

*Article*

# Experimental investigation of influence electrical discharge energy on the surface layer properties after EDM

Rafał Świercz<sup>1,\*</sup> , Radovan Holubek<sup>2</sup> <sup>1</sup> Warsaw University of Technology, Institute of Manufacturing Technology, Warsaw, 00-661, Poland;<sup>2</sup> Slovak University of Technology in Bratislava, Materials Sciences and Technology in Trnava, Institute of Production Technologies, 91701 Trnava, Slovakia, [radovan.holubek@stuba.sk](mailto:radovan.holubek@stuba.sk);\* Correspondence: dr hab. inż. Rafał Świercz; [rsw@meil.pw.edu.pl](mailto:rsw@meil.pw.edu.pl)

Received: 01.04.2020; Accepted: 20.05.2020

**Abstract:** The modern industry looks for new technologies that lead to improving the durability of parts from difficult-to-cut materials. One of the main fields of study on manufacturing difficult-to-cut materials is using electrical discharge machining (EDM). In this work, the experimental investigation of the influence of discharge current and pulse time, which defines the discharge energy, on surface roughness and average white layer thickness, was carried out. The surface layers properties after machining have a key role in the durability of manufacturing parts. Conducted research indicates that an increase in current and pulse time leads to growing the diameter and power of the discharge channel. It's causing the generation of the roughness of greater height and distance between the individual vertices. The plasma stream generated as a result of electric discharges causes the melting and evaporation of the material locally, while micro streams of liquid metal "thrown" to the gap from craters re-solidify on the surface of the material. Experimental studies and their analysis indicate that the main factors influencing the surface topography and average thickness of the white layer after EDM is the discharge energy.

**Keywords:** EDM; discharge energy; surface layers, electrical discharge machining

## Introduction

Growing requirements of the modern industry caused looking for new technologies that lead to improving the durability of manufacturing parts. In the case of machining elements with complex shapes of difficult-to-cut materials, the researches are focused on non-conventional technology like electrical discharge machining (EDM). The complexity of physical phenomena caused by electric discharges, their stochastic nature causes difficulties in identifying the impact of parameters and processing conditions on the material removal process. Therefore, new solutions in EDM are being sought that will ensure obtaining the desired features of surface topography and material microstructure. The research on the electrical discharge machining concerns a wide research area including, the analysis of the influence of machining parameters on the surface roughness [1,2], melted layer thickness and material removal efficiency [3÷6]. As a result of the impact of electrical discharges, the properties of the surface layer are changing. Surface topography is a result of superimposing individual electrical discharge traces. Research conducted by Klinka [7], Macedo [8] indicates that the shape of the crater resulting from a single electrical discharge depends on the electrode polarization used. When using positive polarization, the electrons emitted from the cathode (workpiece) reach the anode surface faster, causing its erosion. The ions emitted from the anode moving to the cathode carry more energy, causing more intense local evaporation of the material. Craters formed on the surface of the cathode using straight polarization (cathode (-), anode (+)) are characterized by much greater depth, while the craters formed on the anode have a flat, symmetrical shape. Torres [9] noted that also the material of the working electrode in combination with the processing parameters and the polarization used significantly affects the size of the generated craters.

Electrical discharges lead to local melting and evaporation of material. The local high temperature from plasma channel cause changes in the microstructure of materials. Research carried out so far [10,11] has indicated that in case of manufacturing tool steel in the surface layers three characteristic layers can be observed: white layer, heat affect zone and tempered. Furthermore, in the white layer typical defects of microstructure such as micro-cracks can be observed. Micro cracks are an undesirable effect, resulting in reduced fatigue resistance and corrosion resistance.

Reducing of the unfavorable features of the surface layer of materials after EDM is carried out in different ways. In many cases, additional finishing treatments are applied, the purpose of which is to change the properties of the surface layer or to remove it completely. These include: electro-erosion alloying [12], electrochemical treatment [13,14], laser surface treatment [15÷17], coating [18÷21] as well as mechanical and hybrid treatments. [22]

The main goal of conducted experimental research was to determine the impact of parameters defining the energy of discharge on the features of the surface roughness and the average thickness of the white layer.

