TECHNICAL TRANSACTIONS 12/2017
CZASOPISMO TECHNICZNE 12/2017
MECHANICAL ENGINEERING
DOI: 10.4467/2353737XCT.17.222.7765

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Austenitic steel surface integrity after EDM in different dielectric liquids

Stan powierzchni stali austenitycznej po obróbce EDM w różnych ciekłych dielektrykach

Abstract

Electrodischarge machining (EDM) can be used as an alternative machining method compared to conventional ones, especially while very good surface integrity and high machining accuracy during machining of difficult-to-cut materials is needed. In EDM, the dielectric liquid has a crucial influence on the technological material surface integrity since it ensures the occurrence of controlled electrical discharges between the tool and the workpiece, cooling and solidification of gaseous EDM debris, removing erosion products and also dispersing heat generated during the process. In the paper, the influence of a carbon-based and a water-based dielectric liquid on the selected structural and morphological characteristics of 304 stainless steel after EDM sinking was investigated. The surface roughness, micro hardness and quality as well as the chemical changes after the corrosion test of machined surfaces were analysed.

Keywords: electrodischarge machining, dielectric, surface layer, austenitic steel

Streszczenie

Obróbka elektroerozyjna (EDM) stanowi alternatywę dla konwencjonalnych metod obróbkowych, szczególnie przy kształtowaniu materiałów trudnoskrawalnych, gdy konieczne jest otrzymanie powierzchni o bardzo dobrej jakości. W EDM ciekły dielektryk ma kluczowy wpływ na właściwości technologicznej warstwy wierzchniej materiału obrabianego, umożliwiając zachodzenie kontrolowanych wyładowań elektrycznych pomiędzy elektrodą roboczą a przedmiotem obrabianym, schładzanie i usuwanie produktów powstałych w wyniku obróbki oraz odprowadzanie wygenerowanego w trakcie procesu ciepła. W artykule przedstawiono wpływ dielektryka węglowodorowego i wodnego na wybrane cechy strukturalne i morfologiczne stali nierdzewnej 304 po procesie drążenia elektroerozyjnego. Analizie poddano chropowatość powierzchni, mikrotwardość oraz zmiany składu chemicznego obrabianych powierzchni po przeprowadzonej próbie korozyjnej.

Słowa kluczowe: obróbka elektroerozyjna, dielektryk, warstwa wierzchnia, stal austenityczna

1. Introduction

Electrodischarge machining is one of the most commonly used non-conventional machining methods in all branches of the industry [15]. Materials with electrical conductivity above 10^{-2} S/cm can be machined by the EDM process [7], irrespective of the machined material chemical structure and mechanical properties (such as hardness). EDM is also characterised by very high machining accuracy and achievable surface roughness [1, 11]. Another advantage of using the EDM machining method is the possibility of getting complicated shapes of elements, also with thin walls, 3-D macro, micro and nano features, which would be impossible to obtain with conventional machining methods [11, 15].

In EDM-sinking, material removal takes place as a result of the occurrence of a plasma channel (erosion effect) between the tool electrode and the workpiece surface, separated by dielectric liquid [2, 12]. In each pulse, the machining material is melted and evaporated during each discharge occurring at a single location [19]. The debris in the molten phase is cooled, resolidified and then evacuated by dielectric liquid from the machining gap. The thermal character of the material removal mechanism causes the occurrence of the heat-affected zone in the workpiece surface layer [2]. The heat-affected zone consists of an upper layer of the recast and is characterised by a solidified material, the occurrence of microcracks, high porosity, increased dimensions of grains arising from other alloys, which come either from the tool electrode or the dielectric liquid [5]. Recently, many experiments [9, 13, 14, 16] have been conducted to show how complicated the mechanism of material removal during single electrodischarge machining is. However, it is still challenging to observe the complex material removal in real EDM conditions, where a huge number of discharges occur.

