ANALYSIS OF THE INFLUENCE OF TOOL ELECTRODE WEAR ON SURFACE QUALITY IN DIE-SINKING EDM TECHNOLOGY

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During the electro-erosive process, metal particles are gradually removed not only from the machined material but also from the tool electrode. Here, the removal of material from the tool electrode is generally considered to be an undesirable consequence of the electro-erosive process. The extent of this wear can be relatively accurately quantified using several indicators. Of these, the percentage of loss of the working part of the tool electrode has the highest informative value. The resulting quality of the eroded area after die-sinking EDM also depends on the magnitude of the given parameter. Therefore, based on experimental measurements, the paper aimed to describe the performed analysis of the influence of the wear of the shaped tool electrode on the quality of the machined surface after die-sinking EDM in terms of surface roughness parameters. The wear of the shape tool electrode in terms of volume loss was measured by the indirect method through weight loss. Experimental results showed that when machining tool steel with a finishing operation, a much lower wear rate of the shape tool electrode was recorded compared to the roughing operation. At the same time, it was found that when the shape tool electrode wear exceeds the level of about 8%, there is a significant deterioration of all qualitative indicators of the machined surface.

KEYWORDS

Die-sinking Electrical Discharge Machining (Die-sinking EDM), Main Technological Parameters (MTP), Percentage Electrode Wear (PEW), tool steel, Shaped Tool Electrode (STE).

1 INTRODUCTION

During the electro-erosive process, metal particles are removed not only from the workpiece but also from the shaped tool electrode (STE). The extent of this removal depends not only on the type of the used workpiece material but also on the electrode material, the setting of technological and process parameters, the properties of the dielectric fluid, etc. [Abdulkareem 2010]. These facts were also confirmed by Torres, A. et al. Additionally, they found that positive polarity leads to higher material removal, while negative polarity leads to lower surface roughness values [Torres 2015]. Multiobjective optimization of main technological parameters (MTP) in EDM using a Cu electrode was performed by Patel, AD et al. They concluded that a lower value of the MTP setting significantly reduces electrode wear [Patel 2012]. In turn, Slatineanu, L. et al. provided theoretical considerations regarding electrode wear during simultaneous EDM using electrodes of different diameters [Slatineanu 2010], while Ivanov, A. et al. identified electrode wear as a source of natural tolerances in micro-EDM [Ivanov 2007]. Gangil, M. et al. also pointed out that a specific combination of workpiece and electrode material plays an important role in the STE wear process [Gangil 2017]. Salcedo, AT et al., found that under the same conditions, the use of a Cu electrode leads to greater removal of metal particles when machining a material with a low melting point than when machining a material with a higher melting point [Salcedo 2017]. However, a significant difference also occurs in the achieved quality of the eroded surface. Under the same machining conditions, when machining a material with a higher melting point, a higher quality of eroded surface in terms of surface roughness parameters is achieved compared to a material with a lower melting point [Kiyak 2007]. The same applies to STE wear. Higher electrode wear leads to deterioration of the quality indicators of the eroded area [Yaman 2020]. Therefore, the aim of the experimental research was to identify the extent of the effect of STE wear on the quality of the eroded surface in terms of surface roughness parameters.

2 THEORETICAL BASIS FOR SOLVING THE PROBLEM

During the electro-erosive process discharges occur at the point with the strongest electric field [Meshram 2020]. Positive and negative ions begin to move due to the action of this resulting field. Their movement accelerates considerably and reaches high velocities [Zhang 2017]. Under these conditions, an ionized conductive channel is formed, which allows an electric current to flow between the electrodes, and thus allows a discharge formation [Świercz 2017]. This, in turn, causes movement and precipitation of other particles. The resulting plasma band is characterized by a very high temperature (up to 12000 °C) [Corny 2016], which causes melting and evaporation of metal particles not only from the workpiece but also from the tool electrode [Dubjak 2016]. In addition, the formation of a crater is accompanied by local melting of the material surface, heat-affected layer [Tavodova 2014] and plastic deformation of the crater and its surroundings [Mičietova 2013, Hlavac 2018]. Electric discharges result in craters, which are characterized not only by their size but also by shape. The size and shape of the formed craters depend mainly on the value of the supplied discharge energy and the discharge interval [Rani 2020]. At the same time, their size and shape has a significant effect on the roughness of the eroded surface, the accuracy of machined shapes, as well as the overall efficiency of the electro-erosive process [Antar 2011].

