of 130.0 mm and the MTP setting at the L1 level (I 9 A, t_{on} 20 μs , t_{off} 10 μs , and U 70 V). The highest Ra value was recorded when machining material with a material thickness of 30.0 mm and MTP setting at L9 level (I 19 A, t_{on} 32 μs , t_{off} 15 μs , and U 70 V). It was found that the opposite sides of the eroded surface show deviations ΔRa in the range of 0.025 μm to 0.050 μm .

At the same time, the smallest deviation ΔRa was recorded when machining samples with a thickness of $H = 130.0$ mm at the L1 level of the MTP setting, and conversely, the highest when machining samples with a thickness of $H = 30.0$ mm at the L9 level. It follows that, in addition to the MTP, the micro geometry of the machined surface in WEDM is also influenced by the thickness of the machined material H , while the value of the Ra indicator decreases with the increasing thickness of the machined material at an identical MTP setting.

Table 3. Measured values of the micro geometry output indicator of the machined surface Ra according to the four-factor three-level plan of experiments.

Run No.	MTP				Experimental Results							
	I (I)	t_{on} (μs)	t_{off} (μs)	U (V)	Ra (μm) for Adjacent Side of the Cut		Ra (μm) for Opposite Side of the Cut		Maximum Deviation ΔRa (μm)		Percentage (%)	
					$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm
1	9	20	10	70	1.04	0.98	1.1	1.03	0.030	0.025	5.45	4.85
2	9	26	15	80	1.37	1.29	1.43	1.35	0.030	0.030	4.20	4.44
3	9	32	20	90	1.72	1.63	1.8	1.69	0.040	0.030	4.44	3.55
4	14	20	15	90	2.06	1.94	2.14	2.01	0.040	0.035	3.74	3.48
5	14	26	20	70	2.39	2.27	2.48	2.34	0.045	0.035	3.63	2.99
6	14	32	10	80	2.65	2.52	2.74	2.59	0.045	0.035	3.28	2.70
7	19	20	20	80	2.84	2.69	2.93	2.77	0.045	0.040	3.07	2.89
8	19	26	10	90	2.98	2.83	3.08	2.91	0.050	0.040	3.25	2.75
9	19	32	15	70	3.08	2.92	3.18	3.01	0.050	0.045	3.14	2.99

Table 4. Measured values of the micro geometry output indicator of the machined surface Rz according to the four-factor three-level plan of experiments.

Run No.	MTP				Experimental Results							
	I (I)	t_{on} (μs)	t_{off} (μs)	U (V)	Rz (Mm) for Adjacent Side of the Cut		Rz (μm) for Opposite Side of the Cut		Maximum Deviation ΔRz (μm)		Percentage (%)	
					$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm	$H = 30$ mm	$H = 130$ mm
1	9	20	10	70	4.75	4.52	5.04	4.73	0.15	0.11	5.75	4.44
2	9	26	15	80	6.32	5.94	6.63	6.19	0.16	0.13	4.68	4.04
3	9	32	20	90	7.94	7.51	8.29	7.78	0.17	0.14	4.22	3.47
4	14	20	15	90	9.47	8.93	9.85	9.24	0.19	0.16	3.86	3.35
5	14	26	20	70	10.98	10.41	11.42	10.77	0.22	0.18	3.85	3.34
6	14	32	10	80	12.17	11.58	12.63	11.97	0.23	0.20	3.64	3.26
7	19	20	20	80	13.05	12.38	13.53	12.78	0.24	0.20	3.55	3.13
8	19	26	10	90	13.73	13.02	14.24	13.45	0.26	0.22	3.58	3.20
9	19	32	15	70	14.16	13.42	14.69	13.87	0.27	0.23	3.61	3.24

Based on the measured data in Table 4, it can be concluded that the highest value of the qualitative indicator of the micro geometry of the machined surface Rz was recorded when machining material with a material thickness of 30.0 mm and the MTP setting at the L9 level (I 19 A, t_{on} 32 μs , t_{off} 15 μs , and U 70 V). The lowest value of Rz was recorded for the sample with a material thickness of 130.0 mm and MTP setting at L1 level (I 9 A, t_{on} 20 μs , t_{off} 10 μs , and U 70 V). In addition, the results showed that the opposite sides of the eroded surface show deviations of ΔRz in the range of 0.11 μm to 0.27 μm . At the same time, the smallest deviation ΔRz was recorded when machining samples with a thickness of $H = 130.0$ mm at the L1 level of the MTP setting. Conversely, the highest when machining samples with a thickness of $H = 30.0$ mm at the L9 level of the MTP setting. It follows that

as the thickness of the machined material increases with the identical MTP setting, the value of the Rz indicator decreases.

The results of experimental measurements of the output qualitative indicators of the macro geometry of the machined surface Δz_f and Δy_C of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 with material thickness $H = 30.0$ and 130.0 mm using WEDM technology with a brass wire electrode AC Brass LP 1000 are shown in Tables 5 and 6.

Table 5. Measured values of the output indicator of the macro geometry of the machined surface Δz_f according to the four-factor three-level plan of experiments.

Run No.	MTP				Experimental Results							
	I (I)	t_{on} (μs)	t_{off} (μs)	U (V)	z_f (μm) for Adjacent Side of the Cut		z_f (μm) for Opposite Side of the Cut		Maximum Deviation Δz_f (μm)		Percentage (%)	
					H = 30 mm	H = 130 mm	H = 30 mm	H = 130 mm	H = 30 mm	H = 130 mm	H = 30 mm	H = 130 mm
1	9	20	10	70	8.2	16.8	7.8	16.1	0.2	0.35	4.88	4.17
2	9	26	15	80	8.7	18.1	8.1	17.2	0.3	0.45	6.90	4.97
3	9	32	20	90	9.1	19.3	8.4	18.2	0.35	0.55	7.69	5.70
4	14	20	15	90	9.6	20.5	8.8	19.1	0.4	0.7	8.33	6.83
5	14	26	20	70	10.1	21.9	9.1	20.4	0.5	0.75	9.90	6.85
6	14	32	10	80	10.4	23.4	9.3	21.7	0.55	0.85	10.58	7.26
7	19	20	20	80	10.9	24.8	9.7	22.8	0.6	1	11.01	8.06
8	19	26	10	90	11.2	26.5	9.9	24.2	0.65	1.15	11.61	8.68
9	19	32	15	70	11.5	28.3	10.1	25.7	0.7	1.3	12.17	9.19

Table 6. Measured values of the macro geometry output indicator of the machined surface Δy_C according to the four-factor three-level plan of experiments.

Run No.	MTP				Experimental Results							
	I (I)	t_{on} (μs)	t_{off} (μs)	U (V)	y_C (Mm) for Adjacent Side of the Cut		y_C (μm) for Opposite Side of the Cut		Maximum Deviation Δy_C (μm)		Percentage (%)	
					$\varnothing$ 30 mm	$\varnothing$ 130 mm	$\varnothing$ 30 mm	$\varnothing$ 130 mm	$\varnothing$ 30 mm	$\varnothing$ 130 mm	$\varnothing$ 30 mm	$\varnothing$ 130 mm
1	9	20	10	70	120.7	65.3	118.1	64.1	1.3	0.6	2.15	1.84
2	9	26	15	80	121.8	66.1	118.9	64.7	1.5	0.7	2.38	2.12
3	9	32	20	90	124.1	66.9	120.7	65.2	1.7	0.9	2.74	2.54
4	14	20	15	90	125.7	69.2	121.9	67.3	1.9	1.0	3.02	2.75
5	14	26	20	70	128.1	69.8	124.1	67.8	2.0	1.0	3.12	2.87
6	14	32	10	80	129.9	70.2	125.5	68.1	2.2	1.1	3.39	2.99
7	19	20	20	80	131.4	71.1	126.7	68.9	2.4	1.1	3.58	3.09
8	19	26	10	90	133.8	71.9	128.9	69.6	2.5	1.2	3.66	3.20
9	19	32	15	70	136.5	74.2	131.4	71.7	2.6	1.3	3.74	3.37