The character of the EDM-machined surface integrity changes is connected with machining conditions, such as pulse time, current intensity, tool electrode material and the applied dielectric liquid [23]. Dąbrowski [6, 17] points out that the main factors which influence the machined element's surface integrity are current intensity and pulse time, while the other machined parameters are defined. The current intensity increases the results in a higher amount of material removal during a single discharge. The current intensity growth causes the surface quality deterioration [22, 25]. The extended pulse duration reduces the energy density (which improves surface quality by reducing surface roughness) of the discharge spots by expanding the plasma channel and, as a consequence, the material removal rate decreases and the tool electrode wear is reduced [12, 22, 23]. Tool wear, which is determined by tool electrode material properties, has a significant influence on the EDM machining accuracy. The tool electrode is removed during the EDM process simultaneously by generated sparks, causing a characteristic corner and end (radial and axial) working electrode wear [12, 20]. It is also worth mentioning that the melted electrode material can diffuse to the workpiece surface layer. Świercz and Oniszczuk [18, 21] attempt in their works to solve an interesting problem of the current pulses' character influence on the machined surface integrity, as basic factors determining the EDM machining results. It was found that for short pulse times and low current values, the surfaces' geometrical structure is characterised by a huge number of rough peaks. The current intensity increase results in the increase of the discharge channel's diameter and power increase, which definitely brings higher roughness, characterised by a higher height as well as the distance between particular rough peaks.

The type of dielectric liquid is another important factor, which determines the machined surface integrity [23]. Proper dielectric circulation in the machining gap is required to maintain needed peak performance and to control the electric spark [4]. There are several functions of dielectrics: insulation, ionisation, cooling and waste removal [4]. Due to the fact that each dielectric has a specific composition and physical properties, it is very important to choose the one that would be optimal, ensuring the best surface integrity and accuracy in a particular situation. The type of a dielectric influencing the technological surface properties is still a complex problem, which will be described and investigated in more details further in this paper.

2. The role of a dielectric in EDM

Many authors [4, 17, 26] point to the crucial role of the dielectric type in electrodischarge machining. Dielectrics ensure the possibility of the occurrence of controlled electrical discharges between the tool electrode and the workpiece, cooling and solidifying of gaseous EDM debris from the discharge, removing erosion products from the machining gap and also dispersing heat generated during the process from the tool electrode and workpiece material [4]. Currently used dielectrics can be divided into three groups: hydrocarbon-based dielectric liquids, water-based dielectric liquids and gaseous dielectrics [4].

Table 1. Physical parameters of chosen dielectrics with examples of commercial product names [26–28]

Physical parameter	**Dielectric type**		
	kerosene	De-ionised water	air
Thermal conductivity λ (W/m·K)	0.14	0.62	0.016
Melting point δ (°C)	–	0	–
Specific heat C (J/kg· °C)	2100	4200	1.005
Viscosity η (Pa·s)	2.3×10^{-6}	1×10^{-6}	
Density ρ (kg/m^3)	860	1000	1.29
Composition (vol%)	100% hydrocarbon	100% H_2O	78% N_2, 21% O_2, 1% other gases

Physical parameter	Dielectric type		
	kerosene	De-ionised water	air
Type of EDM with used dielectric	EDM-sinking	EDM-wire, Micro-hole drilling	Dry EDM
Examples of dielectric liquids	**Carbon-based:** 30 NEUTRAL, OIL VITOL-2, VITOL-2-S, VITOL-KO (manufacturer: Sodick Co., Ltd), EDM 3033 (manufacturer: EDM Zap)	**Water-based:** VITOL-KS, VITOL-KN (manufacturer: Sodick Co., Ltd)	

Carbon-based dielectric liquids were applied at the earliest and are still the most commonly used, especially during EDM-sinking, because of their low viscosity, which improves flushing of the machining area [26]. On the other hand, there are a few drawbacks connected with a low flash point and evaporation temperature (quick transformation to the volatile state). What is important, fumes arising during machining (carbon monoxide and methane) are toxic. Fumes generated by electric discharge diffuse deeply into the white layer, which results in generating carbide separations [4]. That affects further technological operations – during heat treatment, the carbonisation of the surface layer increases, and along the grain's boundaries, the microcracks expansion occurs [4, 26] These kinds of liquids are not environmentally friendly, they also have a negative influence on human health. On the other hand, using carbon-based dielectric liquids makes it possible to get higher machining accuracy compared to water-based dielectric liquids [4].

