MECHANISM OF MATERIAL REMOVAL DURING DIE-SINKING EDM OF TOOL STEEL EN 90MnCrV8

LUBOSLAV STRAKA, GABRIEL DITTRICH

Department of Automotive and Manufacturing Technologies
Faculty of Manufacturing Technologies of the Technical University of Kosice with a seat in Presov, Presov, Slovakia

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luboslav.straka@tuke.sk

Mechanism of material removal after die-sinking electrical discharges machining, is quite complex. The principle is based on electrical discharge which occurs between workpiece and tool electrode. The electrical discharges always occur when complying the specific conditions, i.e. reaching the desired mutual distance (gap), mutual combination of main technological parameters and sufficient discharge energy. The size of discharge energy has a significant impact on the character of a crater in the workpiece and tool electrode. Desirable is only crater in the workpiece. The crater produced during one electric discharge in tool electrode is generally regarded as the negative site in die-sinking electrical discharges machining. The creation of this crater in the tool electrode has a direct effect on its wear. Paper aimed to describe the mechanism of material removal and its physical regularities of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) in die-sinking electrical discharges machining.

KEYWORDS

Die-sinking Electrical Discharge Machining (Die-sinking EDM), Electrode Wear Ratio (EWR), Main Technological Parameters (MTP), Material Removal Rate (MRR) Tool Wear Rate (TWR).

1 INTRODUCTION

The formation of electrical discharges during die-sinking EDM occurs by points, or by surface in the place of the strongest electrical voltage. The actions of electrical discharges with high current density, the small particles are collected from the workpiece and electrode. In place of electrical discharge, the surface of the material rapidly heats [Straka 2016a], melts [Tothova 2015] and partially evaporates [Tavodova 2014]. In place of electrical discharge is expelled from the place of discharge by the material vapour to form a crater with a specific shape and size. Its size and a shape depends on workpiece and electrode material, discharge energy, properties of dielectric fluid [Banker 2013], but also on setting of main technological parameters (MTP) [Murcinkova 2013].

2 FUNDAMENTALS OF A CRATER CREATION AFTER AN ELECTRICAL DISCHARGE

The resulting product of one electrical discharge in die-sinking EDM is the formation of the crater in the workpiece, and also in the tool electrode [Straka 2016b]. However, the difference between the two craters is that the crater is desirable only in the workpiece [Baron 2016]. The crater produced during one electric discharge in tool electrode [Kiyak 2007] is generally regarded as the negative site in die-sinking EDM. The creation of this crater in the tool electrode has a direct effect on its wear [Straka 2016c]. A series of investigations have been conducted on tool electrode wear in die-sinking EDM. Soni and Chakraverti studied the surface quality, material removal rate, wear ratio, and dimensional accuracy in EDM of alloy steels [Soni 1995]. Singh investigated the effect of machining parameters on tool electrode wear in die-sinking EDM of En-31 tool steel with different electrode materials [Singh 2004]. Also, Luis et al. have carried out a study on tool electrode wear in die-sinking EDM of silicon carbide using the technique of design of experiments (DoE) [Luis 2005]. The crater, formed during one electric discharge in die-sinking EDM on workpiece and tool electrode [Micietova 2013], is generally regarded as the hemispherical segment.

It is generated by high-intensity of electric discharge. They are put into motion positive and negative ions (phase t_1). Their speed accelerates [Krenicky 2011] to the value at which occurs to the formation ionized channel (phase t_2). In this state, it begins between the workpiece and electrode to flow an electric current I (10^6 A.mm^{-2}) which causes the electric discharge (phase t_3). The resulting plasma zone with very high temperatures (reaches up to 10000 °C) consequently causes melting [Dubjak 2016] and evaporating [Straka 2016d] of individual particles of material (phase t_4). A temperature drop due to the drop [Corny 2016] in current I (phase t_5) causes the implosion of the bubbles, and thus the gas pressure drop, resulting in disruption of the material (cavitation) and formation of the crater. In this phase the discharge current I and the voltage U decreases to zero. The shape of formed crater, and its size, depends on MTP, properties of dielectric fluid, and type materials of workpiece [Panda 2016] and tool electrode. In phase t_6 is a state similar to phase t_1, and thus before discharge. Mechanism of material removal on workpiece and tool electrode in particular phases of discharge (t_1 to t_6) during die-sinking EDM shows Fig. 1.

