INFLUENCE OF GRAPHITE TOOL ELECTRODE SHAPE ON TWR AND MRR AT EDM

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Electrical Discharge Machining (EDM) is one of progressively developing machining technology. Its advantage over other progressive machining technologies is the high achieved accuracy of the machined surface. Moreover, in this case, it is machining without force, which means that the mechanical properties of the material to be machined do not impose almost any limits. However, during EDM, the material is not only removed from the workpiece, but also from the tool electrode, causing wear. However, a number of factors have an impact on the Tool Wear Rate (TWR) during the electrical discharge process. It is mainly its chemical and physical properties, the type of material being machined, but also its geometric shape. Therefore, based on the experimental measurements performed, the aim of the paper was to identify the influence of the geometric shape of the graphite tool electrode on the TWR and MRR size during EDM of tool steel EN 90MnCrV8. On the basis of the obtained results, set recommendations for the correct choice of the geometric shape of graphite tool electrodes used in EDM tool steels.

KEYWORDS

Tool Electrode (TE), Tool Wear Rate (TWR), Material Removal Rate (MRR), Electrical Discharge Machining (EDM).

1 INTRODUCTION

During EDM, the material is removed by thermal energy, to which a cyclically repeating electrical discharge is converted between the two electrodes. The first of the electrodes represents the workpiece, the second tool. However, it should be emphasized here that material removal is not only done on the material side but also on the tool electrode side. The decisive factor is the size of their mutual proportion. It is necessary to achieve minimization of percentage part of material taken from tool electrode and workpiece [Fabian 2013]. It is also desirable from the point of view of the productivity of the EDM process that the material removal of the workpiece should be as high as possible. Since EDM is a machining without force, it appears that the mechanical properties [Baron 2016] of the material to be machined will not have a significant impact [Fedák 2013] on TWR or MRR.

Based on the results of several researches, it has been unequivocally confirmed that the combination of workpiece materials and tool electrode has a decisive influence on TWR and MRR during the erosion process. At the same time, the chemical composition and physical properties of both the workpiece material and the tool electrode have a decisive share in the size of the TWR and MRR during the EDM. Often used tool electrode materials are graphite, copper, brass and tungsten, and the like. At the same time, each of these materials is characterized by its characteristic chemical composition as well as individual physical properties. In particular, their electrical and thermal conductivity has a decisive influence. Another important parameter is the melting temperature of the tool electrode material. This is confirmed by the results of some of the researches that can be mentioned [Khan 2008]. He argues in his work that a higher thermal conductivity and a higher melting point of the tool electrode material have a positive impact on the extent of wear. Despite the application tool electrode with a high thermal conductivity and high melting point [Hošovský 2018] materials combined with modern electrical erosion devices cannot achieve zero wear of the tool electrode. Moreover, it is also a slight increase in the ratio MRR and TWR using tool electrodes with specific shapes. At the same time during the execution of certain special operations can occur during EDM to increase TWR respectively decline MRR. For example, the machining of long holes of small diameter where the rinsing conditions are impaired [Hašová 2016]. This variation may in some cases move even with the same combination of workpiece and tool electrode materials up to 30%. It was even recorded with identical settings of technological and process parameters. According to some researchers, the emergence of this deviation may be related to the inappropriate choice of geometric shape [Botko 2018] of the tool electrode. Therefore, the objective of the experimental research carried out was to contribute, in particular, to the database of existing knowledge through [Faltinová 2018] a clear formulation of the individual patterns [Chunquan 2018] in relation to events that bind to TWR and MRR during EDM of tool steels with graphite tool electrode. Subsequently, on the basis of the results obtained, set general recommendations for the correct choice of the geometric shape of the tool electrodes used in electrical discharge machined.

2 WEAR OF THE TOOL ELECTRODE DURING THE EROSION PROCESS

First of all, it should be emphasized that it is desirable for the MRR to be as high as possible during the electrical discharge process. In contrast, the TWR value should be as low as possible [Jurko 2014]. At the same time, the wear of the tool electrode during EDM is generally considered to be an undesirable side effect. By applying advanced materials for the production of tool electrodes, which are characterized by high thermal and electrical conductivity, as well as a high melting point, the TWR and MRR ratio can be minimized. The following Table. 1 shows an overview of the selected physical properties of the materials [Panda 2018] that are used to produce tool electrodes for EDM.