Water-based dielectric liquids (de-ionised water, tap water, pure water with additives such as ethylene glycol, dextrose, sucrose, glycerine) are more thermally stable compared to carbon-based dielectric liquids [4] because they have eight times higher vaporisation energy and lower boiling-point. Greater thermal stability facilitates receiving higher discharge energy and as a consequence results in obtaining higher machining efficiency and lower working electrode wear [26]. The surface roughness is better, the number of microcracks is reduced compared to machining with carbon-based liquids. Further heat treatment does not affect microcracks expansion; however, material oxidisation is observed [4]. On the other hand, properties of water-based liquids are hard to stabilise (in the course of time the isolation features are lost) and the machining accuracy is definitely lower compared to carbon-based dielectric liquids [4]. The main area of application of such a kind of dielectrics is electrodischarge wire cutting and high ration hole drilling. An important advantage of using water-based dielectrics is lower environment contamination. What is more, they do not affect the human body [4].

Dry electrodischarge machining is a method, which uses gas (e.g. air or oxygen) as a dielectric. The melted material is removed from machining gap by the high-pressure gas flow, supported by a thin-walled pipe electrode [4]. The role of gas is to cool, solidify and prevent molten material from welding into the tool electrode and machined surface. Furthermore, high-pressure gas jet extinguishes the plasma channel between sequent discharges, which facilitates dielectric strength recovering in the machining gap [4]. It should be emphasised that tool electrode wear ratio during dry EDM is very low and, what is more, it is independent of the single pulse duration [4]. Dry EDM is not commercially used in industrial applications yet [26], even though it is economically and environmentally friendly, compared to other dielectrics, because of huge problems with heat dissipation during electrodischarge machining.

Zhang et al. [26] investigated the external and sectional appearance of the craters after a single pulse discharge, to characterise material removal in different dielectrics. Significant differences were found, comparing geometrical craters' shapes formed while using different dielectric types (oxygen, air, de-ionised water, kerosene, W/O emulsion) in the same machining conditions. It was stated that the machining efficiency was lower in the gaseous dielectric. However, observed melted material volume in kerosene liquid was much lower compared to other dielectrics. It shows that there is a huge difference between the volume of the melted material and the removed material (it is known that a higher removal material rate is observed in the carbon-based dielectric liquid than in water-based or gaseous dielectrics) [26]. Basing on the experiments and simulations, the authors [26] suggested that a higher efficiency of material removal rate is connected with a higher pressure above the discharge point [26]. On the basis of a literature review, it was stated that there are huge differences between dielectrics, which have the crucial influence on machined surface integrity.

The technological properties of EDM machined elements determine the possibility of their applications in specific environments, where high machining accuracy and very good surface integrity are needed. The main aim of this work was to identify the influence of carbon-based and water-based dielectric liquids on the selected structural and morphological characteristics of 304 stainless steel after electrodischarge sinking. The investigated material is commonly used in all the branches of industry (automotive, chemical, food-processing, construction, turbomachinery industry and an energy sector) due to the very good thermal, physical, chemical and mechanical properties. One of the most important features of austenitic steels is high corrosion resistance and resistance to adverse working environments (high oxidation, acidity, temperature) [3]. Austenitic stainless steels are also commonly used in production of medical devices and implants because of corrosion resistance, formability, reasonable fatigue resistance, due to their biocompatibility ("tolerant of life", can be understood as "being able to cope with the full variety of conditions prevailing during its lifetime") [8]. In this aspect, EDM can be used for efficient production of specific medical devices, such as tools for insertion and extraction or recovery of implants, surgical cathodes and syringe components, splints and supports for orthotic and prosthetic devices, bone and jam reamers for dental implants, tooling and dies for manufacturing and stamping medical equipment and tools [7]. In reasonable cases (implants customisation) [10], EDM can also be used for shaping surfaces in surgical screws and bolts or knee, shoulder and hip joints implants [7]. It is important to underline that manufacturing technology has a significant influence on biocompatibility, and especially when machining is carried out in the final stage of the production process one can state that that biocompatibility is determined by manufacturing technology.