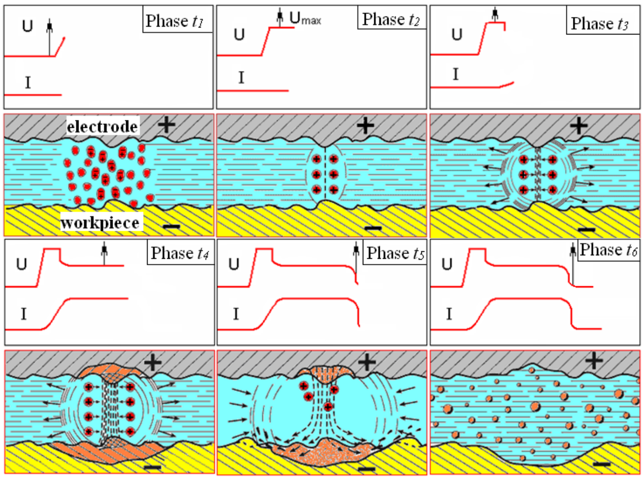
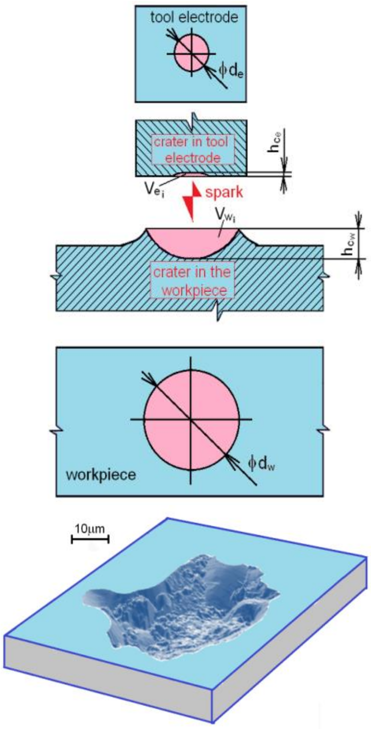


Figure 1: Mechanism of material removal on workpiece and tool electrode in particular phases of discharge (t_1 to t_6) during die-sinking EDM

The shape of crater in the phase t_5 is defined mainly by its diameter and depth (Fig.2). Both of these characteristics are directly dependent on the MTP and properties of the dielectric fluid [Straka 2017]. The formation of crater on the tool electrode [Botko 2019] is generally regarded as the undesirable phenomenon [Han 2016], because it primarily contributes to the wear. In practice, it is therefore necessary to achieve that Material removal rate (MRR) was much bigger than the size of tool wear rate (TWR). It is necessary that the ratio MRR to TWR reached with die-sinking EDM as large as value "1". Value ratio MRR/TWR<1 means the larger volume of the material removal from the workpiece as the tool electrode, which is undesirable.



Vm(e)$_i$ – material removal volume of workpiece (tool electrode), $h_{Cw(e)}$ – crater depth in the workpiece (tool electrode), $d_{w(e)}$ – crater diameter in workpiece (tool electrode)

Figure 2: Volume and shape of crater after one discharge cycle in die-sinking EDM

The volume of material removal from workpiece and tool electrode during one of the discharge cycle of the die-sinking EDM can be determined according to the formula (1):

$$V_{total} = k \cdot W_{total}, \tag{1}$$

where V_{total} denotes total material removal volume of workpiece V_{mi} and tool electrode V_{ei} during one of the discharge cycle of the die-sinking EDM (mm³), k is proportionality factor, and W_{total} is total energy of electrical discharge (J).