Table 1. Overview of selected physical properties of materials commonly used for EDM tool electrodes

TE material	Electrical conductivity ($S.m^{-1}.10^6$)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Melting point (°C)	Boiling point (°C)	Tensile strength (MPa)	Modulus of elasticity ($MPa . 10^3$)	Density ($g.cm^{-3}$)
Copper	59.6	390	1,083.0	2,595.0	220	130	8.93
Graphite	0.1	125	3,000.0	> 4,000.0	34	5.9	2.20
Brass	16	130	930.0	1,150.0	550	110	8.47
Tungsten	17.9	162	3,390.0	> 5,930.0	750	351	19.3

From the physical properties [Žitňanský 2013] of the tool electrode material, the TWR parameter depends mainly on the value of its thermal and electrical conductivity [Ferdinandov 2018]. The melting temperature of the tool electrode material also significantly affects this parameter. As can be seen from Tab. 1, copper [Pandová 2017] has a good thermal conductivity of 390.0 $W.m^{-1}.K^{-1}$ and at the same time a high electrical conductivity of 59.6 $S.m^{-1}.10^6$ which provides a suitable prerequisite for achieving a low parameter value TWR. On the other hand, its disadvantage is the relatively low melting point of 1,083.0 °C, which negatively affects the TWR parameter. Graphite, in turn, has a high melting point of 3,000.0 °C, resulting in a lower TWR value. However, its disadvantage is a slightly lower value of thermal conductivity of 165.0 $W.m^{-1}.K^{-1}$ and at the same time a significantly lower value of electrical conductivity of 0.1 $S.m^{-1}.10^6$ compared to copper. Brass, in turn, has a low value for both thermal and electrical conductivity and low melting temperature, resulting in a high TWR. Therefore, this kind of material [Michalik 2018] is not very suitable for form tool electrodes. This kind of material is mainly used for its good mechanical properties (tensile strength 550MPa) mainly for wire tool electrodes, which are continuously renewed during the electrical discharge process [Sanchez 2007]. Moreover, in this method of electrical discharge machined, TWR is not a decisive parameter for assessing the efficiency and economy of an electrical discharge process [Melnik 2018]. Tungsten has excellent parameters for important physical properties in terms of low TWR. Its main drawback practical application [Krenický 2011], however, is too high a price.

Since it is not possible to exclude TWR completely, even with the use of state-of-the-art electrical discharge devices, which allow ideal setting of technological and process parameters, it is necessary to orient at least to minimize the proportion [Mičietová 2013] of TWR and MRR parameters. In assessing the wear rate of the tool electrode, the magnitude of the volume loss of material from the active surfaces [Mouralova 2016] of the tool electrode is primarily assessed. At the same time, changes in shape at key locations of tool electrodes [Puri 2003], such as e.g. sharp corners, edges, protrusions and the like. On the following Fig. 1 shows the delicate areas of simple tool electrodes used in EDM, which exhibit increased wear intensity.

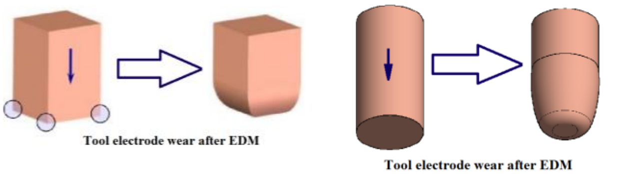


Figure 1. Wear points of simple tool electrodes susceptible to wear during EDM

TWR is one of the parameters relating to shape tool electrodes, which allows to comprehensively characterizing the removal rate of material from the tool electrode during EDM [Salcedo 2017]. Its value can be empirically determined through a relationship (1):

$$TWR = \frac{V_e}{t}\left(\mathrm{mm}^3 \cdot \mathrm{min}^{-1}\right) \quad (1)$$

where:

Ve - is the total volume of material removed from the tool electrode (mm^3),

t - machining time (min).

As mentioned above, to increase the efficiency of the EDM process to minimize the ratio of material removed from the tool electrode to the material taken from the workpiece, it is necessary to know the size of the MRR. This is generally defined as the amount of volume of material removed from a workpiece (usually in mm^3) per time unit (usually min). The MRR parameter value can be empirically determined by the relationship (2):

$$MRR = \frac{S.h}{t}\left(\mathrm{mm}^3 \cdot \mathrm{min}^{-1}\right) \quad (2)$$

where:

S – is the area of material removed from the workpiece (mm^2),

h – depth of material removed from the workpiece (mm),

t – machining time (min).