3. Materials and methods

Sinking electrodischarge machining of 304 austenitic stainless steel was conducted on a research post equipped with electrodischarge generator BP 95, manufactured by a Polish company ZAP B.P. Końskie-Kutno (Fig. 1). The influence of two kinds of dielectric liquids on the surface layer quality was investigated: distilled water and carbon-based dielectric liquid – Exxsol D80, at the three values of current intensity (1, 5 and 10 A). These dielectrics were chosen as representatives of the most commonly used kinds of dielectric liquids in industry. Such current intensity values were selected to have stable EDM machining conditions with the generator used. Machining in distilled water was conducted with the ∅10.84 mm cylindrical copper working electrode (cathode), machining in Exxsol D80 with the ∅4.44 mm cylindrical copper working electrode. Simple polarity of the working electrode and machined element was used (working electrode was the cathode (-), workpiece was the anode (+). Other machining conditions were constant in both dielectric liquids: pulse time 100 μs and off time 10 μs.

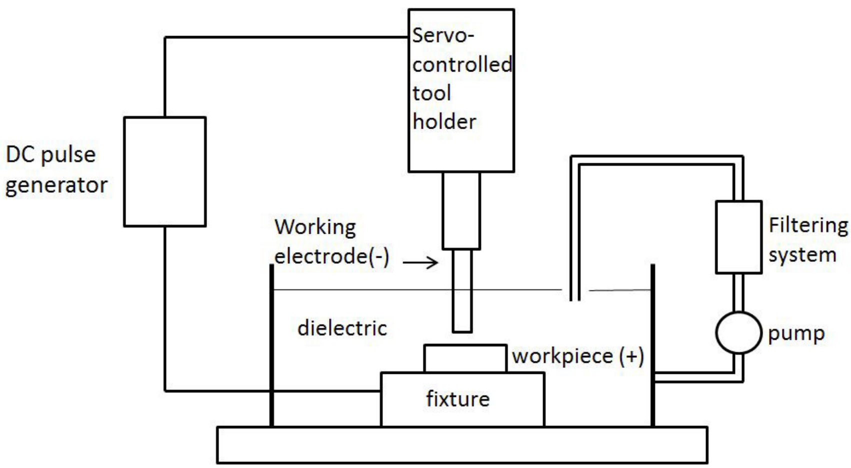


Fig. 1. Scheme of the research test stand

After machining, the following test were carried out on the machined surfaces. Surface roughness was measured using Taylor Hobson Surtronic 25 with the sampling length of 0.8 mm. The Vickers hardness of each machined surface was determined with the INNOVATEST machine (loading level 0.5 N, at 10 s time). The measurements were repeated five times at each machined surface. Then, with the Scanning Electron Microscope, SEM photos were taken to identify structural and morphological changes of machined surfaces. The determination of changes in the chemical composition after EDM was investigated by the EDS method (Energy Dispersive X-Ray Spectroscopy). This qualitative method was chosen to find out what kind of chemicals appear in the surface layer, after using different dielectric liquids. The corrosion resistance of each sample was investigated by placing the samples in 65% nitric acid in 22 °C for 14 days. After this time, SEM photos and EDS analysis were repeated.

4. Discussion of results

On the basis of the roughness average (Ra) (Fig. 2) and mean roughness depth (Rz) (Fig. 3) measurements on the EDM machined surfaces, it is possible to say that with the increase of current intensity machining causes a proportional increase of Ra and Rz surface roughness. A proportional increase of Ra was also observed at machining in the carbon-based dielectric; however, machining with a current intensity value of 10 A in the carbon-based dielectric liquid caused an Rz roughness decrease (Fig. 3). It is possible that the increase of discharge energy in the machining gap was high enough to remove the whole molten material (exploding pressure) away from the crater. In these machining conditions solidified molten material may not build-up on the craters' edges.