The total volume material removal from the workpiece and the tool electrode depends mainly on the total energy of electric discharges which is determined by the MTP setting.

Accordingly the amount of material taken during a series of discharge cycles is proportional to the discharge energy that can be calculated according to the formula (2):

$$W_{total} = \int_0^{t_{on}+t_{off}} U(t) \cdot I(t) dt, \tag{2}$$

where W_{total} denotes total energy of electrical discharge (J), $U(t)$ is electric voltage of discharge between workpiece and tool electrode in time $t(V)$, $I(t)$ is peak current in time $t(A)$, t_{on}(µs) is pulse on-time duration, and t_{off}(µs) is pulse off-time duration.

By deriving integral Eq. 2 can be estimated energy electrical discharge for a particular discharge cycle according to the formula (3):

$$W_{cycle} = U_{cycle} \cdot I_{cycle} \cdot (t_{on} + t_{off}) \tag{3}$$

where I_{cycle} denotes peak current of the particular discharge cycle (A), U_{cycle} is voltage of discharge of the particular discharge cycle (V), t_{on} is pulse on-time duration of the particular discharge cycle (µs), and t_{off} is pulse off-time duration of the particular discharge cycle (µs).

The complex parameter that characterizes the amount of material removal from the workpiece per unit time during die-sinking EDM is MRR. In general, it is defined amount of material removal (µm³, mm³) per time unit (min, s). Mathematically it can be expressed by formula (4):

$$MRR = \frac{Vm_{total}}{t} \left(\mathrm{mm}^3 \cdot \mathrm{min}^{-1}\right) \tag{4}$$

where Vm_{total} denotes total volume of material removal from the workpiece during die-sinking EDM (mm³), and t is total machining time (min).

Parameter TWR defines the total volume of material removal (µm³, mm³) of tool electrode during die-sinking EDM per time unit (min, s). Mathematically it can be expressed by formula (5):

$$TWR = \frac{Ve_{total}}{t} \left(\mathrm{mm}^3 \cdot \mathrm{min}^{-1}\right) \tag{5}$$

where Ve_{total} denotes volume of material removal from tool electrode during EDM (mm³), and t is total machining time (min).

Parameters MRR and TWR are in addition to the MTP also affected by mechanical [Hasova 2016], physical and chemical properties [Panda 2014] of the material of the workpiece and the tool electrode [Malega 2017]. For example, steel has high strength, high melting point [Rimar 2016], and low thermal and electrical conductivity [Świercz 2017] which result in a higher MRR. On the contrary, the Cu has good thermal and electrical conductivity, resulting in a low TWR.

Another complex parameter that defines ratio between of material removal from the tool electrode and the workpiece is EWR (Electrode Wear Ratio). Mathematically it is defined as the ratio of the amount of material (µm³, mm³), taken from the tool electrode Ve_{total} and workpiece Vm_{total} in accordance with the formula (6):

$$EWR = \frac{Ve_{total}}{Vm_{total}} \cdot 100\ (\%) \tag{6}$$

where Vm_{total} denotes total volume of material removal of workpiece during die-sinking EDM (mm³), and Ve_{total} is total volume of material removal of tool electrode during die-sinking EDM (mm³).

3 CONDITIONS OF EXPERIMENTS

The experiments were carried out on samples of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with a tensile strength *Rm*=770MPa, hardness of basic material about 62HRC. It is a medium-alloyed manganese-chromium-vanadium tool steel containing alloying elements 0.78-0.85% of C, 1.85-2.15% of Mn and 0.25% of Cr. Table 1 shows the basic mechanical, physical and chemical properties of medium-alloyed manganese-chromium-vanadium tool steel EN 90MnCrV8 (W.-Nr. 1.2842). In the experiment was used Cu a shaped tool electrode of circular cross section with a 10mm diameter and a length 50mm. Tool electrode material was copper with a purity 99.9% and designation EN CW004A (DIN E Cu 58-Cu ETP, W.-Nr. 2.0060).