The range of measured data of the parameter z_f in Table 5 ranges from $7.8 \mu m$ to $28.3 \mu m$. The lowest z_f value was recorded at a thickness of 30.0 mm and the MTP setting at the L1 level (I 9 A, t_{on} 20 μs , t_{off} 10 μs , and U 70 V) and the highest at 130.0 mm thickness and the MTP setting at L9 level (I 19 A, t_{on} 32 μs , t_{off} 15 μs , and U 70 V). Based on the measured data, it can also be concluded that the opposite sides of the eroded surface show deviations Δz_f in the range of $0.2 \mu m$ to $1.3 \mu m$. At the same time, the smallest deviation Δz_f was recorded when machining samples with a thickness of $H = 30.0$ mm at the L1 level of the MTP setting and the largest when machining samples with a thickness of $H = 130.0$ mm at the L9 level of the MTP setting. It follows that, in addition to MTP, the thickness of the machined material H has an influence on the macro geometry of the machined surface in WEDM, while the value of the Δz_f indicator increases with the increasing thickness of the machined material.

Based on experimental measurements (Table 6), the y_C parameter was found to be in the range of 64.1 μm to 136.5 μm . At the same time, the lowest y_C value was recorded for the sample with $\varnothing$ 130.0 mm and an MTP setting at L1 level (I 9 A, t_{on} 20 μs , t_{off} 10 μs , and U 70 V). On the contrary, the highest value of the qualitative indicator of the macro geometry of the machined surface y_C was recorded when machining the sample with $\varnothing$ 30.0 mm and setting the MTP at the L9 level (I 19 A, t_{on} 32 μs , t_{off} 15 μs , and U 70 V). It was also found that the opposite sides of the eroded surface showed deviations Δy_C in the range of 0.6 μm to 2.6 μm . The lowest value of deviation Δy_C was recorded when machining samples with $\varnothing$ 130.0 mm at the L1 level, with the highest at $\varnothing$ 30.0 mm at the L9 level. Therefore, it can be concluded that, in addition to MTP, the macro geometry of the machined surface during WEDM is also influenced by $\varnothing$, while as its value increases, the deviation Δy_C decreases.

3. Results

3.1. Four-Factor Analysis of the Influence of Selected MTP on Micro- and Macro-Geometric Indicators of Symmetrically Machined Surfaces by WEDM Technology

Based on the average values of the micro-geometry output indicators of the machined surface R_a and R_z of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 using WEDM technology with a brass wire electrode AC Brass LP 1000 recorded in Tables 3 and 5, a four-factor analysis of the influence of selected MTP was performed using the Taguchi method. The results of the performed four-factor analysis on the three-level MTP settings are presented in the graphs in Figures 6 and 7.

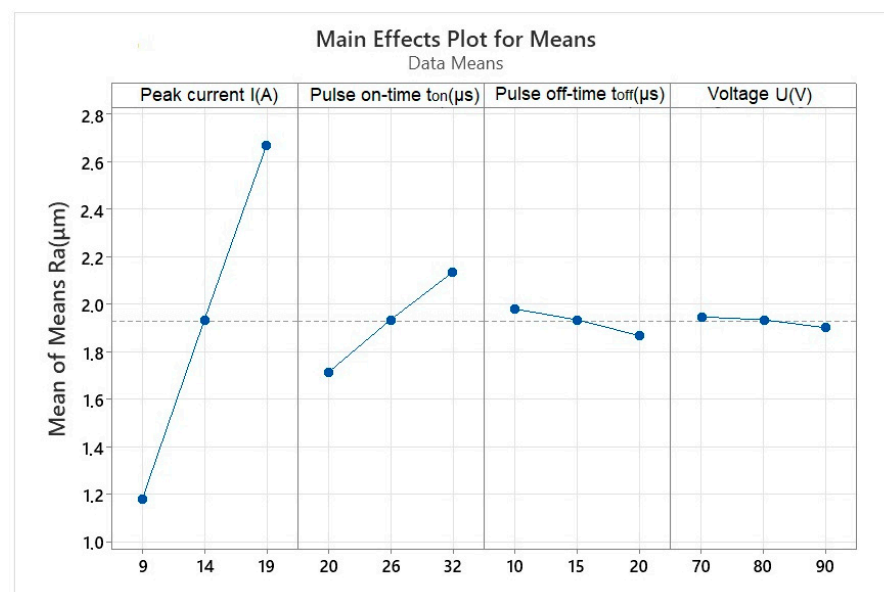


Figure 6. Four-factor analysis of the main effect of MTP with three-level settings on the output indicator of micro geometry of the machined surface R_a of symmetrically machined surfaces by WEDM technology.

From the performed four-factor analysis of the main effect of MTP with four-level settings on the output indicators of micro geometry of the machined surface R_a and R_z of symmetrically machined surfaces by WEDM technology, the following facts were found. It was found that parameter I has the greatest influence on the indicator of the micro geometry of the machined surface R_a and R_z , followed by t_{on} . U and t_{off} have the smallest influence of the considered parameters. At the same time, it was found that the best and better quality of the machined surface in terms of R_a and R_z indicators can be achieved with the

combination of MTP with the minimum value of the parameters I and t_{on} and, at the same time, with the maximum value of the parameters U and t_{off} .

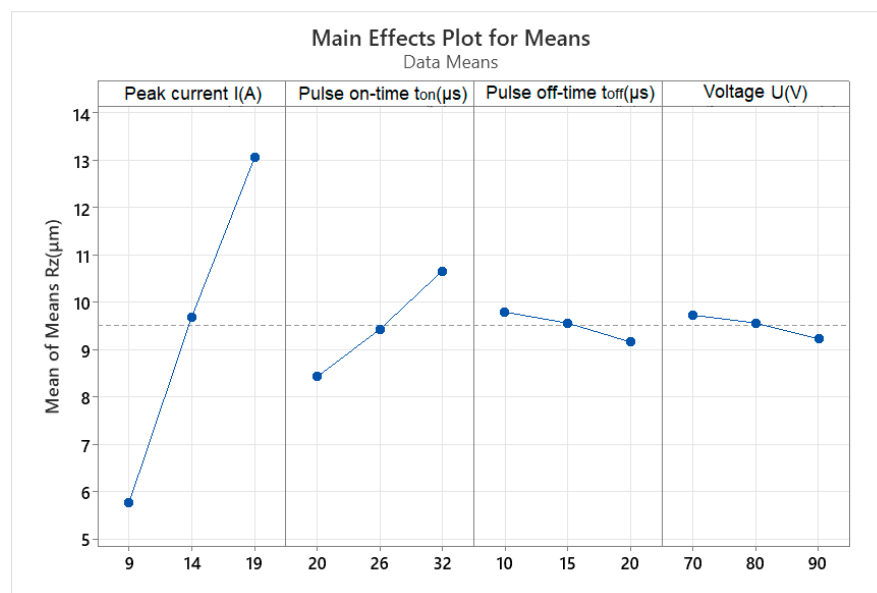


Figure 7. Four-factor analysis of the main effect of MTP with three-level settings on the output indicator of micro geometry of machined surface Rz of symmetrically machined surfaces by WEDM technology.

Based on the average values of the output indicators of the macro geometry of the machined surface z_f and y_C of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 using WEDM technology with a brass wire electrode AC Brass LP 1000 recorded in Tables 5 and 6, a four-factor analysis of the influence of selected MTP was performed using the Taguchi method. The results of the performed four-factor analysis on the three-level MTP settings are presented in the graphs in Figures 8 and 9.