The amount of material removed from the workpiece and the tool electrode V_i due to the action of electric discharges during the electro-erosive process is directly proportional to the discharge energy. Its size can be mathematically described using equation (1):

$$V_i = K.W_i\,, \quad (1)$$

where the parameter W_i represents the discharge energy and the parameter K is a factor that carries different values for the cathode and the anode. The characteristics of the surface, which is created after electro-erosive machining, are significantly different from the surfaces [Mouralova 2016], that are machined using classical chip machining methods [Panda 2018]. Besides, the discharge that arises between the workpiece and the tool electrode creates irregular craters of various sizes on the surface. Their size and shape depend on a large number of factors [Sanchez 2007]. The ones having a significant influence are the material of the workpiece and the tool electrode, the type of dielectric fluid used [Yan 2018] and the setting of technological and process parameters [Kumar 2017].

STE wear in Die-sinking EDM is very important from an economic point of view [Malega 2017], because it worsens the overall efficiency of the EDM process [Maščenik 2019]. At the very beginning of the industrial use of Die-sinking EDM technology, STE wear was at the level of 40-60% of its total active volume. Due to modern electrical pulse generators, current EDM equipment can have a wear of less than 10%. In the first place, it depends on the conditions of the electro-erosive process, a proper material combination of the tool and the workpiece, etc. [Grigoriev 2019]. However, even today in the case of specific conditions, it is not unusual to achieve STE wear at the level of 30%. A particularly specific situation is the machining of sintered carbide using Cu STE, in which its level of wear reaches 80%.

When quantifying the extent of STE wear, the loss of material from critical points is especially decisive. These are mainly sharp corners, edges or protrusions above the electrode surface. Those can be calculated using the relations (2 to 4):

degree of wear of STE tip: $$S_v = \frac{a_p}{L_v} \quad (2)$$

degree of wear of STE edge: $$S_h = \frac{a_p}{L_h} \quad (3)$$

degree of wear of the STE side edge: $$S_b = \frac{a_p}{L_b} \quad (4)$$

where a_p is the greatest depth of the eroded cavity in the workpiece from its upper edge, L_v is the wear of the STE tip, L_h is the wear of the STE edge and L_b is the wear of the STE side edge. An important parameter in assessing the degree of wear of STE is its total wear, the intensity of wear, percentage of loss, and relative wear. These significant indicators describing the degree of STE wear can be calculated using equations (5 to 8):

volume loss of STE material: $$V_e = V_{e1} - V_{e2} \ (\mathrm{mm}^3) \quad (5)$$

wear intensity of STE: $$m_i = \frac{V_e}{t} \ (\mathrm{mm}^3 \cdot \mathrm{min}^{-1}) \quad (6)$$

relative wear of STE: $$m_v = \frac{V_e}{V_m} \cdot 100 \ (\%) \quad (7)$$

percentage loss of STE: $$m_{pp} = \frac{V_{e1}}{V_{e2}} \cdot 100 \ (\%) \quad (8)$$

where V_{e1} is the volume of STE before machining, V_{e2} is the volume of STE after machining, V_m is the volume of material removed from the workpiece and t is the machining time. Based on the identification of these parameters, it is possible to determine the extent of STE wear relatively precisely. Subsequently, based on the identified extent of electrode wear, it is possible to predict the achieved quality of the eroded surface not only in terms of geometric accuracy [Islam 2010] but also in terms of roughness parameters [Oniszczuk-Swiercz 2020].