Table 1: The main chemical, mechanical and physical properties of steel EN 90MnCrV8 (W.-Nr. 1.2842)

Steel designation	Chemical composition (%)							
	C	Mn	Si	Cr	Ni	V	Pmax	Smax
EN 90MnCrV8 (W.-Nr. 1.2842)	0.75- 0.85	1.85-2.15	0.15-0.35	max. 0.25	max. 0.35	0.1-0.2	0.03	0.035
	Mechanical and physical properties							
	Tensile strength *Rm* (MPa)	Yield strength $Rp_{0,2}$(MPa)	Hardness in the annealed condition (HB_{max})	Hardness In treated condition (HRC_{min})	Specific heat capacity (J/kg.K)	Thermal conductivity (W/m.K) at 20°C	Specific electric resist. (Ω.mm²/m)	Electrical conductivity (Siemens.m/mm²)
	770.0	550.0	220.0	62.0	460.0	30.0	0.35	2.85

Table 2 lists the basic mechanical and physical properties of material tool electrode EN CW004A.

Table 2: The basic mechanical and physical properties of material tool electrode EN CW004A

Material designation	Melting point (°C)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Electrical conductivity ($S.m.mm^{-2}$)	Tensile strength (MPa)	Modulus of elast. (GPa)
EN CW004A	1083.0	390.0	58.0	220.0	130.0

In the experiment was used electroerosive equipment PENTA 433 GS CNC by company Penta Trading Ltd. This is a CNC device [Michalik 2016] which is capable of operating in autonomous operation. Table 4 lists the basic technical parameters of electroerosive equipment PENTA 433 GS CNC.

Basic technical parameters of electroerosive equipment PENTA 433 GS CNC

max. Axis Travel
X 0.4×*Y* 0.3×*Z* 0.3m

max. Work Table Size
X 0.7×*Y* 0.35m

dielectric fluid (capacity) oil (300l)

Machining current
max. 300A

Workpiece Weight
max. 0.7t

Electrode Weight
max. 100kg

Figure 3: Die-Sinker EDM PENTA 433 GS CNC of Co. Penta Trading Ltd.

Parameter EWR, which comprehensively defines the quantity of material [Mathew 2014] taken from the tool electrode [Monka 2016] and the workpiece [Straka 2013], is substantially dependent on the setting of the MTP. Table 3 provides an overview of the MTP in die-sinking EDM of tool EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A including limit settings used in the experiment.

Table 2: The range of setting the MTP in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A and their assumed influence on EWR

Setting range of the MTP	Influence of MTP on EWR
Peak current "*I*" 5.0-35.0 A	With increasing value of *I* rapidly increase EWR.
Pulse on-time duration "t_{on}" 20.0-130.0 μs	With increasing value of t_{on} it occurs to the significant decrease of EWR.
Pulse off-time duration "t_{off}" 10.0-90.0 μs	With increasing value of t_{off} it occurs to the slight decrease of EWR.
Voltage of discharge "*U*" 80.0-95.0 V	With increasing value of *U* it occurs to the gradual increase EWR.
Gap "auto"	Increasing the gap value leads to a decrease in EWR.
Flushing "*upper rinse*"	With increasing of dielectric pressure to decrease of EWR.
Dielectric fluid "*oil*"	--

From this overview is clear that the greatest expected effect on EWR of mentioned process parameters has peak current *I* and pulse on-time duration t_{on}. On the contrary, the least expected effect on EWR has pulse off-time t_{off} and voltage of discharge *U*.

4 EXPERIMENTAL EXECUTION AND RESULTS

Based on the above theoretical analysis of the expected impact of the MTP in die-sinking EDM tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP tool electrode EN CW004A on EWR was considered in experiment with the impact of peak current, pulse on-time duration, pulse off-time duration and voltage of discharge. Effects of the peak current *I* in the range of 5 to 35A on EWR are shown on Fig. 4.