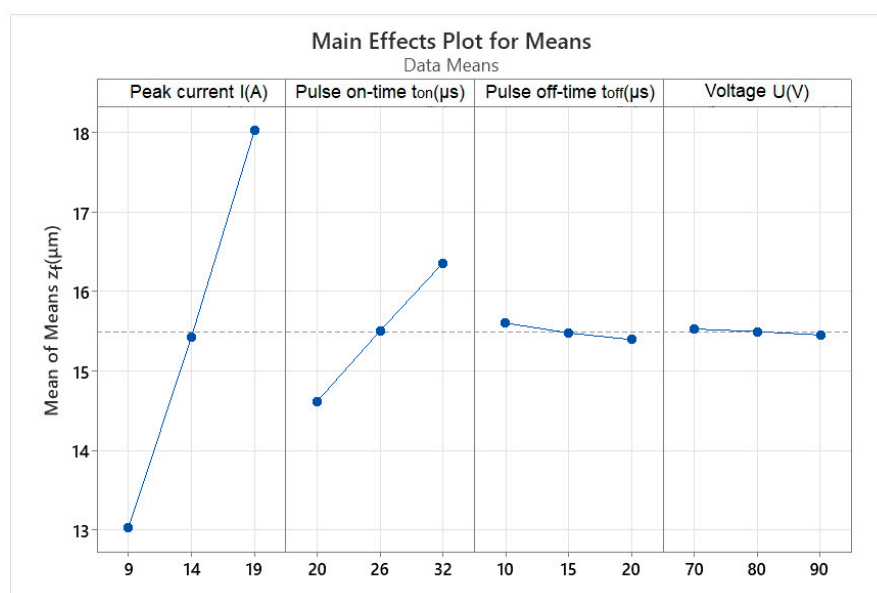


Figure 8. Four-factor analysis of the main effect of MTP with three-level settings on the output indicator of macro geometry z_f of the machined surface of symmetrically machined surfaces by WEDM technology.

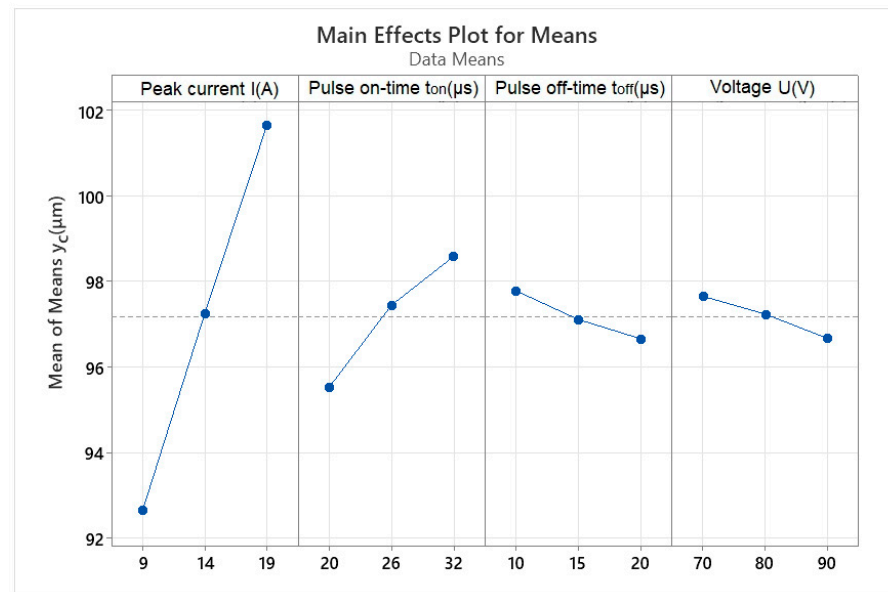


Figure 9. Four-factor analysis of the main effect of MTP with three-level settings on the output indicator of macro geometry of the machined surface y_C of symmetrically machined surfaces by WEDM technology.

From the performed four-factor analysis of the main effect of MTP with three-level settings on the output indicators of the machined surface macro geometry z_f and y_C of symmetrically machined surfaces by WEDM technology, the following facts were found. It was found that parameter I has the greatest influence on the indicator of the macro geometry of the machined surface z_f and y_C , followed by t_{on} . U and t_{off} have the smallest influence of the assessed parameters. At the same time, the parameters U and t_{off} have an almost negligible influence on the z_f indicator. At the same time, it was found that the best and better quality of the machined surface in terms of z_f and y_C indicators can be achieved with the combination of MTP with the minimum value of the parameters I and t_{on} and, at the same time, with the maximum value of the parameters U and t_{off} .

3.2. Modeling and Simulation of Macro-Geometric Indicators of the Machined Surface During Symmetrical WEDM of Tool Steel

In order to mathematically model the output micro- and macro-geometric indicators of symmetrically machined surfaces by WEDM technology, multiple regression models (MRM) were compiled at the 95% confidence level. The proposed MRMs apply to the machining of tool steel EN X37CrMoV5-1 through WEDM technology with brass wire electrodes $\varnothing 0.25$ mm. They are applicable for a wide spectrum of material thickness H . The input parameters of MRM are the independent variables of MTP (I , t_{on} , t_{off} , and U). The output parameters of MRM are dependent micro- and macro-geometric indicators of the eroded area (R_a , R_z , Δz_f , and Δy_C). The higher validity of the proposed MRM is represented by the value of determination coefficients (R^2), which is close to the value of 1. The MRM, which is represented by Equation (3), was compiled on the basis of experimentally measured values recorded in Table 3 with regard to the minimization of the R_a indicator.

$$R_a = -0.7158 + 0.14875 \cdot I + 0.03507 \cdot t_{on} - 0.01125 \cdot t_{off} - 0.002292 \cdot U \quad (3)$$

Figure 10 shows the MRM for the micro geometry output indicator R_a of symmetrically machined surfaces of EN X37CrMoV5-1 tool steel using WEDM technology with brass wire electrode $\varnothing 0.25$ mm, including model building sequence and incremental impact

of variables. Multiple regression of the Ra indicator depending on the input MTP was performed with regard to its minimization.