## Materials and Methods

The purpose of the experimental research was to determine the influence of electrical discharge energy on the surface layers properties tool steel 1.2713. This type of material was chosen because of its wide range of applications on die matrices, matrices inserts, hydraulic and mechanical press dies, which are primarily manufactured using EDM. Tool steel 1.2713 is characterized by high dimensional stability and cracks resistance with dynamically changing pressures and rapid heating and cooling during operation. Experimental investigations were carried out on the EDM machine of Charmilles Form 2LC ZNC. The machined samples steel 1.2713 hardened up to 52 HRC has dimensions of 12 x 12 x 3 mm, the electrode was copper and commercial EDM fluid 108 MP-SE 60 was used as the dielectric. Figure 1 shows the schematic diagram of the setup. Investigation of influence discharge energy on surface integrity of tool steel 1.2713 after EDM includes analyses of surface roughness  $Ra$  and average thickness of the white layer.

The surface roughness was measurements on the Form Talysurf Series 2 scanning profilometer. Metallographic surface structure studies were performed using a NIKON Eclipse LV 150 optical microscope coupled to a NIS-Elements BR 3.0 image analyzer. Specimens were included in the resin; next, they were machined with grinding and polishing. Micro-etching was performed with nital 5% to reveal the microstructure of the material. The thickness of the white layer in 10 sections was measured for each sample and the average value was calculated.

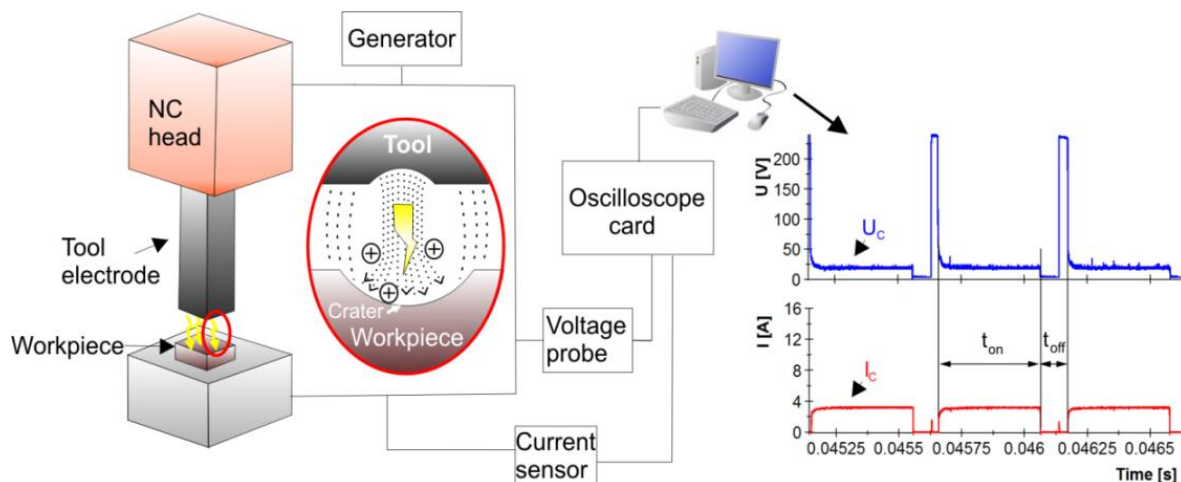


Fig. 1. Schematic illustration of experimental setup

The main goal of the conducted research was to find the relationship between discharge energy and surface layers properties. For constant voltage  $U_c$ , discharge current  $I_c$  and pulse time  $t_{on}$  define the discharge energy, according to Equation (1):

$$E = \int_0^{t_{on}} U_c(t) \cdot I_c(t) dt \quad (\text{mJ}), \quad (1)$$

The discharge voltage  $U_c$  has the main influence on the ionization of the channel through which the current flows. For higher discharge voltage, it is possible to set a larger gap between electrodes and thereby facilitate its rinsing and draining of the dielectric products. Discharge current  $I_c$  directly affects the amount of eroded material. Maximum current values are used for roughing to ensure proper process performance. Depending on the material of the working electrode, the maximum current density should not exceed 15 A/cm<sup>2</sup> for copper electrodes and 25 A/cm<sup>2</sup> for graphite electrodes. Pulse duration  $t_{on}$  associated with the current determines the amount of thermal energy delivered to the workpiece. With the increase in pulse duration and current, both the diameter and the depth of the craters increase. Time interval  $t_{off}$  is responsible for stabilizing conditions in the gap (remove erosion products, deionization of the discharge channel).