Based on the TWR and MRR parameters, the magnitude of the relative electrode wear parameter (REW) can then be determined empirically. This is given by the ratio of TWR and MRR, and its size can be expressed as a percentage according to the relationship (3):

$$REW = \frac{TWR}{MRR} \cdot 100 \ \ (\%) \quad (3)$$

3 MATERIALS AND METHODS USED IN THE EXPERIMENT

3.1 *Technical specification of used electrical discharge device*

All experimental samples were made in company 1. PN Prešov on Agietron IMPACT 3 electrical discharge device (Fig. 2). It is a modern electroerosion device, which is used by the given company to deepening cavities of molds for casting metals [Yan 2018] under pressure.

Figure 2. Electrical discharge device Agietron IMPACT 3 by company Agie Charmilles

In the following Table 2 shows the basic technical specification of the Agietron IMPACT 3 electrical discharge equipment used by the Swiss company Agie Charmilles.

Table 2. Basic technical specification of electrical discharge equipment Agietron IMPACT 3

Basic device parameters	Maximum range
Max. Axis Travel X/Y/Z	1070×530×350 mm
Max. Work Table Size	880×680 mm
Max. Workpiece Weight	800 kg
Max. Electrode Weight	200 kg
Max. Machining current	72/104 A
Total machine weight	3900 kg
Dielectric fluid (capacity)	oil (620 l)

3.2 *Technical specification of used tool electrodes*

Three types of shaped graphite tool electrodes [Zhang 2017] were used in the experiment. In the first case, the type of electrode was a square section of the active part, with all edges sharp. In the latter case, the type of electrode was a square section of the active part, the peripheral edges being rounded. In the third case, the type of electrode was square section of the active part, with all edges rounded. EX-60 graphite was used as tool electrode material. On the following Fig. 3 shows the instrument electrode models used in the experiment.

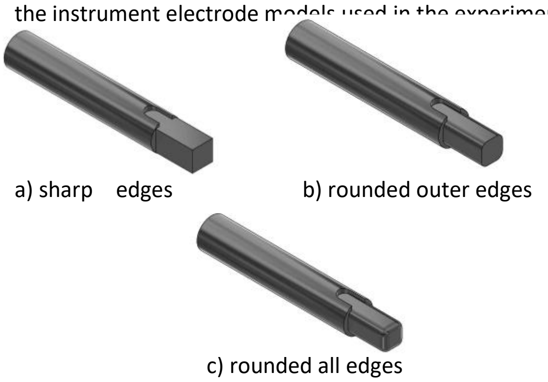


Figure 3. Models shaped tool electrode with a square cross-section of the active part

In all three cases, it was a shape tool electrode with a square section of the active part with dimensions 11.0 x 11.0 mm and length of the active part 20.0 mm. Semi-finished product size ϕ16.0 mm and length 100.0 mm. The semi-finished product for the production of the given tool electrodes was a graphite round bar marked EX-60. It is a fine graphite that is commonly used in the production of tool electrodes with sharp but also rounded edges of complex shapes designed for electrical discharge machining of molds and dies. The following Table 3 shows a detailed overview of the physical properties of the EX-60 material used in the experiment for the production of molded tool electrodes.

Table 3. Overview of physical properties of graphite marked EX-60

Physical properties	EX-60
Specific electrical resistance	14.0 $\Omega.m^{-1}$
Thermal conductivity	80.0 $W.m^{-1}.K^{-1}$
Bending strength limit	50.0 MPa
Modulus of elasticity	10.5 MPa
Density	1.8 $g.cm^{-3}$
Medium grain size	10.0 µm
Hardness (HRB/Shore)	70/62

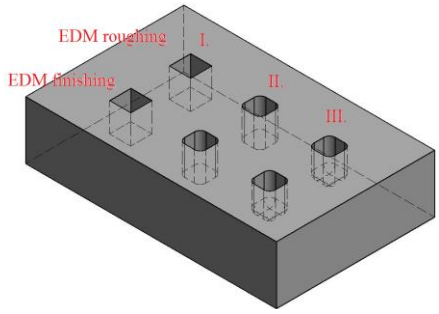
A special groove with a width of 7.0 mm and a length of 10.0 mm was made on the side of the shaped tool electrodes for the purpose of better rinsing of the working space and also for the establishment and entering of corrections into the CNC electrical discharge machine Agietron IMPACT 3.