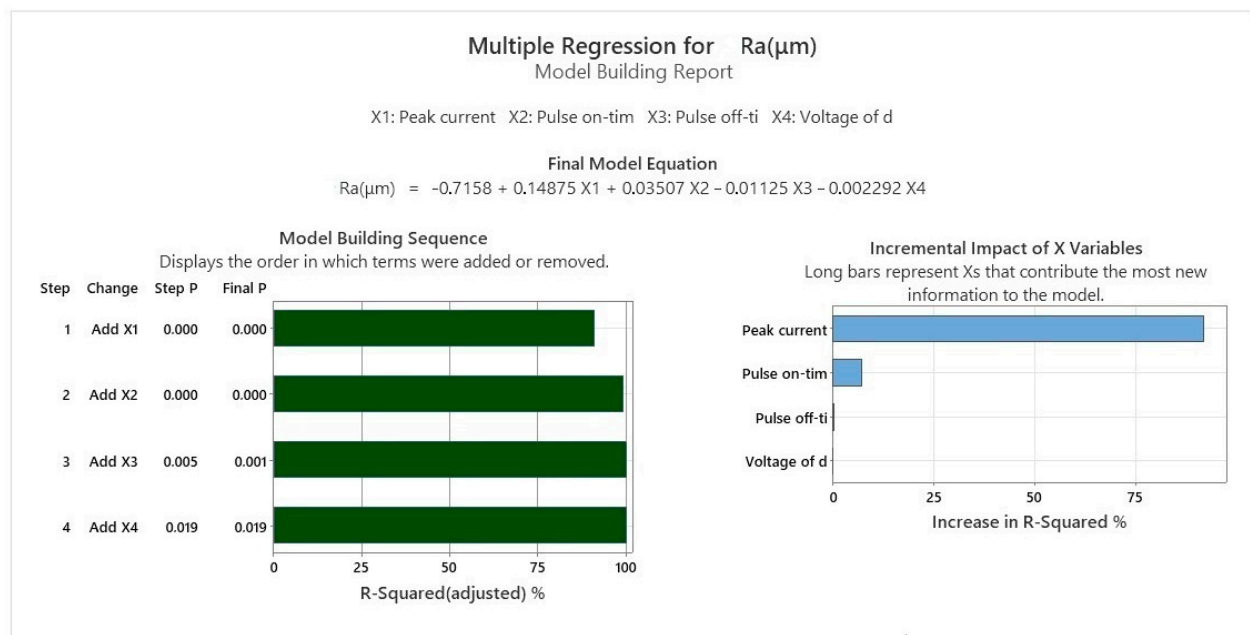


Figure 10. The protocol of the performed multiple regression for the output indicator of micro geometry Ra of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology.

In an identical way, on the basis of the experimentally measured values recorded in Table 4, the compiled MRM output indicator of micro geometry Rz of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology is represented by Equation (4):

$$Rz = -2.53 + 0.7537 \cdot I + 0.1806 \cdot t_{on} - 0.0337 \cdot t_{off} - 0.0265 \cdot U \quad (4)$$

Figure 11 shows the result of the performed multiple regression, which describes the dependence of the micro-geometry output indicator Rz of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology on input-independent MTP. At the same time, it presents the model building sequence and incremental impact of variables within the multiple regression of the Rz indicator with regard to its minimization.

Equation (5) represents the MRM, which was compiled on the basis of experimentally measured values of the macro-geometry output indicator Δz_f of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology recorded in Table 5:

$$\Delta z_f = 5.058 + 0.49917 \cdot I + 0.14444 \cdot t_{on} - 0.02083 \cdot t_{off} - 0.00375 \cdot U \quad (5)$$

Figure 12 shows the result of the performed multiple regression, which describes the dependence of the macro geometry output indicator Δz_f of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology on input-independent MTP. At the same time, it presents the model building sequence and incremental impact of variables within the performed multiple regression of the Δz_f indicator with regard to its minimization.

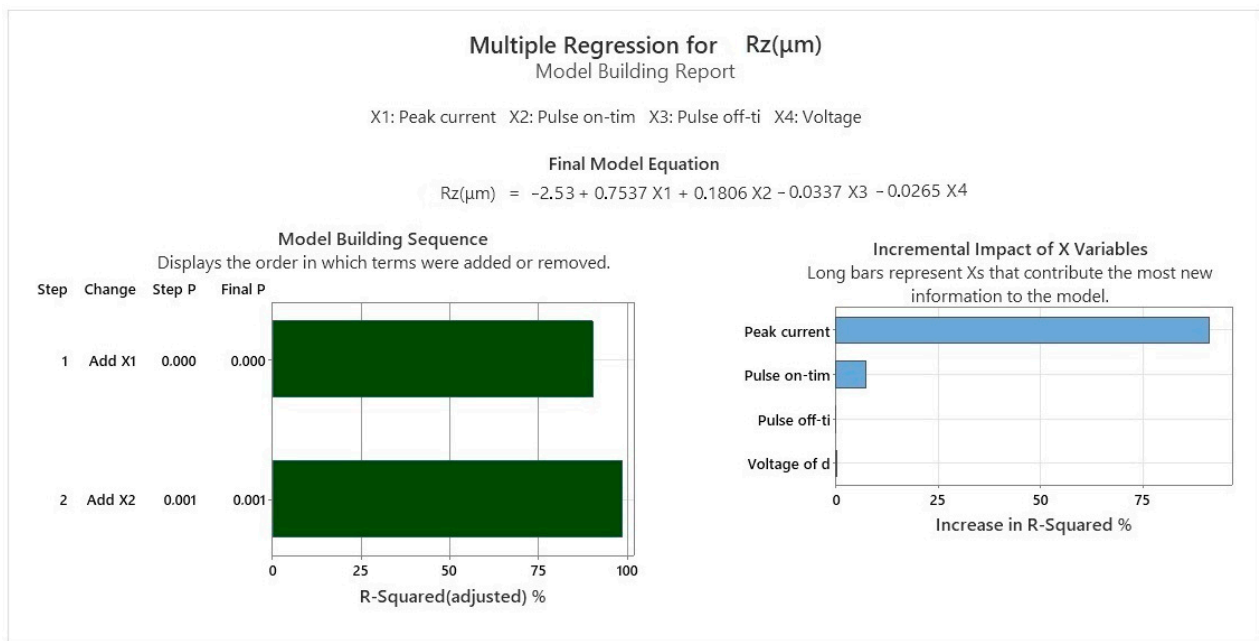


Figure 11. The protocol of the performed multiple regression for the output indicator of the R_z micro geometry of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology.

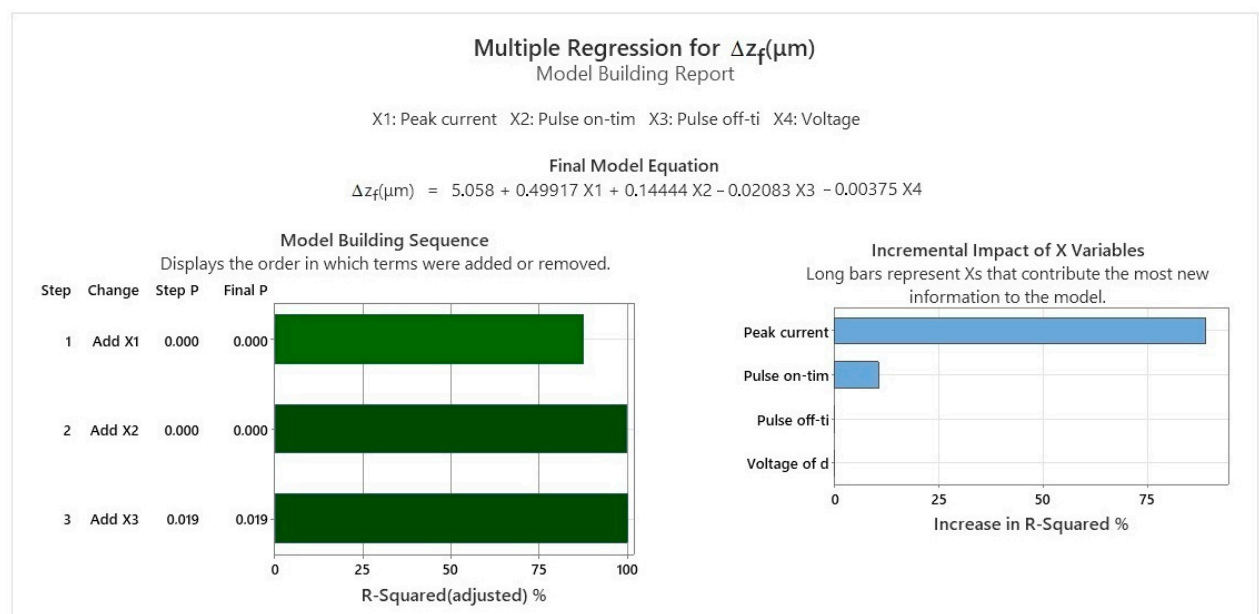


Figure 12. The protocol of the performed multiple regression for the macro geometry output indicator Δz_f of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology.