3 CONDITIONS OF EXPERIMENTS

Experimental samples were prepared using an electro-erosive machine AGIE Form 30. It is an electro-erosive device that is equipped with one of the most modern electrical pulses generators [Michalik 2016]. Thanks to the integrated intelligence [Baron 2016], it enables achieving a high quality of the eroded area [Hasova 2016] while maintaining high productivity and economic efficiency of the electro-erosive process [Ngocpi 2020]. Additionally, the electro-erosive process is constantly optimized [Van 2020] based on an individual assessment [Olejarova 2016] and evaluation of each impulse [Raksiri 2010]. This significantly reduces STE wear even for the finest finishes. The following Fig. 1 shows the electro-erosive machine AGIE Form 30 that was used in the experiment to make samples.

Figure 1. Electro-erosive machine AGIE Form 30

The following Table 1 shows the basic technical parameters of the electro-erosive machine AGIE Form 30.

Table 1. Basic technical parametres of the electro-erosive machine AGIE Form 30

Technical parameter	Value
Dimensions of the EDM machine	2000×2600×2700 mm
Weight of the EDM machine	3000 kg
Work table dimensions	800×600 mm
Positioning accuracy	0.5 μm
Max. workpiece weight	1000 kg
Max. electrode weight	100 kg
Generator type	AGP FORM
Max. material removal	1000 mm^3.min^{-1}
Max. machining current	104 A
Power supply of the EDM machine	3×380V/400V±10% 50/60 Hz
Volume of dielectric fluid	750 l

In the experiment, Inno Plus dielectric fluid was used during the electro-erosive machining. It is a purely synthetic oil. The advantage of this dielectric fluid over commonly used mineral oils is that it requires less frequent changes. This type of dielectric fluid places special emphasis on the safety of the EDM operator and the environment. It also contains chemical additives that increase the electrical conductivity in the spark gap [Grigoriev 2019] and thus make a significant contribution to reducing the total ionization time. This also leads to a higher intensity of the removal of the metal particles from the workpiece [Rouniyar 2019].

STE was made using copper. The advantage of applying this type of material is the achievement of the high-quality eroded surface [Straka 2017], even without the use of other finishing technologies [Botko 2019]. Simultaneously, the structural integrity of Cu electrodes makes it possible to attain a relatively high resistance to its wear even in the case of reduced ability and intensity of flushing using a dielectric fluid [Evin 2020]. For instance, compared to a graphite electrode, they have twice the resistance to damage and better machinability [Mouralova 2020]. However, in terms of STE wear, these materials have similar properties. With Cu STE it is possible to machine most materials, including carbides, while the delivered quality of the machined surface is at the level of Ra = 0.4 μm and less.

Cu STE, which was used in the experiment, consists of two parts. The first component signifies a working part with dimensions of 15x15x30 mm. The second component represents a clamping part with dimensions of ϕ25x40 mm. These two parts form one compact unit. The following Figure 2 shows the used Cu STE.

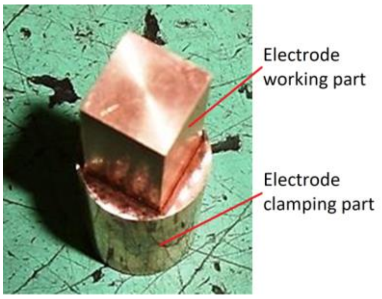


Figure 2. Compact Cu STE with working part dimensions of 15x15x30 mm

Tool steel EN X37CrMoV5 1 (W.-Nr. 1.2343) was used to make the experimental samples. It is chromium-molybdenum-vanadium steel, which is suitable for hardening in oil and air. It is characterized by high hot strength, very good hardenability, and resistance to hardness reduction by tempering. Its other favorable qualities include very good toughness and plastic properties at normal and elevated temperatures. Furthermore, this tool steel shows very high resistance to the formation of small cracks during thermal fatigue and low sensitivity to sudden temperature changes [Miglierini 2004]. It is suitable for heat treatment, while the standard after the heat treatment reaches a hardness of 55 HRC and a strength of 1800 MPa [Tomeczek 2001]. Practically, it is used for the production of individual mold parts or thermoforming tools [Panda 2019], cutting tools, dies, mandrels, jaws, punches, etc.