3.3 Technical specification of the material used in the experimental samples

Experimental samples were made from alloyed tool steel EN 90MnCrV8 (W.-Nr. 1.2842). It is a material that is characterized by high hardness, wear resistance, compressive strength and good toughness. In practice, it is widely used in the production of tools and tools for hot and cold work [Wang 2017]. The following Table 4 shows the basic physical properties of the material used in the experimental samples designated EN 90MnCrV8.

Table 4. Tab. 4 Selected physical properties of alloyed tool steel EN 90MnCrV8 (W.-Nr. 1.2842)

Steel properties	EN 90MnCrV8 (W.-Nr. 1.2842)
Electrical conductivity	2.85 $S.m.mm^{-2}$
Thermal conductivity (at 20°C)	30 $W.m^{-1}.K^{-1}$
Tensile strength, Rm	770 MPa
Yield strength, $Rp_{0.2}$	550 MPa
Density	7.85 $g.cm^{-3}$
Hardness after hardening	62 HRC



I. Application of sharp edged electrode (EDM roughing / finishing)
II. Application of an electrode with rounded outer edges (EDM roughing / finishing)
III. Application of the electrode with rounded all edges (EDM roughing / finishing)

Figure 4. Model of experimental sample after application of graphite tool electrode with square area of active surface with sharp and rounded edges after EDM roughing and finishing operation

The 100.0 x 60.0 x 30.0 mm steel block was the experimental sample. On the Fig. 4 is a model of an experimental sample [Simkulet 2017] that is obtained by applying a graphite shaped tool electrode with a square active surface area with sharp and rounded edges in an EDM roughing and finishing operation.

3.4 Specification of applied technological parameters

In order to obtain relevant results of experimental measurements, the technological [Świercz 2017] and process parameters were set in two variants. In the first variant, technological [Ťavodová 2014] and process parameters [Świercz 2018] were set, which correspond to the conditions for roughing EDM operations [Straka 2017]. In the second variant, the technological and process parameters were set, which correspond to the conditions for finishing EDM operations [Straka 2016]. At the same time, identical technological and process parameters were set within the experimental measurements [Vagaská 2013] due to validity when comparing [Straka 2016] the obtained results within a particular variant when applying a graphite shaped [Straka 2017] tool electrode with a square cross section of the active surface with sharp but also rounded edges. In the following Table 5 shows the basic technological parameters that were applied in the production of experimental samples.

Table 5. Overview of basic technological parameters applied in the preparation of experimental samples

Type designation of the electrical discharge device	Agietron IMPACT 3	
Material tool electrode	graphite	graphite
Kind of applied EDM operation	roughing	finishing
Design of the tool electrode	sharp edges rounded outer edges rounded all edges	
Roughness of eroded surface Ra (µm)	7.1	1.6
Number of operations	1	1
Peak current *I* (A)	10.0	6.0
Pulse on time duration t_{on} (µs)	50.0	30.0
Pulse off time duration t_{off} (µs)	90.0	70.0
Maximum voltage *U* (V)	75.0	80.0
Replacing the electrode	manual	
Dielectric	IonoPlus IME-MH	
Generator [A]	72	

Other technological and process parameters were set with a view to ensuring the stability and efficiency of the electrical discharge process. However, these are technological parameters that have almost no impact on the MRR and TWR size.

4 RESULTS OF EXPERIMENTAL MEASUREMENTS OF RELATIVE WEAR OF TOOL ELECTRODE

In the experiment, the size of the relative wear of the graphite tool electrode (REW) with square area of the active surface with sharp and rounded edges in the EDM roughing and finishing operation was assessed. The input parameters for the evaluation were the total volume of material removed from tool electrode V_e (mm^3) and workpiece V_w (mm^3) during a given EDM operation. Since it would be rather complicated to measure the volume of material removed, an indirect method of measuring its volume through weight loss was chosen. Measurement of the initial weight of the steel sample block was performed using conventional laboratory scales. In the case of measuring the weight of a graphite tool electrode, a given measuring device could not be used. Since graphite is one of the absorbent materials, it was necessary to dry the graphite electrode by heating it prior to initial weighing. To do this, a device using the Loss on Drying (LOD) method was used.