Considering the above relationship, a literature review, parameters for EDM roughing, semi-finishing, and finishing machining was established. Table I presents the conditions of the experiment.

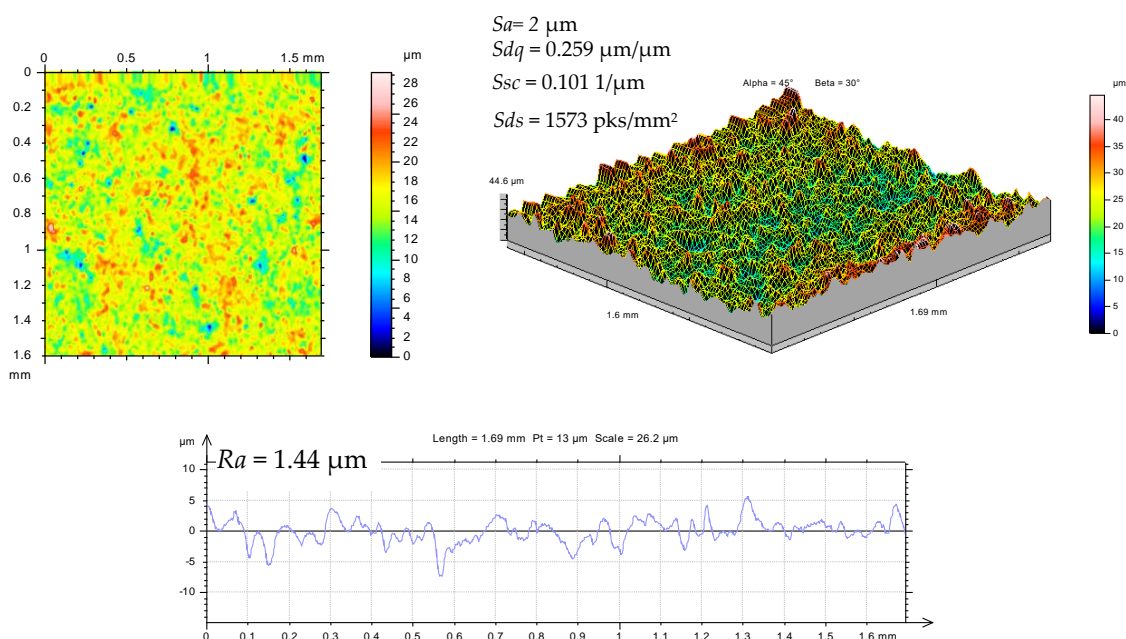
**Table I.** Electrical discharge machining (EDM) conditions.

Electrode	Copper cross-section 12 × 12 mm
Material	1.2171 tool steel
Polarization of electrode	Positive polarity
Discharge current $I_c$ (A)	3, 8.5, 14.5
Open voltage $U_0$ (V)	225 V
Discharge voltage (V)	25
Pulse time $t_{on}$ ( $\mu$ s)	13, 200, 400
Time interval $t_{off}$ ( $\mu$ s)	0.3 $t_{on}$
Manufacturing depth (mm)	0.2