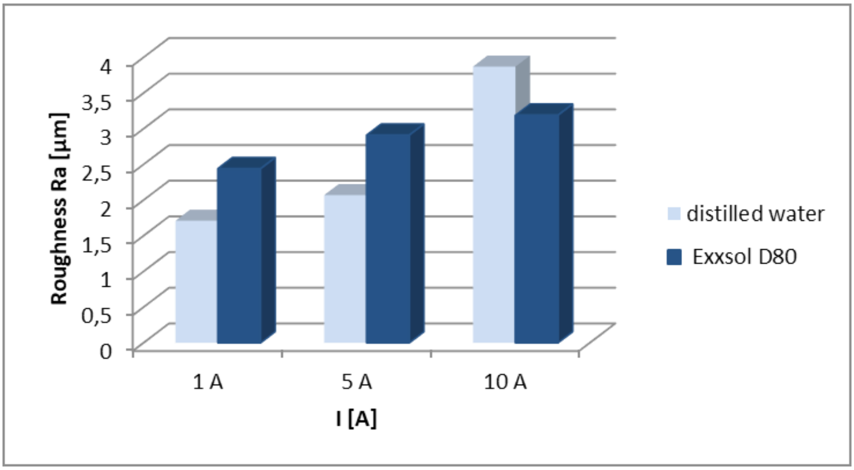


Fig. 2. The influence of current intensity on the value of Ra surface roughness during EDM with different dielectrics

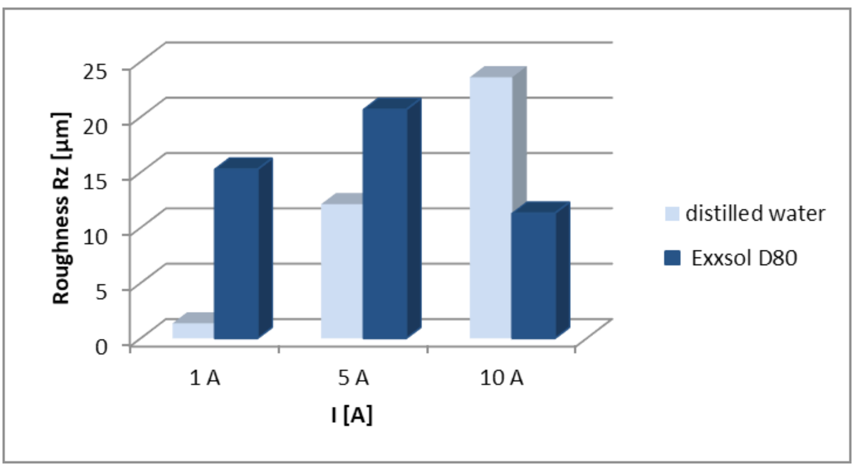


Fig. 3. The influence of current intensity on the value of Rz surface roughness during EDM with different dielectrics

Using distilled water as a dielectric determines the arising density of a single discharge and as a result removing higher material amount during single discharge; therefore, Rz increases. It was also noticed that machining in distilled water at *I* = 10 A was more stable than in the case of Exxsol D80. According to Zhang [26] results of electrodischarge machining of 8407 mould steel, the first decrease of crater removal depth was observed either while using distilled water or kerosene as a dielectric liquid, then increase with the increase of pulse duration.