Before eroding, the material of the experimental samples was heat-treated by annealing to remove internal stresses [Straka 2016c] at a temperature of 600 °C, followed by martensitic hardening at a temperature of about 1050 °C [Domanski 2016]. Due to the removal of internal stresses that may have arisen in the hardening process [Straka 2016a], tempering at a temperature of 500 °C with a time duration of 2h was applied [Turtelli 2006]. By applying the previously mentioned heat treatment, the final hardness of the material of the experimental samples reached the level of 53 HRC. The following Table 2 shows the chemical composition of the material of experimental samples EN X37CrMoV5 1, including selected mechanical and physical properties.

In the performed experiment, a two-phase MTP setting was used in the production of samples. In the first phase, the MTP setting (I = 4.0 A, U = 200 V, t_{on} = 25.6 μs and t_{on} = 6.4 μs) was used in the production of experimental samples No.f1 to No.f5, which took into account the execution of the best possible quality of the machined surface in terms of roughness parameters of the surface *Ra, Ry,* and *Rq*. In the second phase of the production of experimental samples No.r1 to No.r5, the MTP setting was used in order to achieve the highest possible performance of the electro-erosive process, but with the application of optimization elements [Zhu 2019] to achieve acceptable quality [Zidek 2018] of the eroded area in terms of roughness parameters *Ra, Ry* and *Rq*. Other technological and process parameters were set to ensure the stability of the electro-erosive process [Straka 2016b]. The process of production of the experimental samples from tool steel EN X37CrMoV5 1 using Cu STE on the EDM machine AGIE Form 30 is shown in Fig. 3.

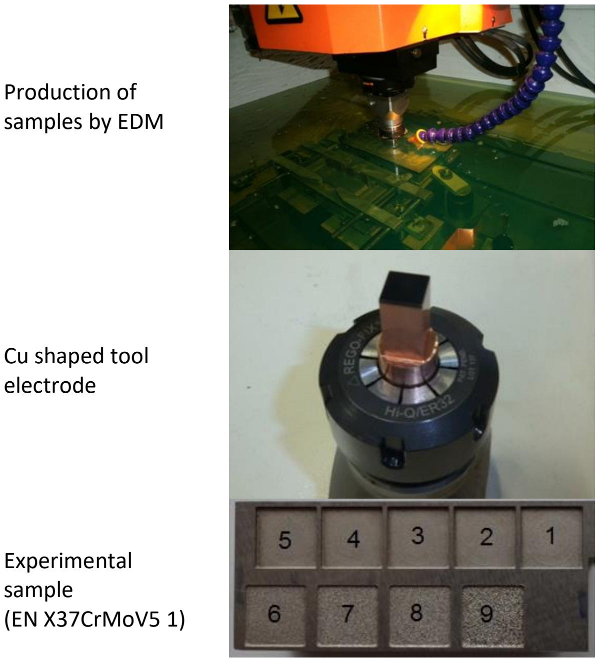


Figure 3. Production of experimental samples from tool steel EN X37CrMoV5 1 using Cu STE