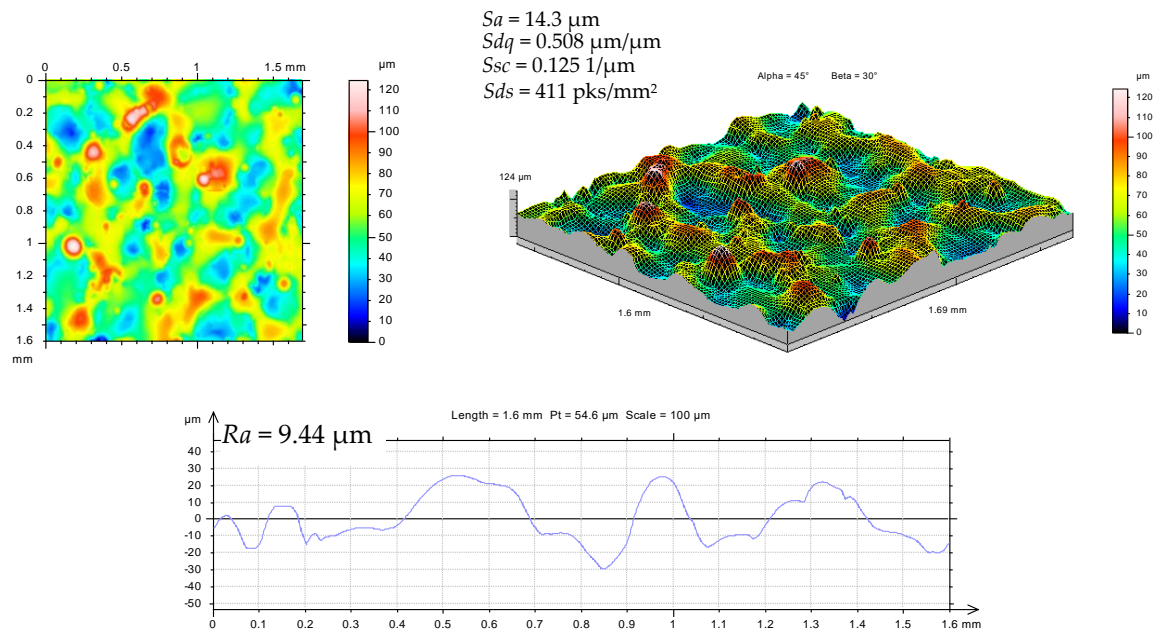
## Results and Discussion

### Analysis of surface layers properties after EDM

Research carried out so far indicate that in the EDM material is mainly removed as a result of the heat stream inside the plasma channel created as a result of electrical discharges between two electrodes. The surface topography is created by overlapping traces of individual electrical discharges. The properties of surface topography have a strong influence on fatigue strength and other tribological properties [23,24]. Depending on the pulse energy, there are significant differences in its properties. For samples manufactured with the smallest (Fig. 2) and highest (Fig. 3) values of discharge energy, additional measurements of surface topography were conducted. In analyzed cases to describe influence discharge energy on the shape of the roughness, the following parameters were chosen: density of the top ( $S_{ds}$ ), and the quadratic slope of the surface ( $S_{dq}$ ) and the arithmetic mean curvature to the top ( $S_{sc}$ ). For sample manufacturing with discharge energy  $E = 1,2$  mJ the top has a sharp edge ( $S_{dq} = 0.259 \mu\text{m}/\mu\text{m}$ ), with a small rounding radius of the vertices ( $S_{sc} = 0.101 1/\mu\text{m}$ ), which leads to an increase in the coefficient of friction. The large value of density of the top ( $S_{ds} = 1573$  pks/mm<sup>2</sup>), which indirectly defines the distance between adjacent summits, indicates that craters are depth and diameter of the crater is small. Comparative analysis samples indicate the values of the  $S_{sc}$ ,  $S_{dq}$ , and  $S_{ds}$  parameters depend mainly on the discharge energy. The highest discharge energy leads to the crater having the largest diameter and height and rounded vertices.

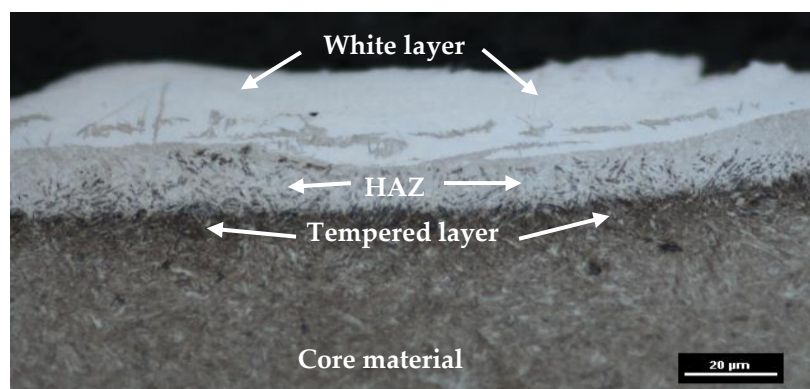


**Fig. 2.** The surface topography of the tool steel 1.2173 after EDM with finishing parameters  $I_c = 3$  A,  $t_{on} = 13 \mu\text{s}$ ,  $U = 25$  V,  $E = 1.2$  mJ



**Fig. 3.** The surface topography of the tool steel 1.2173 after EDM with roughing parameters  $I_c = 14.5$  A,  $t_{on} = 400$   $\mu$ s,  $U = 25$  V,  $E = 171.6$  mJ