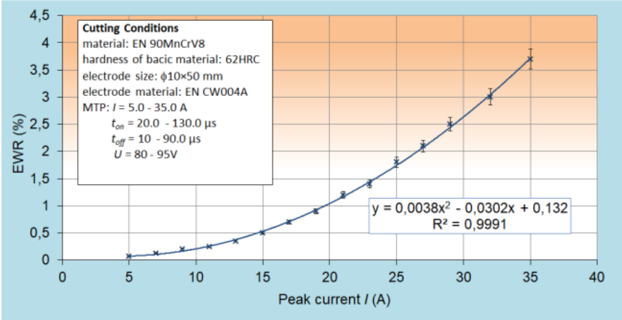


Figure 4: Influence of peak current *I* in the range of 5 to 35A on EWR in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A

From the Fig. 4 can be in detail observed that with increasing value of peak current I in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A is substantially increased the size of EWR. At the lowest value of peak current *I*=5A was achieved the lowest value of EWR = 0.07%. Conversely, at the highest value of peak current *I*=35A was also achieved the highest value of EWR = 3.70%. Effects of the pulse on-time duration t_{on} in the range of 20 to 130μs on EWR are shown on Fig. 5.

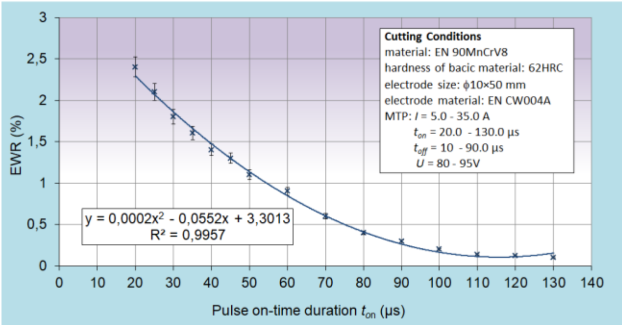


Figure 5: Influence of pulse on-time duration ton in the range of 20 to 130μs on EWR in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A

From the Fig. 5 can be in detail observed that with increasing value of pulse on-time duration ton in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A it occurs to the significant decrease of EWR. At the lowest value of pulse on-time duration t_{on} = 20μs was achieved the highest value of EWR = 2.40%. Conversely, at the highest value of t_{on} = 130μs was achieved the lowest value of EWR = 0.10%. Effects of the pulse off-time duration t_{off} in the range of 10 to 90μs on EWR are shown on Fig. 6.

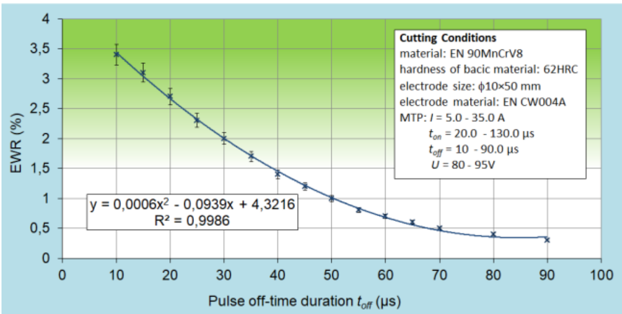


Figure 6: Influence of pulse off-time duration toff in the range of 10 to 90μs on EWR in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A

From Fig. 6 can be observed in detail that with increasing value of pulse off-time duration toff in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A it occurs to the slight decrease of EWR. At the lowest value of pulse off-time duration t_{off} = 10µs was achieved the highest value of EWR = 3.40%. Conversely, with the highest value of t_{off} = 90µs was achieved the lowest value of EWR = 0.30%. Effects of the voltage of discharge *U* in the range of 80 to 95V on EWR are shown on Fig. 7.