4 EXPERIMENTAL EXECUTION AND RESULTS

Within the performed experiment, there were assessed selected parameters of the wear of Cu STE with the working part dimensions of 15x15x30 mm, and also its influence on the quality of the eroded surface in terms of the roughness parameters *Ra, Ry,* and *Rq* during roughing and finishing operations. In the means of the Cu STE wear, these parameters were evaluated: weight m_{eu} and volume Ve loss of the working part of Cu STE after erosion and the percentage loss PEW (%) of the working part of Cu STE as well. Since it would be relatively complicated to measure the volume loss Ve from Cu STE, an indirect method via the weight loss m_{eu} was chosen. The measurement of the electrode weight was performed using classical laboratory scales. The initial weight of the electrode was recorded, and after each experimental sample that was produced by EDM machine AGIE Form 30, the electrode was weighed again. Between each check erosion of the experimental sample Cu STE was used in a standard manufacturing process. The following Tab. 3 demonstrates the recorded and calculated parameters of the Cu STE wear during the machining of tool steel EN X37CrMoV5 1.

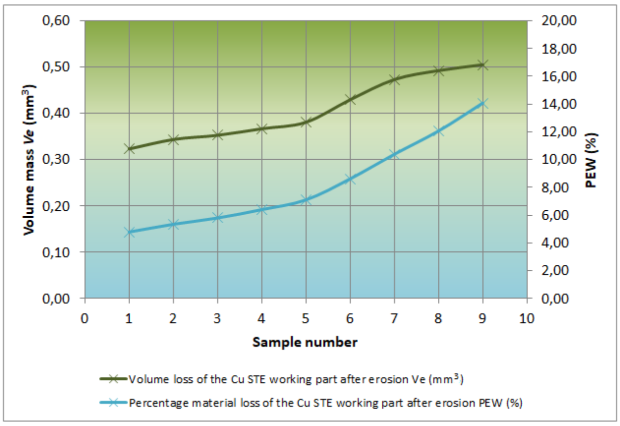
Table 2. Chemical composition of the material of experimental samples EN X37CrMoV5 1 (W.-Nr. 1.2343) and selected mechanical and physical properties

Chemical composition of tool steel EN X37CrMoV5 1 (W.-Nr. 1.2343)							
C	Si	Mn	Cr	Mo	V	P_{max}	S_{max}
0.37%	1.0%	0.38%	5.15%	1.3%	0.4%	0.03%	0.05-0.1%
Selected mechanical and physical properties of tool steel EN X37CrMoV5 1 (W.-Nr. 1.2343)							
Density $g.cm^{-3}$	Modul of elasticity E [GPa]	Specific heat capacity $J.g^{-1}.K^{-1}$	Thermal conductivity $W.m^{-1}.K^{-1}$ at 20°C	Specific electric resist. $\Omega.mm^2.m^{-1}$	Tensile strength Rm (MPa) (in natural state)	Yield strength $Rp_{0,2}$ (MPa) (in natural state)	Hardness after quenching HRC
7.80	215	0.46	25.0	0.52	1400	1200	50-56

Table 3. Results of experimental measurements of weight and volume loss of the Cu STE material

Cu Shaped Tool Electrode (STE)									
Applied operation type of the Die-sinking EDM	**finishing**					**roughing**			
Sample number	No.f1	No.f2	No.f3	No.f4	No.f5	No.r1	No.r2	No.r3	No.r4
Theoretical initial weight of the Cu STE working part m_{e1} (g)	52.65	50.13	47.45	44.70	41.84	38.95	35.50	31.81	27.97
Weight loss of the Cu STE working part after erosion m_{eu} (g)	2.52	2.68	2.75	2.86	2.89	3.45	3.69	3.84	3.94
Volume loss of the Cu STE working part after erosion *Ve* (mm^3)	0.32	0.34	0.35	0.37	0.37	0.44	0.47	0.49	0.51
Theoretical weight of the CuSTE working part after erosion m_{e2}(g)	50.13	47.45	44.70	41.84	38.95	35.50	31.81	27.97	24.03
Percentage material loss of the Cu STE working part after erosion PEW (%)	4.79	5.35	5.80	6.40	6.91	8.86	10.39	12.07	14.09

Based on the results of experimental measurements of the weight loss m_{eu} (g) of the working part of Cu STE after erosion and empirically determined values of its volume *Ve* (mm^3) and percentage PEW (%) of material loss, dependency graphs were constructed and are referenced in Figure 4.