EDM is characterized by the impact of local thermal processes, resulting in a change in the surface layer. Based on microscopic studies, three characteristic sublayers have been identified (Fig. 4): external melting (white layer), heat affected zone (HAZ – which are visible in the form of a light structure directly under the white layer) and tempered layer. The white layer (WL) is formed by melting and rapidly solidifying the thin metal layer on the surface of the crater. The white layer in its structure may have a chemical decomposition both the core material and the working electrode. This is due to the process of electric discharge, which results in the melting and evaporation of both the workpiece and the working electrode. Under the white layer is a heat affected zone, with increased hardness relative to the core material. This layer is built of martensite and residual austenite. The resulting structure formed by the diffusion of carbon from the pyrolysis of the oil and rapid heat dissipation. Under the HAZ, there is a tempered zone. The tempered layer is formed by the influence of discharge energy which causing heating of this material zone and then it's cooling by conduction the heat to the core material. The occurrence of individual layers was observed for all samples.



**Fig. 4.** Metallographic structure after EDM process

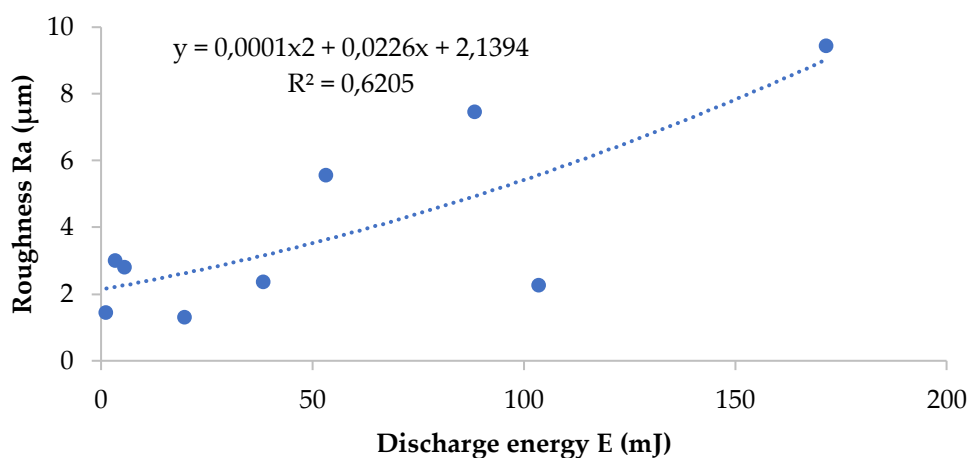
### ***Analyses of discharge energy on the average of roughness $Ra$ and thickness of white layer***

In this research, an analysis of the influence discharge energy on surface layer properties was conducted. A series of experimental tests was performed for roughing, semifinishing, and finishing machining. The results of the experiments are presented in Table II. Roughness  $Ra$  was in the range of  $1.44$   $\mu$ m to  $9.44$   $\mu$ m and average thickness of the white layer from  $3.95$   $\mu$ m to  $28$   $\mu$ m. The obtained values of roughness  $Ra$  and average thickness of the white layer corresponded to finishing and roughing machining.

**Table II.** Matrix of the experimental set-up

Exp. no.	EDM Parameters			Observed values	
	Discharge current	Pulse time	Discharge Energy	Surface roughness	Average thickness of the White Layer
	$I$ (A)	$t_{on}$ ( $\mu$ s)	$E$ (mJ)	$Ra$ ( $\mu$ m)	( $\mu$ m)
	3	13	1.2	1.44	3.95
	8.5	13	3.4	3	7
	14.5	13	5.6	2.8	6.8
	3	200	19.8	1.31	10
	8.5	200	53.3	5.55	19.265
	14.5	200	88.4	7.46	21
	3	400	38.4	2.35	10.85
	8.5	400	103.6	2.26	14.1
	14.5	400	171.6	9.44	28

Analyses of influence discharge energy on roughness parameters  $Ra$  shows (Fig. 5) that the roughness are mainly dependent on the value of discharge energy. With the increased discharge energy roughness parameter  $Ra$  is increasing. However, these relations are not directly proportional. At low currents (about 3 A) increasing the pulse time (and therefore energy) does not result in a significant increase in the  $Ra$  parameter. This effect indicates significant changes in the heat flux density inside the plasma channel, depending on the value of current and pulse time. With the same current and with the increasing the pulse time  $t_{on}$ , only the diameter of craters changed but the value of  $Ra$  not changed. With the increasing pulse duration and current, the diameter and the depth of the craters increase. The obtained results confirm the Gaussian distribution of the heat stream inside the plasma channel.