Equation (6) represents the MRM, which was compiled on the basis of experimentally measured values of the macro geometry output indicator Δy_C of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology recorded in Table 6:

$$\Delta y_C = 83.55 + 0.9017 \cdot I + 0.2549 \cdot t_{on} - 0.1125 \cdot t_{off} - 0.0492 \cdot U \quad (6)$$

Figure 13 shows the result of the performed multiple regression, which describes the dependence of the macro geometry output indicator Δy_C of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology on input-independent MTPs. At the same time, it presents the model building sequence and incremental impact

of variables within the performed multiple regression of the Δy_C indicator with regard to its minimization.

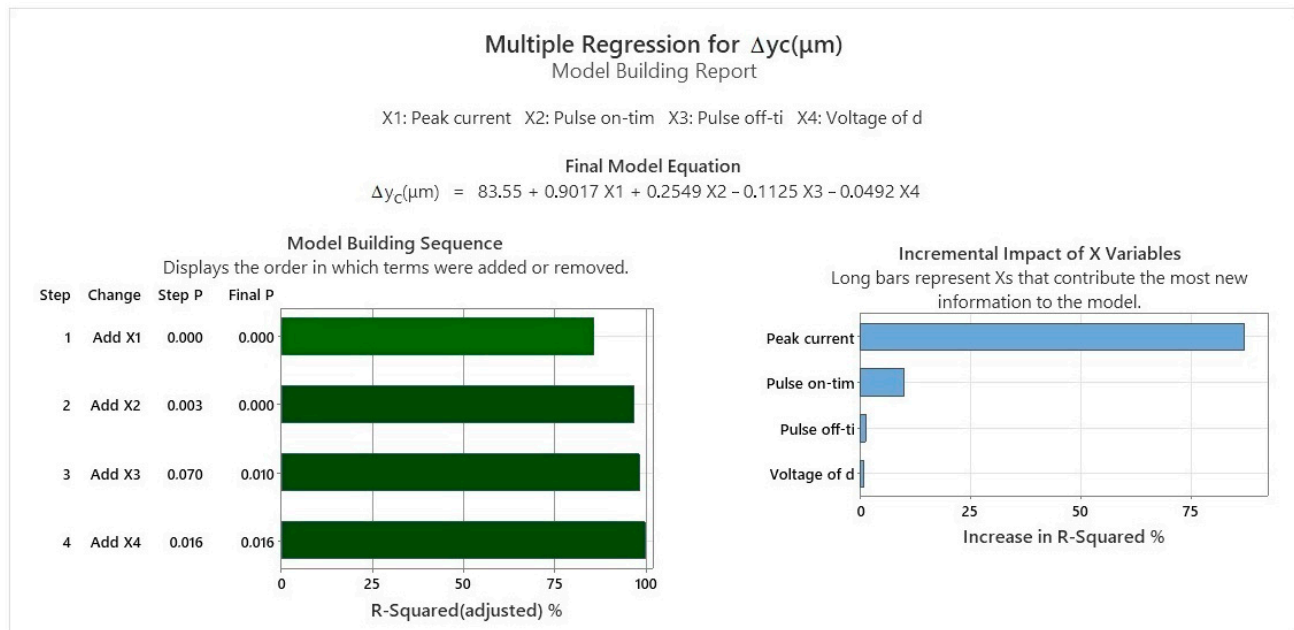


Figure 13. The protocol of the performed multiple regression for the macro geometry output indicator Δy_C of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology.

On the basis of the performed multiple regression, which is described by the compiled MRM (3) to (6), a simulation of the monitored micro- and macro-geometric indicators (R_a , R_z , Δz_f , and Δy_C) was performed for WEDM tool steel EN X37CrMoV5-1 with brass wire electrode. All indicators were simulated with regard to their minimization depending on the input MTP (I , t_{on} , t_{off} , and U) for a wide spectrum of the parameter H . Simulation of the output indicator of the macro geometry Δz_f of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 by WEDM technology depending on the indicators R_a , R_{zm} and H parameters is described by Regression Equation (7):

$$\Delta z_f = 14.69 - 0.0043 \cdot H - 8.04 \cdot R_a + 0.000179 \cdot H^2 + 1.848 \cdot R_a^2 + 0.04502 \cdot H \cdot R_a \quad (7)$$

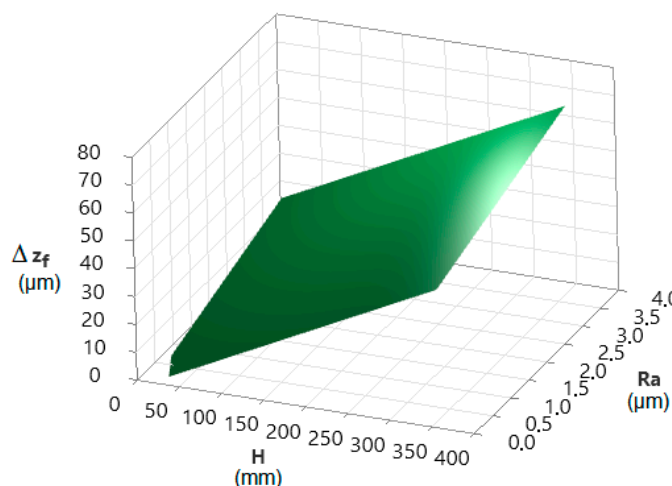
$$\Delta z_f = 7.203 + 0.0019 \cdot H + 0.0091 \cdot R_z + 0.000249 \cdot H^2 + 0.008888 \cdot H \cdot R_z \quad (8)$$

Subsequently, 3D dependences (Figure 14) were constructed, which graphically show the simulation of the output macro-geometric indicator of the eroded surface Δz_f during symmetrical WEDM of tool steel EN X37CrMoV5-1 with brass wire electrode AC Brass LP 1000 in the range of thicknesses $H = 10.0$ mm to 360.0 mm.

From the performed prediction shown in Figure 14 it can be observed that with the increasing value of the index R_a and R_z of the eroded surface and at the same time with the increasing value of the parameter H for WEDM tool steel EN X37CrMoV5-1, the simulated value of the output macro-geometric indicator of the eroded surface Δz_f also increases. With the thickness of the machined material $H = 10.0$ mm and a constant value of $R_a = 0.20$ μm , the simulated value of the indicator $\Delta z_f = 7.3$ μm . At a constant value of $R_a = 3.80$ μm and thickness $H = 10.0$ mm, the simulated value of the indicator $\Delta z_f = 12.50$ μm . With the thickness of the machined material $H = 360.0$ mm and the value $R_a = 0.20$ μm , the predicted value of the indicator $\Delta z_f = 36.70$ μm . At the value $R_a = 3.80$ μm and the thickness $H = 360.0$ mm, the predicted value of the indicator $\Delta z_f = 91.1$ μm . From the simulated values of the output macro-geometric indicator of the eroded surface Δz_f for symmetrical WEDM of tool steel EN X37CrMoV5-1, it can be concluded that the lowest value is possible with the

smallest thickness of the machined material H , and at the same time the lowest value of the Ra and Rz indicators.

Surface Plot of Δz_f vs Ra ; H



Surface Plot of Δz_f vs Rz ; H

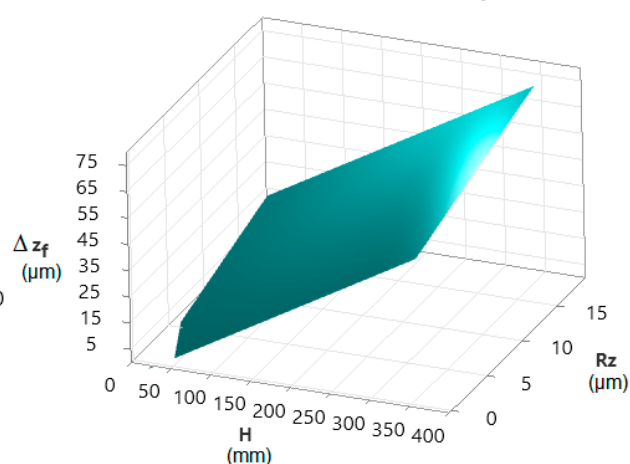


Figure 14. Simulation of the output macro-geometric indicator of the eroded surface Δz_f during symmetrical WEDM of tool steel EN X37CrMoV5-1.