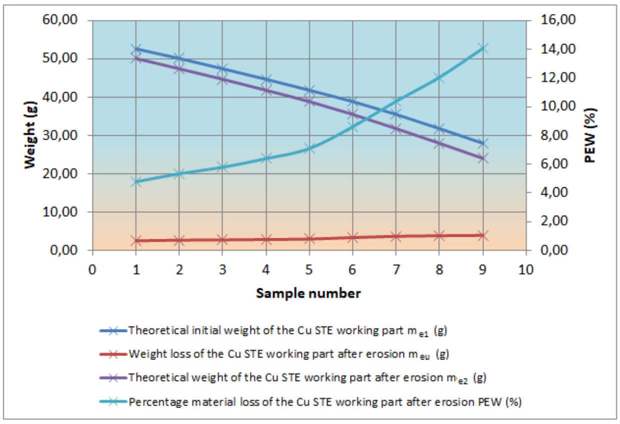


Figure 4. The course of wear of Cu STE during machining of tool steel EN X37CrMoV5 1

Several facts can be observed based on the results of experimental measurements of weight and volume loss of Cu STE material during machining of tool steel EN X37CrMoV5 1. First of all, in the finishing operations, a lower wear rate of Cu STE was noted compared to the roughing operations. The dependency graph of the percentage loss PEW (%) of the Cu STE material also shows that the curve broke when the regimen of die-sinking EDM changed. PEW (%) acquired a steeper characteristic during the transition to roughing die-sinking EDM operations.

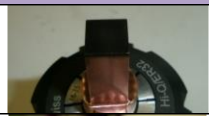
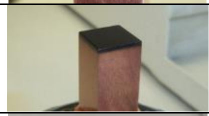
For the complexity of the assessment of the influence of Cu STE wear during machining of tool steel EN X37CrMoV5 1, a measurement of the roughness parameters *Ra, Rz*, and *Rq* of the eroded surface was performed for individual samples. Measuring device Mitutoyo SJ 400 was used to measure the roughness parameters of the eroded surface of the experimental samples. It is a contact measuring device with a measuring range of ±1000 μm and a measuring accuracy of 0.01 μm. The measurement was performed at a length of 8 mm. Figure 5 shows the course of measuring the roughness parameters of the eroded surface of experimental samples made of tool steel EN X37CrMoV5 1.

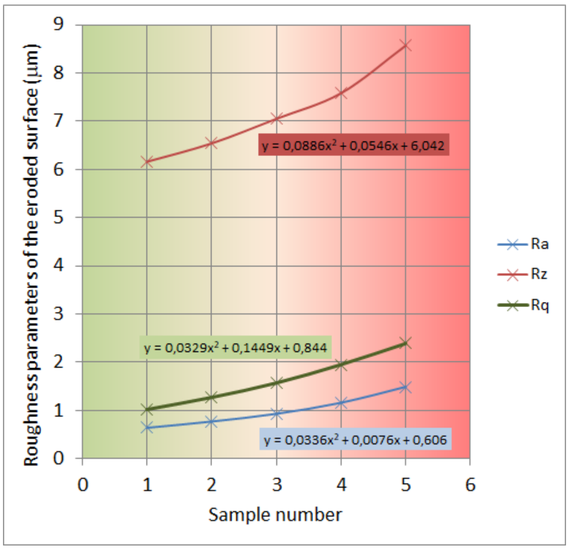
Figure 5. Measuring the roughness parameters of the eroded surface of experimental samples using Mitutoyo SJ 400

Table 4 shows the measured values of the roughness parameters *Ra, Rz,* and *Rq* of the eroded surface of experimental samples made of tool steel EN X37CrMoV5 1, including illustrations of the eroded surface of the sample and the wear state of Cu STE.