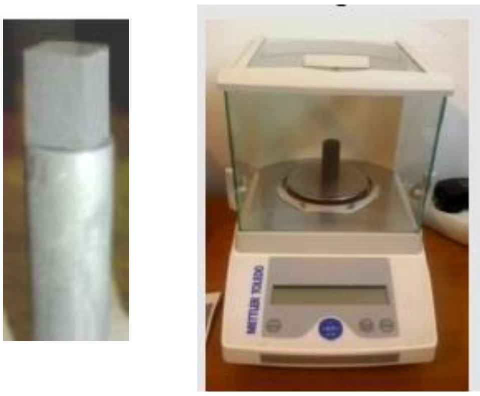


Figure 5. Measurement of graphite tool electrode weight loss by METTLER Toledo PL-IC 303

It is a method which has been weight graphite electrode tool designed in such a state when there is no further decrease its relative humidity. The measurement [Židek 2018] was carried out using a METTLER Toledo PL-IC 303 apparatus as shown in Fig. 5.

Each operation performed on the Agietron IMPACT EDM was followed by weighing both the steel sample block and the individual graphite electrodes. Weighing graphite tool electrodes was again performed in accordance with the LOD method. The results of the experimental measurements are shown in the following Table 6 and 7.

Several facts can be observed based on the results of experimental measurements of the weight loss and the volume of graphite tool electrode material and workpiece steel block in different EDM operations using graphite tool electrodes with square area of active surface with sharp and rounded edges. In the first place, it can be observed that significantly higher values of both MRR and TWR were achieved compared to finishing operations in EDM roughing operations. At the same time, it can be observed that when applying a graphite tool electrode with a square cross section of the active surface with sharp edges, higher values of the TWR parameter were recorded than with the application of the electrode with rounded and also all edges. At the same time, a higher value was seen in both roughing and finishing operations. A similar trend was also observed when assessing the MRR parameter. In the present case, both the roughing and finishing operations have higher MRR values recorded using the sharp-edged graphite tool electrode.

Table 6. Results of experimental measurements of weight loss and volume of graphite tool electrode material

Graphite tool electrode						
Kind of applied EDM operation	roughing			finishing		
Tool electrode shape	sharp edges	rounded outer edges	rounded all edges	sharp edges	rounded outer edges	rounded all edges
Initial weight of tool electrode m_{e1} (g)	33.032	32.751	32.656	33.032	32.751	32.656
Weight of tool electrode after operation m_{e2} (g)	32.824	32.547	32.456	32.836	32.559	32.468
Weight loss of tool electrode m_{eu} (g)	0.208	0.204	0.200	0.196	0.192	0.188
Volume of tool electrode material loss V_e (mm^3)	115.556	113.333	111.111	108.889	106.667	104.444
TWR mm^3.min^{-1}	1.156	1.079	1.010	0.838	0.762	0.696

Table 7. Results of experimental measurements of weight loss and volume of steel block material in experimental sample

Steel block experimental sample						
Kind of applied EDM operation	roughing			finishing		
Tool electrode shape	sharp edges	rounded outer edges	rounded all edges	sharp edges	rounded outer edges	rounded all edges
The initial weight of the steel block sample m_{w1} (g)	2,510.43	2,480.44	2,453.99	2,495.44	2,467.18	2,441.19
Weight of steel block sample after operation m_{w2} (g)	2,495.28	2,467.18	2,441.19	2,480.44	2,453.99	2,428.48
Weight loss of steel block sample m_{wu} (g)	15.15	13.27	12.80	14.99	13.19	12.72
Volume of material loss of steel block sample V_w (mm^3)	1,930.00	1,690.00	1,630.00	1,910.00	1,680.00	1,620.00