**Fig. 5.** Influence of energy on surface roughness

The primary elements of the material microstructure which have a strong influence on properties of surface integrity are the thickness of the white layer. The relationship between discharge energy and thickness of the white layer is presented in figure 6.

The white layer is characterized by high variations in thickness (from 3  $\mu$ m to 28  $\mu$ m). The average thickness of the white layer depends mainly on the amount of thermal energy supplied to the workpiece. Increasing the amplitude of the current at the lowest pulse time does not significantly change the WL thickness. With the growth of discharge energy  $E$ , the amount of melted and evaporated material increases. The plasma stream generated as a result of electric discharges causes the melting and evaporation of the material locally, while micro streams of liquid metal "thrown" from craters solidify on the surface of the material. The increase in power flux density increases the amount of material removal in a single pulse while leading to an increase in the volume of material ejected from the crater. As a consequence, more molten material, which is not removed from the crater, re-solidifies on the surface.

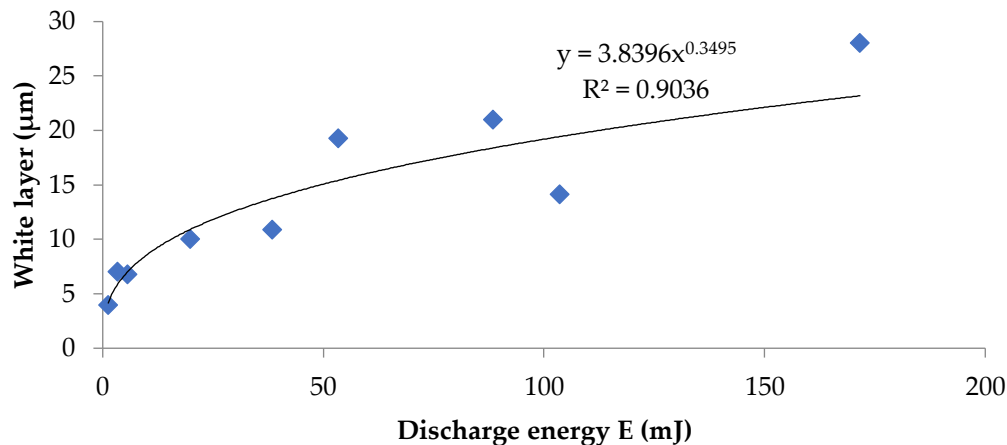


Fig. 6. Influence of energy on thickness of the white layer

## Conclusions

Experimental studies and their analysis show that the main factors influencing the surface topography after EDM is the discharge energy. For short pulse times and the smallest current values, the surface topography is characterized by a high density of vertices. The increase in current and pulse time increases the diameter and power of the discharge channel. It's leading to the generation of the roughness of greater height and distance between the individual vertices.

The theoretical and experimental analysis of the impact of the investigated EDM parameters on the crater formation process indicates that on the surface of craters re-solidified melted materials occur. The analyses of the metallographic structure show three characteristic layers: white layer, heat affected zone (HAZ), and tempered layer. The thickness of the white layer depends on the discharge energy and increases with increasing discharge energy. The absence of gas bubbles observed in the remelted layer indicates that the heat flux acting on this layer did not cause it to boil. The layer recrystallized from the liquid phase. The significant volume of melted material observed in the macroscopic images indicates that a large part of the liquid metal is "thrown" into the gap and re-solidifies on it again.

The conducted research showed that considering only the value of the discharge energy in relation to the surface topography and the average white layer thickness is not enough. Furthermore, it is important to determine the density of the heat flux and its shape inside the plasma channel, which determines the amount and geometry of the removed material in a single pulse.

**Author Contributions:** conceptualization R.Ś. and R.H.; methodology R.Ś. and R.H.; validation R.Ś. and R.H.; formal analysis R.Ś.; investigation R.Ś.; writing—original draft preparation R.Ś.; writing—review and editing R.Ś and R.H.; supervision R.Ś.

**Funding:** Please add: This research received no external funding

**Conflicts of Interest:** The authors declare no conflict of interest.

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