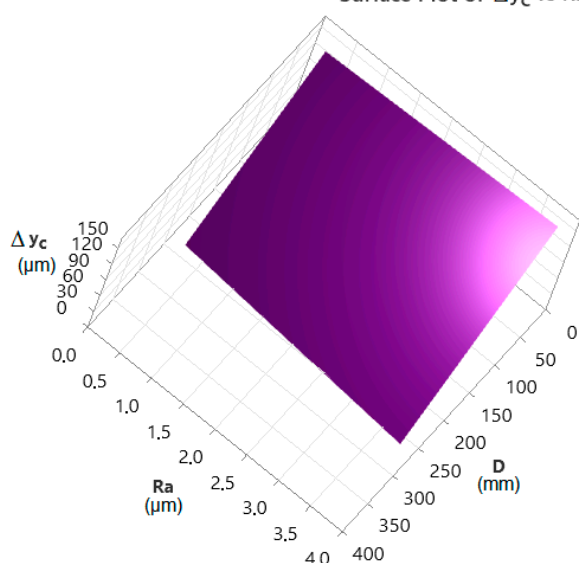
In the same way, the simulation of the output macro-geometric indicator of the eroded area Δy_c was performed in the case of symmetrical WEDM of tool steel EN X37CrMoV5-1. This prediction is described by the following Regression Equations (8):

$$\Delta y_c = 135.24 - 0.5031 \cdot D - 1.189 \cdot Ra - 0.000131 \cdot D^2 + 2.248 \cdot Ra^2 - 0.02404 \cdot H \cdot Ra \quad (9)$$

$$\Delta y_c = 124.963 - 0.54610 \cdot D + 2.977 \cdot Rz + 0.000151 \cdot D^2 - 0.05599 \cdot Rz^2 - 0.006798 \cdot H \cdot Rz \quad (10)$$

Three-dimensional graphical dependence in Figure 15 shows the performed simulation of the output macro-geometric indicator of the eroded area Δy_c during symmetrical WEDM of tool steel EN X37CrMoV5-1 with a brass wire electrode based on Regression Equations (9) and (10).

Surface Plot of Δy_c vs Ra ; D



Surface Plot of Δy_c vs Rz ; D

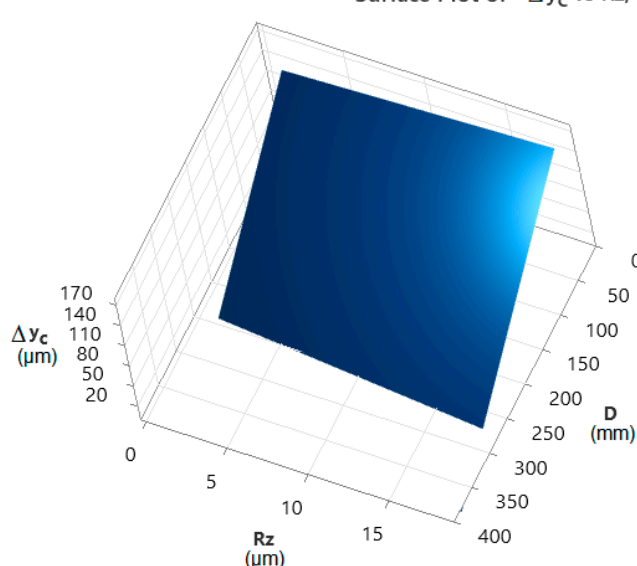


Figure 15. Simulation of the output macro-geometric indicator of the eroded surface Δy_c during symmetrical WEDM of tool steel EN X37CrMoV5-1.

From the graphs in Figure 15, it is evident that with increasing $\varnothing$ of the machined surface of tool steel EN X37CrMoV5-1 and with a constant value of the Ra and Rz indicators, there is a decrease in the predicted value of the output macro-geometric indicator of the eroded surface Δy_C . With a $\varnothing$ of the machined material of 10.0 mm and a constant value of Ra = 0.20 μm , the simulated value of the indicator $\Delta y_C = 129.80 \mu\text{m}$. With roughness Ra = 3.80 μm and $\varnothing$ 10.0 mm, the simulated value of the indicator $\Delta y_C = 157.20 \mu\text{m}$. At $\varnothing$ 220.0 mm and a constant value of Ra = 0.20 μm , the predicted value of the indicator $\Delta y_C = 17.50 \mu\text{m}$. With roughness Ra = 3.80 μm and $\varnothing$ 220.0 mm, the predicted value of the indicator $\Delta y_C = 26.40 \mu\text{m}$. From the simulated values of the output macro-geometric indicator of the eroded surface Δy_C for symmetrical WEDM tool steel EN X37CrMoV5-1, it can be concluded that the lowest value is possible at the largest $\varnothing$ and, at the same time, lower value of the Ra and Rz indicators.

3.3. Optimization of Micro- and Macro-Geometric Indicators of the Machined Surface During Symmetrical WEDM of Tool Steel

Based on the obtained multiple regression reports for the optimization of the output micro- and macro-geometric indicators of the machined surface Ra, Rz, Δz_f , and Δy_C for WEDM tool steel with regard to their minimization and MTP setting I , t_{on} , t_{off} and U , several facts can be observed. First of all, it can be observed that with the increasing value of the parameters I and t_{on} , and at the same time with the decreasing value of the parameter t_{off} and U for WEDM tool steel, there is a significant increase in the output micro-geometric indicators Ra and Rz. At the same time, the most favorable value of the parameter Ra = 0.98 μm and Rz = 4.52 μm was achieved at the L1 level with the setting of MTP (I 9 A, t_{on} 20 μs , t_{off} 10 μs and U 70 V. On the contrary, their highest value Ra = 3.18 μm and Rz = 14.69 μm was achieved at the L9 level with the MTP setting I 19 A, t_{on} 32 μs , t_{off} 15 μs , and U 70 V. At the same time, with this MTP setting, there is a significant increase in the output macro-geometric indicators of the machined surface Δz_f and Δy_C .

For a more detailed identification of the change in the assessed output micro- and macro-geometric indicators of the machined surface Ra, Rz, Δz_f , and Δy_C after WEDM of tool steels depending on H and $\varnothing$, their mutual optimization was subsequently performed. Figure 16 shows the graphical optimization of the output micro- and macro-geometric indicators of the machined area Ra, Rz, and Δz_f with regard to their minimization based on their predicted values, which were obtained through MRM defined by Formulas (7) and (8).

From the graphical dependencies shown in Figure 16, it can be observed that with the increasing thickness of the machined material H and the increasing value of the output micro-geometric indicators of the machined surface Ra and Rz for WEDM tool steel, the value of the output macro-geometric indicator of the machined surface Δz_f also increases significantly. With the thickness of the machined material $H = 10.0 \text{ mm}$ and the value Ra = 0.2 μm , the predicted value of the macro-geometric indicator of the machined surface $\Delta z_f = 13.2 \mu\text{m}$. With the thickness of the machined material $H = 360.0 \text{ mm}$ and the value Ra = 3.8 μm , the predicted value of the macro-geometric indicator of the machined surface $\Delta z_f = 94.1 \mu\text{m}$.