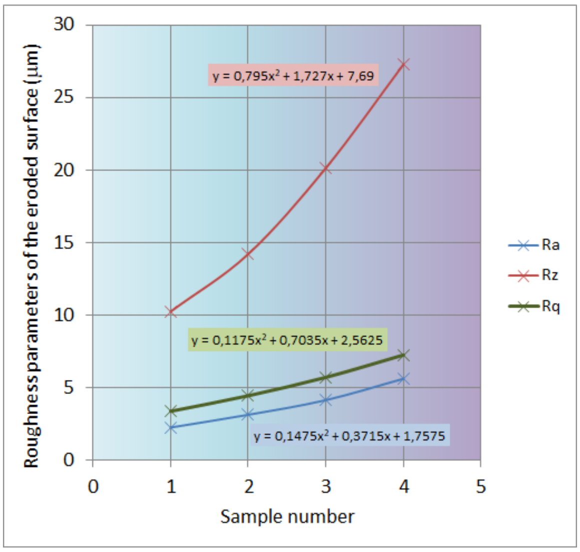
Based on the results of experimental measurements of the roughness parameters *Ra, Rz* and *Rq* of the eroded surface of experimental samples made of tool steel EN X37CrMoV5 1, dependency graphs were constructed and are shown in Fig. 6.

Table 4. Measured values of roughness parameters *Ra,Rz* and *Rq* of the eroded surface of experimental samples made of tool steel ENX37CrMoV5 1

Sample	Type of operation	Eroded surface	Measured values of roughness parameters	Cu shaped tool electrode
No.f1	Finishing		*Ra* = 0.64μm *Rz* = 6.16μm *Rq* = 1.02 μm	
No.f2			*Ra* =0.77 μm *Rz* = 6.54 μm *Rq* = 1.27 μm	
No.f3			*Ra* = 0.93 μm *Rz* = 7.05μm *Rq* = 1.57 μm	
No.f4			*Ra* = 1.16 μm *Rz* = 7.58 μm *Rq* = 1.95 μm	
No.f5			*Ra* = 1.49 μm *Rz* = 8.57 μm *Rq* = 2.39 μm	
No.r1	Roughing		*Ra* = 2.26 μm *Rz* = 10.25 μm *Rq* = 3.38 μm	
No.r2			*Ra* = 3.14 μm *Rz* = 14.21 μm *Rq* = 4.45 μm	
No.r3			*Ra* = 4.15 μm *Rz* = 20.14 μm *Rq* = 5.72 μm	
No.r4			*Ra* = 5.62 μm *Rz* = 27.28 μm *Rq* = 7.26 μm	



a) finishing operation



b) roughing operation

Figure 6. The course of the change of the roughness parameters of the eroded surface *Ra, Rz* and *Rq* due to the wear of Cu STE in different modes of Die-sinking EDM