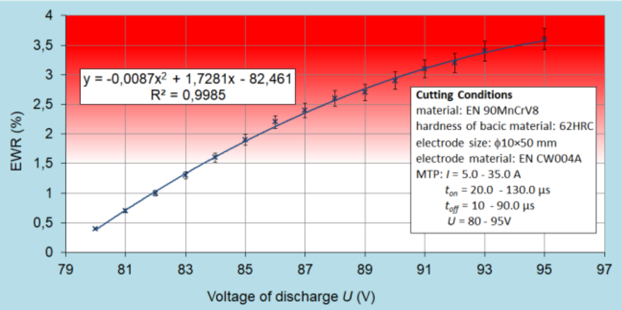


Figure 7: Influence of voltage of discharge U in the range of 80 to 95V on EWR in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A

From the Fig. 7 can be observed that with increasing value of voltage of discharge *U* in die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A it occurs to the gradual increase of EWR. At the lowest value of voltage of discharge *U* = 80V was achieved the lowest value of EWR = 0.40%. Conversely, at the highest value of *U* = 95V was achieved the highest value of EWR = 3.60%.

Recommendation for machining tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A by die-sinking EDM, in terms of choice the MTP [Stephen 2011], i.e. peak current *I*, pulse on-time duration ton, pulse off-time duration t_{off}, and voltage of discharge *U*, is their optimisation [Tamang 2017] in view of the minimization of the parameter EWR [Salcedo 2017]. For achieving the minimum value EWR is required that the combination the MTP at which the parameters peak current *I* and voltage of discharge *U* will preferably acquire the lowest values [Kumar 2017]. Conversely, in choice of pulse on-time duration ton and pulse off-time duration t_{off} it is necessary to choose the highest value. Of course, choosing of the MTP must necessarily to respect the stability [Straka 2014] and performance [Chen 2017] electroerosive process.

5 CONCLUSIONS

The Contribution aimed to describe the mechanism of material removal in the die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A. One of the usually used parameters that quite accurately identifies mechanism of material removal in the die-sinking EDM is TWR. This parameter, however, describes only regularities concerning the wear of the tool electrode. EWR is more complex parameters, which in addition to the tool electrode wear size, describes the size of the MRR from workpiece. The particular value of EWR is substantially dependent on the type of electrode and workpiece material, but also on the setting of the MTP. Unsuitable mechanical, physical and chemical properties of materials [Zidek 2018], used for manufacturing tool electrodes, may adversely affect the value of EWR. The aim of the performed experiments was also to define the individual specifics with a view to minimizing the EWR. On the basis of the analysis were selected the MTP, which substantially affects the extent of the crater (shape and dimension) in the workpiece, but also in the tool electrode, and thus the parameter EWR.

When analysing, by relying on experimental results of measurements, was already identified a number of important facts:

- may be stated that in the die-sinking EDM of tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A on the EWR mainly affects peak current *I* and pulse on-time t_{on};
- to the size of the EWR has a much smaller effect the setting values of pulse off-time t_{off} and voltage of discharge *U*;
- for achieving the minimum value EWR in the die-sinking EDM is necessary optimization of the MTP;
- recommendations in the selection of the MTP in die-sinking EDM the tool steel EN 90MnCrV8 (W.-Nr. 1.2842) with Cu-ETP electrode EN CW004A in terms of minimizing the value is a choice of low values of peak current *I* and voltage of discharge *U*. On the contrary, to minimize the parameter EWR is required the selection of higher levels of pulse on-time duration ton and pulse off-time t_{off}. In the choice of mutual combination MTP, however, it should be taken into account the performance, stability and efficiency of the die-sinking EDM process.

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CONTACTS

assoc. prof. Ing. Luboslav Straka, PhD.
Ing. Gabriel Dittrich
Department of Automotive and Manufacturing Technologies
Faculty of Manufacturing Technologies
Technical University of Košice with a seat in Presov,
Sturova 31, 080 01 Presov, Slovakia
Tel.:+421 55 602 6365
e-mail: luboslav.straka@tuke.sk, gabriel.dittrich@tuke.sk