Based on the performed graphic optimization of WEDM tool steel, it can be concluded that a favorable value of the output macro-geometric indicator of the machined surface Δz_f is achieved when machining material with a thickness H in the range of 100.0 mm to 150.0 mm. At the same time, this favorable value can be achieved with MTP settings, which correspond to the values of the micro-geometric indicators of the machined surface Ra = 0.4 μm to 0.6 μm and Rz = 2.0 μm to 3.0 μm .

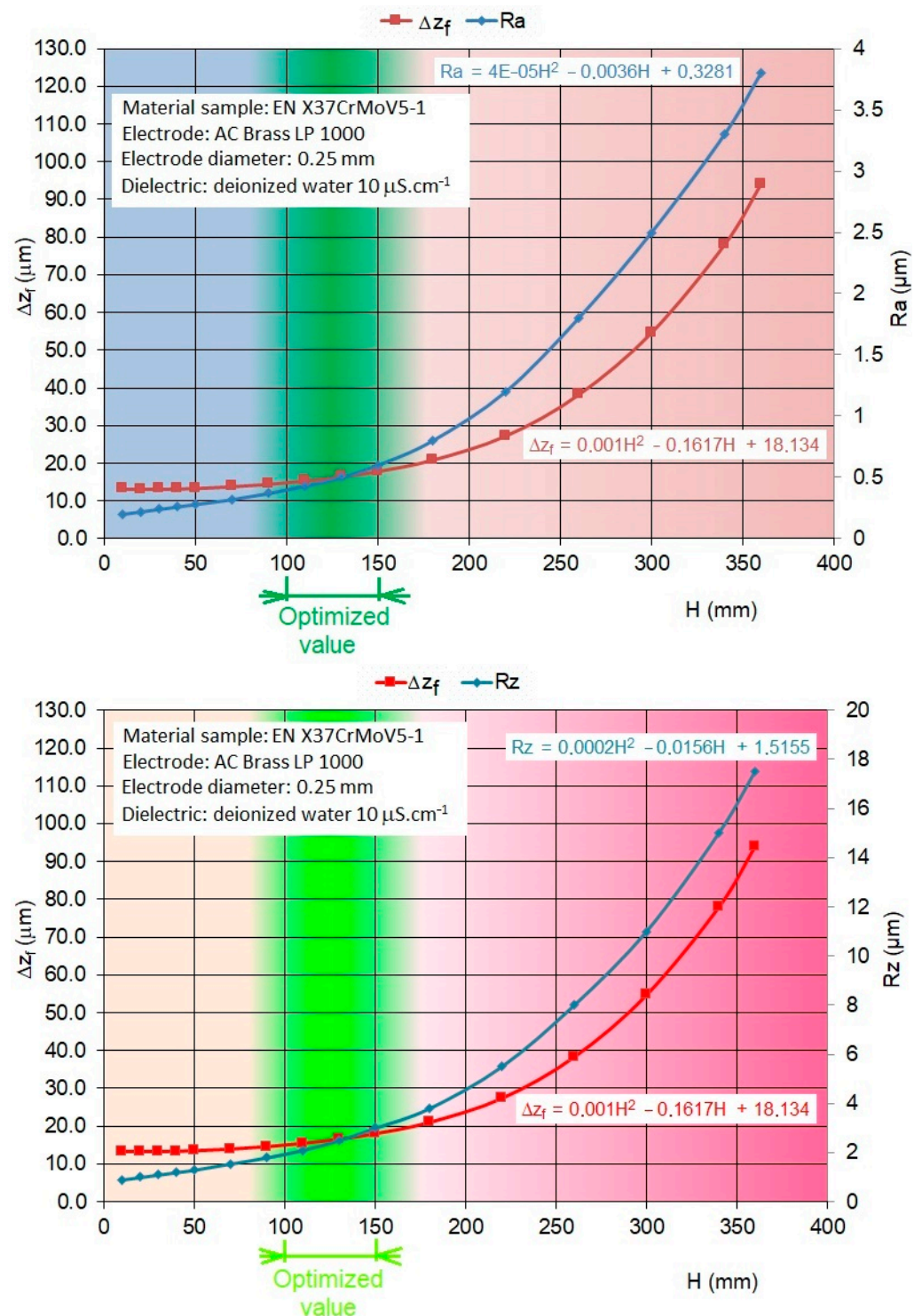


Figure 16. Optimization of the output micro- and macro-geometric indicators of the machined surface Ra , Rz , and Δz_f during WEDM of tool steel with thickness H with regard to their maximization.

Subsequently, graphic optimization (Figure 17) of the output micro- and macro-geometric indicators of the machined surface Ra , Rz , and Δy_C was performed with regard to their minimization based on their predicted values, which were obtained through MRM defined by Formulas (9) and (10).

From the graphical dependencies shown in Figure 17, it can be observed that with the increasing $\varnothing$ of the machined material D for WEDM tool steel, the value of the output macro-geometric indicator of the machined surface Δy_C decreases. However, with the

increasing value of the D parameter, the value of the output micro-geometric indicators of the machined surface, R_a and R_z , increases. With the $\varnothing$ of the machined material $D = 10.0$ mm and the value of $R_a = 0.2$ μm , the predicted value of the macro-geometric indicator of the machined surface $\Delta y_C = 130.1$ μm . With the $\varnothing$ of the machined material $D = 220.0$ mm and the value of $R_a = 1.2$ μm , the predicted value of the macro-geometric indicator of the machined surface $\Delta y_C = 13.2$ μm .