MRR mm^3.min^{-1}	19.30	16.10	14.82	14.69	12.00	10.80

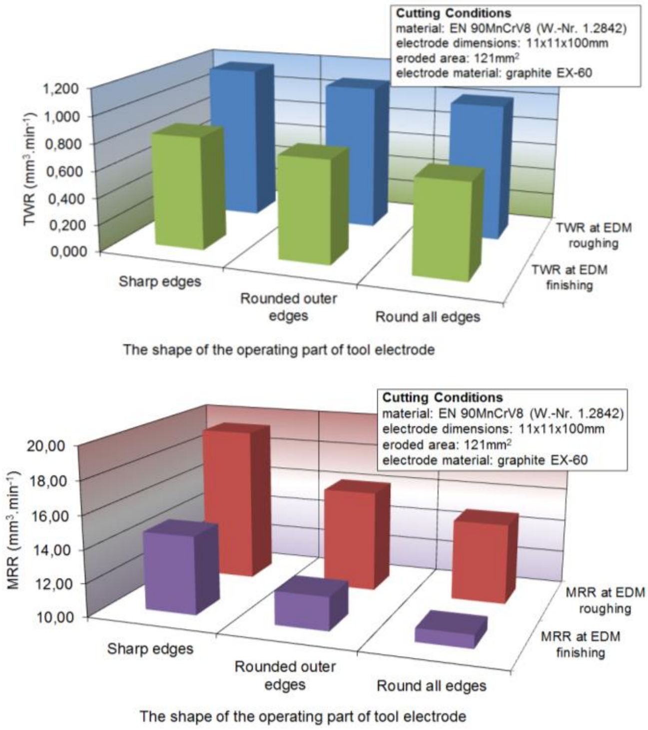


Figure 6. Dependence of TWR and MRR parameters for EDM (roughing / finishing) of tool steel EN 90MnCrV8 with a graphite electrode of square cross section with different active part edges

The graphical dependencies on Fig. 6 depicts the dependence of TWR and MRR parameters for EDM (roughing / finishing) of alloyed tool steel EN 90MnCrV8 with a graphite electrode of square cross section with different active part edges.

The following graphical dependence on Fig. 7 comprehensively describes the relationship between the TWR and MRR parameters for EDM (roughing / finishing) of alloyed tool steel EN 90MnCrV8 with a graphite electrode of square cross section with different embodiments of the active part through the REW parameter.

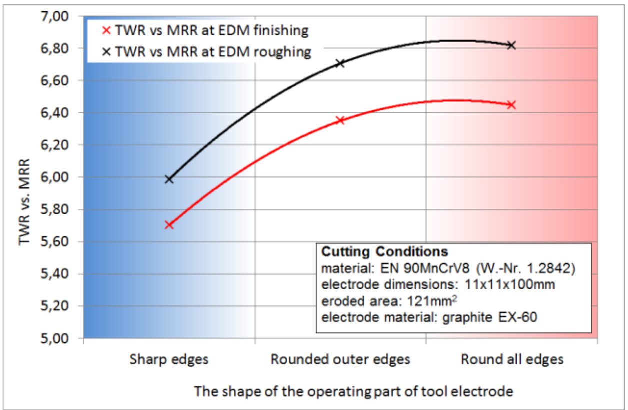


Figure 7. Dependence of the relative wear of the graphite tool electrode of the square cross section with different active part edges for EDM(roughing / finishing) tool steel EN 90MnCrV8

From the aforementioned graphical dependence, an increased degree of relative wear of the REW graphite tool electrodes of square cross section can be observed for EDM (roughing / finishing) of alloyed tool steel EN 90MnCrV8 with rounded edges of their active part. Although graphite tool electrodes with rounded edges exhibit better overall wear out in individual assessment, in a comprehensive assessment that includes the MRR parameter, these results are not as favorable. Therefore, based on these findings, it is possible to recommend the use of graphite tool electrodes with sharp contours of their active part in terms of the REW parameter for EDM tool steels.

5 CONCLUSIONS

One of the important parameters in EDM is the wear of tool electrodes. The overall productivity and cost-effectiveness of the electrical discharge process depend largely on this parameter. However, as the results of experimental research have shown, an individual assessment of the wear rate of the tool electrode during EDM through the TWR parameter can lead to erroneous conclusions. In view of the comprehensive assessment of the overall wear rate in the context of the electrical disharge process productivity, it is therefore preferable to make the assessment in terms of the relative wear of the tool electrode given by the REW parameter. The aim of the paper was therefore to identify the influence of the geometric shape of the graphite tool electrode on the size of the REW parameter during EDM tool steel EN 90MnCrV8. Individual results of experimental measurements showed lower TWR values for EDM of alloyed tool steel with application of graphite tool electrode with rounded contours of its active part. However, in a comprehensive assessment through the REW parameter, these results were not so favorable. Therefore, based on these findings, it is recommended to favor the sharp contours of its active parts in order to achieve an overall favorable electrical discharge process efficiency when machining EN 90MnCrV8 tool steel with a graphite tool electrode.

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