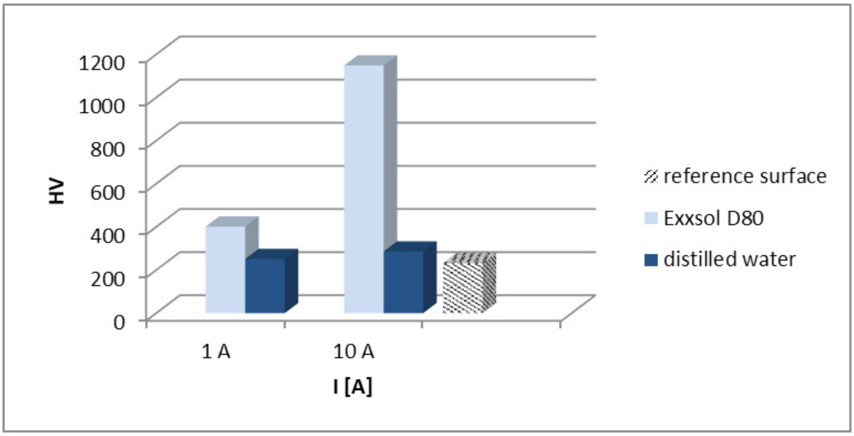


Fig. 4. The influence of current intensity and dielectric liquid type on the micro-hardness in EDM

An influence of the working liquid type on the micro-hardness of the surface layer was observed (Fig. 4). In comparison to the reference sample (surface before EDM) and surface machined in distilled water, machining in carbon-based dielectric causes significant increase of surface hardness. In this case, hardness increases several times with the current intensity increase, starting with the value of HV 400 for I= 1A, up to HV 1150 for I= 10 A. Hardness after machining in distilled water was in the range of HV 250÷300, regardless of current intensity. The hardness of reference sample surface was HV 231; therefore, it should be stated that the impact of the machining in distilled water on the surface hardness can be neglected.

In tables 3 and 4, the SEM photos of electrodischarge machined surfaces in distilled water and Exsoll D80 with various current intensities were presented. The SEM photos of these surfaces after the corrosion test were included as well. As it was mentioned in the introduction, a very high temperature is generated during EDM; that is why the material has melted and evaporated and, as a consequence, craters occur on the machined surface [8]. It was noticed that the current intensity increase causes the craters' diameter increase and boundary grain growth in both dielectrics. The increase of the current intensity while EDM machining was carried out in a carbon-based dielectric resulted in a great number of deep microcracks on the surface. This effect was not observed during EDM machining in distilled water, where a small number of microcracks was observed only when machining with I = 10 A. Also, no additional molten spherical debris was observed, which can mean that proper flushing during machining was provided.

Table 2. SEM photos of electrodischarge machined surfaces in distilled water and kerosene; current intensity $I = 1$ A

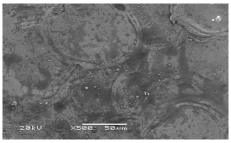
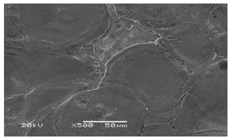
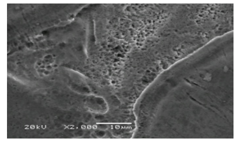
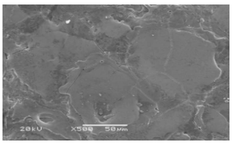
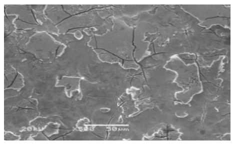
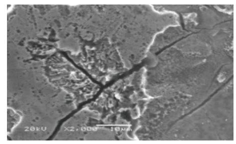
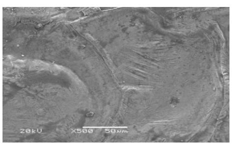
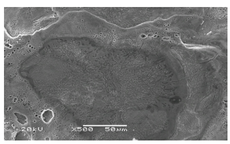
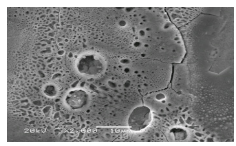
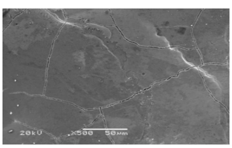
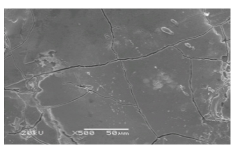
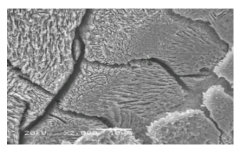
EDM	**EDMed surface after corrosion resistance test**	
Zoom x 500	Zoom x 500	Zoom x 2000
***I* = 1 A Distilled water**		
		