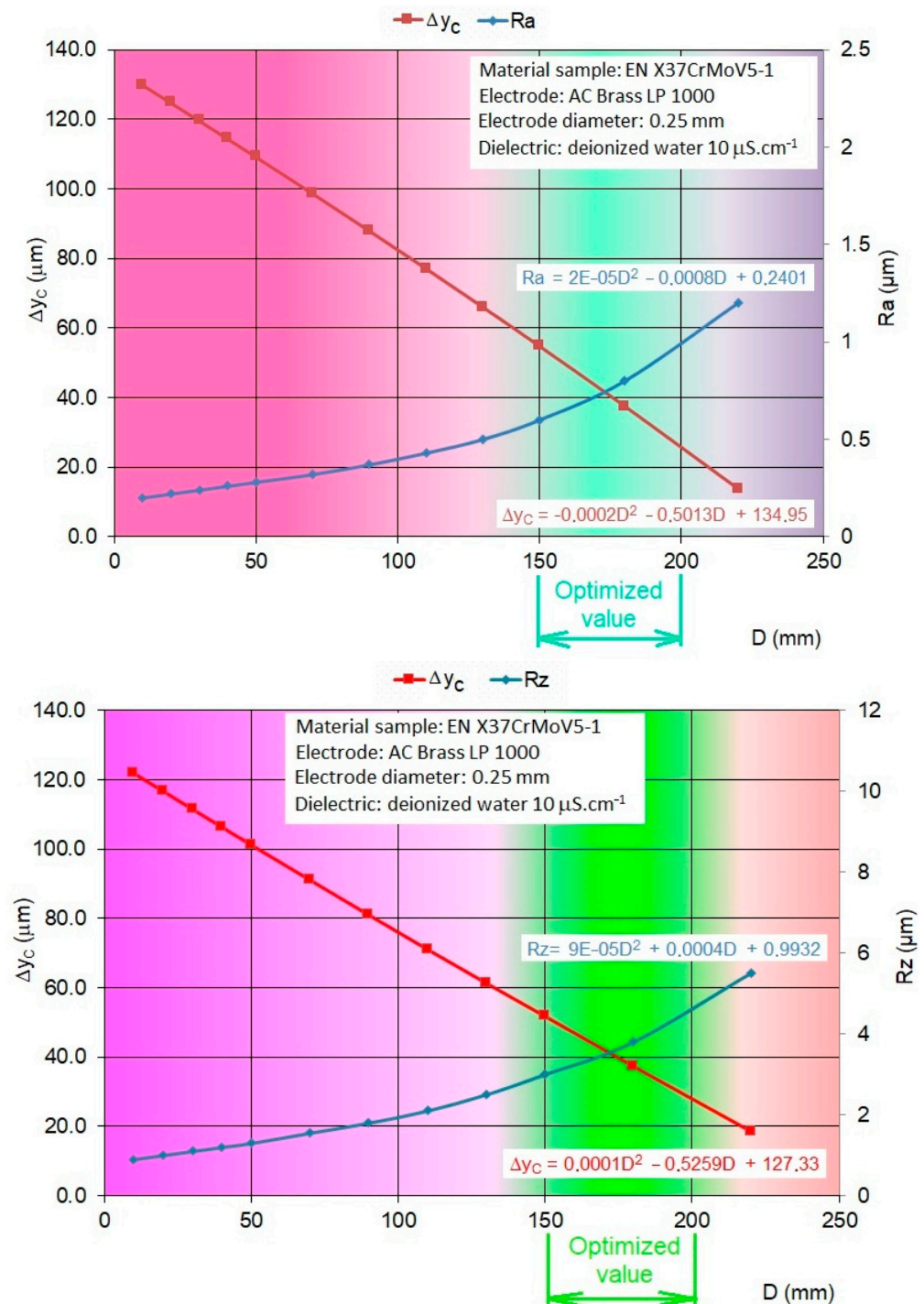


Figure 17. Optimization of the output micro- and macro-geometric indicators of the machined surface R_a , R_z , and Δy_C during WEDM of tool steel with D with regard to their maximization.

4. Discussion

Based on the obtained results of experimental measurements of output micro- and macro-geometric indicators of symmetrically machined surfaces of tool steel EN X37CrMoV5-1 with a brass wire electrode by WEDM technology, the following facts were found. First of all, through a four-factor analysis of the main effect of MTP with three levels of output micro- and macro-geometry settings of the machined surface indicators R_a , R_z , z_f , and y_C , it was found that parameter I has the greatest influence on these indicators, followed by t_{on} . Furthermore, it was found that the lowest value of the indicators R_a , R_z , z_f , and y_C can be achieved at the lowest value of input-independent MTP (I , t_{on}) and, at the same time, the highest value of MTP (t_{off} , U). This is because the potential of the electrical discharge is primarily formed by the intensity of the current and the length of its duration. At the same time, the lower electrical discharge potential has a positive effect on the quality of the machined surface. However, on the other hand, it negatively affects the overall productivity of the electro-erosive process. The voltage parameters and the duration of the break between discharges are only filler parameters to maintain the stability of the electro-erosive process. Additionally, in cooperation with the dielectric liquid, they help to effectively remove eroded material particles from the erosion site, which has a positive impact on improving the quality of the machined surface, both in terms of roughness parameters and geometric accuracy.

At the same time, it was found that the parameters of micro geometry R_a and R_z and macro geometry z_f and y_C influence each other. This means that at a constant thickness H of the machined material, respectively $\varnothing$, when the value of the R_a and R_z indicators decreases, the values of the z_f and y_C indicators also decrease. Additionally, the lowest predicted value of the z_f indicator can be achieved with the thickness of the machined material $H = 10.0$ mm and the roughness of the eroded surface $R_a = 0.20$ μm . The lowest predicted value of the y_C indicator can be achieved at $\varnothing 220.0$ mm and roughness of the eroded surface $R_a = 0.20$ μm .

In addition, based on the results of the WEDM tool steel graphic optimization, it can be concluded that a favorable value of the output macro-geometric indicator of the machined surface Δy_C is achieved when machining material with the range $\varnothing$ of 150.0 to 200.0 mm. At the same time, this favorable value can be achieved with MTP settings, which correspond to the values of the micro-geometric indicators of the machined surface $R_a = 0.6$ to 0.9 μm and $R_z = 3.1$ to 4.6 μm . Given the MPT setting and the optimized parameters of the machined surface, the minimum deviation of the monitored quality indicators of symmetrically machined surfaces with WEDM technology is achieved. This will increase the efficiency of the electro-erosion process by eliminating the need to apply another additional cut to eliminate the resulting deviation.

5. Conclusions

As mentioned in the introduction, the differences in the quality of symmetrically machined surfaces by WEDM technology are a serious problem that has not been solved so far. Therefore, the aim of the conducted experimental research was to minimize the differences in output micro- and macro-geometric indicators of symmetrically machined surfaces by WEDM technology. From the point of view of the micro-geometric indicators of the machined surface, the parameters R_a and R_z were taken into account, and from the point of view of macro-geometric indicators, parameters z_f and y_C . The design and evaluation of the experimental results were carried out with the application of Taguchi's method. Based on the analysis of the current state, the input variable parameters of the electro-erosive process I , t_{on} , t_{off} , and U were identified. Subsequently, based on the experimental measurements, their influence on the output-dependent indicators of the

micro geometry of the eroded surface was identified Ra in the range of 0.98 μm to 3.18 μm and Rz in the range 4.52 μm to 13.53 μm , as well as for macro-geometry output indicators of the eroded surface Δz_f in the range of 7.80 μm to 28.30 μm and Δy_C in the range of 64.10 μm to 136.50 μm . It was found that peak current I and pulse on-time duration have the greatest influence on the given output qualitative indicators of the eroded area. On the contrary, pulse off-time duration t_{off} and voltage of discharge U have the smallest influence. The results of experimental measurements also showed that lower values of indicators Ra, Rz, and Δz_f with identical MTP settings were recorded when machining samples had smaller thicknesses. On the contrary, lower values of Δy_C indicators at identical MTP settings were recorded when machining samples had a larger $\varnothing$. The differences with respect to the thickness and diameter of the machined samples ranged in the case of Ra at the level of 4.85% to 3.14%, in the case of Rz at the level of 4.44 to 3.61%, in the case of Δz_f at the level of 4.17% to 12.17%, and in the case of Δy_C at the level of 1.84% to 3.74%. Subsequently, on the basis of the obtained and numerically processed results, MRMs were compiled, which enable the prediction of the given output indicators of the eroded surface of tool steel EN X37CrMoV5-1 for material thickness in the range of 10.0 mm to 360.0 mm and $\varnothing$ in the range of 10.0 mm to 220.0 mm. Based on them, the value of Δz_f was predicted in the range of 7.3 μm to 96.3 μm and the value of Δy_C in the range of 13.70 μm to 129.80 μm with the corresponding value of the Ra indicator 0.20 μm to 3.80 μm and the Rz indicator 0.90 μm to 17.50 μm . It follows that the lowest values of the micro- and macro-geometric indicators of the machined surface Ra, Rz, z_f , and y_C can be achieved by optimal MTP settings when machining materials with a smaller height and larger profile diameter. By adopting the given recommendations, identical quality in symmetrically machined surfaces can be obtained by WEDM technology. This eliminates the need for another additional cut to achieve identical quality in the giant cutting surfaces.

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Nomenclature

H	thickness (mm)
TS	tool steels
I	peak current (A)
MRM	multiple regression models
MTP	main technological parameters
Ra	micro-geometric indicator (μm)
Rz	micro-geometric indicator (μm)
D	profile diameter (mm)
t_{on}	pulse on-time duration (μs)
t_{off}	pulse off-time duration (μs)
U	voltage of discharge (V)
WEDM	wire electrical discharge machining
Δz_f	flatness deviation (μm)
Δy_C	roundness deviation (μm)

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