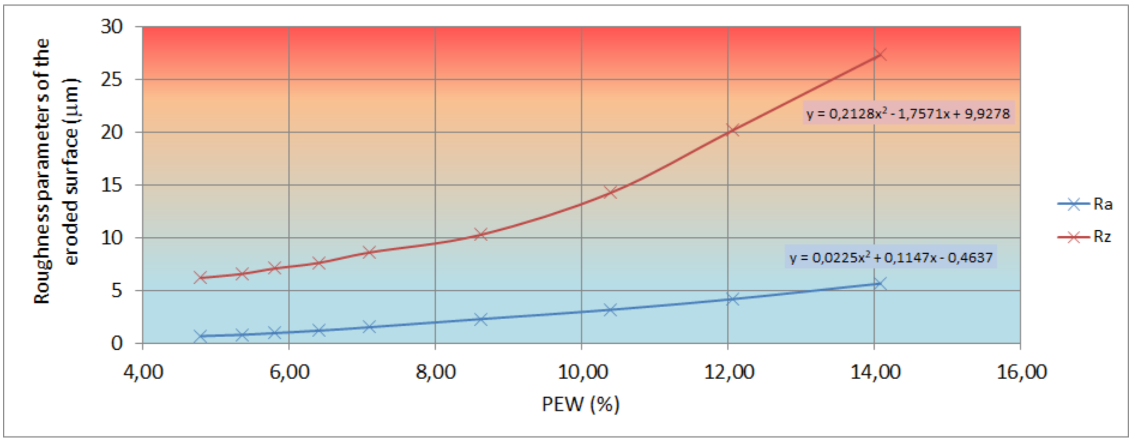


Figure 7. Influence of Cu STE wear on the roughness of the eroded surface in Die-sinking EDM of tool steel EN X37CrMoV5 1

Based on the results of experimental measurements, significant changes in the roughness of the eroded surface of experimental samples made of tool steel EN X37CrMoV5 1 were identified due to the wear of Cu STE in different modes of die-sinking EDM. It was found that because of the wear of Cu STE, there is a significant increase in the roughness parameters *Ra, Rz,* and *Rq* of the eroded surface. Simultaneously, it can be observed that this increase is much milder in the finishing die-sinking EDM operations than in the roughing operations.

The following dependency graph in Fig. 7 comprehensively describes the relationship between the significant parameters of the roughness of the eroded surface *Ra, Rz* and the parameter PEW, representing the degree of wear of Cu STE during machining of tool steel EN 90MnCrV8.

Based on the dependency graph presented above, it can be observed that due to the wear of Cu STE, both of the roughness parameters of the eroded surface made of tool steel EN X37CrMoV5 1 that were monitored increased. The increase in the roughness parameter *Ra* was gradual in the whole range, i.e., during roughing and finishing operations. However, the roughness parameter *Rz* gradually increased in values only during finishing operations. In roughing die-sinking EDM operations, this increase was more rapid. The lowest value of the parameters *Ra* = 0.64 µm and *Rz* = 6.16 µm was recorded in the initial phase of the experiment during the finishing die-sinking EDM operation, practically with zero wear of Cu STE. On the contrary, the highest value of the parameters *Ra* = 5.62 µm and *Rz* = 27.28 µm was recorded in the final phase of the experiment during the roughing die-sinking EDM operation. At this stage, a loss of material from the working part of Cu STE was recorded at the level of 14.08%. Based on the obtained results of experimental research of the influence of Cu STE wear during the machining of tool steel EN X37CrMoV5 1, it is safe to say that PEW has a significant impact on the deterioration of the quality of the eroded surface in terms of roughness parameters. Additionally, it can be stated that even an 8% excess of PEW level leads to a significant deterioration of all its indicators. Therefore, the working part of Cu STE needs to be replaced when the wear level PEW reaches 8.0%.

5 CONCLUSIONS

The quality of the machined surface after die-sinking EDM is influenced by a large number of factors. The primary factors that significantly affect the quality of the machined surface include technological and process parameters, dielectric fluid, and also the extent of the wear of the working part of Cu STE. It is inevitable to identify several parameters in order to be able to determine the exact effect of Cu STE wear on the quality of the machined surface in terms of roughness parameters. Parameters that reliably demonstrate the degree of wear of Cu STE include the weight m_{eu} and volume *Ve* loss of the working part of Cu STE after erosion and the loss percentage of material PEW (%) from its working part as well. With regard to a complex evaluation of the impact of Cu STE wear, its assessment was conducted with the emphasis on the achieved roughness of the machined surface. The aim of the performed experiments was to determine the influence of the PEW parameter of the Cu STE working part on the selected roughness parameters during Die-sinking EDM of tool steel EN X37CrMoV5 1. Particular results of the experimental measurements exhibited a significant influence that the wear of the working part of Cu STE has on the quality of the eroded surface in terms of the assessed roughness parameters. Considering their interdependence, it is suggested to replace the Cu STE during die-sinking EDM of the tool steel whenever the PEW indicator reaches 8%.

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