***I* = 1 A Exsoll D80**		
		

Table 3. SEM photos of electrodischarge machined surfaces in distilled water and kerosene; current intensity $I = 10$ A

EDM	**EDMed surface after corrosion resistance test**	
Zoom x 500	Zoom x 500	Zoom x 2000
***I* = 10 A Distilled water**		
		
***I* = 10 A Exsoll D80**		
		

After the corrosion test, the increase of oxygen separation on the grain boundaries and near the craters was observed. The pit propagation and its intensity increase with the current amplitude were also noticed. On the sample surface machined in the carbon-based dielectric liquid, the intensity of corrosion processes in the area of crevices and microcracks was significantly higher than in distilled water.

On the basis of EDS analysis (Tab. 5,6), it can be stated that the chemical composition of the surface layer changed, comparing to the raw material. On the machined surfaces, a trace amount of copper was found, which indicates that the material melted from the copper electrode transfers to the surface layer. Additionally, in a corrosive environment, the increase of oxygen amount is observed, which indicates that the surface layer oxidation occurs. It is worth emphasising that Energy Dispersive X-Ray Spectroscopy, which was chosen as the test method, is just a qualitative method, which enables qualitative analysis only.

Table 4. Example of EDS analysis after EDM in distilled water with current intensity I= 10A and on reference surface

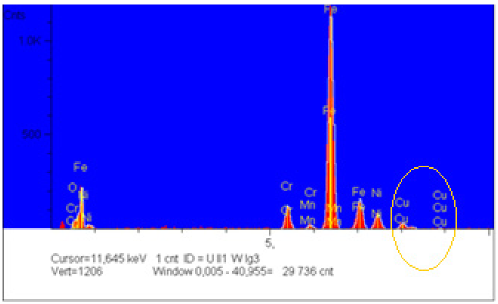
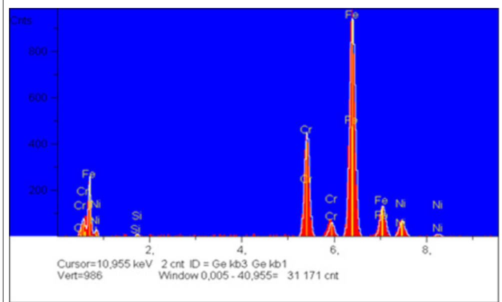
EDMed surface	Reference surface
	

Table 5. Results of EDS analysis on a reference surface, EDMed surface (I= 10 A, deionised water) and EDMed surface after the corrosion resistance test, [%]

Element	Reference sample	EDM	EDMed surface after corrosion resistance test
O	2,2	10,5	30,1
Cr	19,3	15,5	31,3
Fe	70,3	65,3	33,0
Ni	7,8	6,9	2,9
Cu	0	1,3	0,7

5. Conclusions

In this paper, the attempt of the influence identification of a carbon-based and a water-based dielectric liquid on the selected structural and morphological characteristics of 304 stainless steel after electrodischarge sinking was undertaken. It is important to emphasise a possible influence of austenitic steel surface integrity in the aspects of medical devices, taking into account an increasing demand for implants as well as surgical features. It was stated that the workpiece surface layer is affected by heat; however, an appropriate selection of machining conditions (in the investigated case - current intensity and dielectric type) can reduce this effect. During the research, lower roughness and hardness was obtained by using distilled water as a dielectric liquid (see below in Table 7), which is also connected with fewer microcracks.

Table 6. Surface roughness and hardness obtained by EDM machining in different dielectric liquids

Dielectric type	Current amplitude *I* [A]	Ra [μm]	Rz [μm]	Current amplitude *I* [A]	HV	HV standard deviation
Distilled water	1	1.71	1.36	1	251.4	8.55
	5	2.07	12.13	10	286.2	8.03
Exsoll D80	1	2.44	15.27	1	401.5	62.5
	5	2.91	20.67	10	1148.8	141.6

Also, higher corrosion resistance occurred while the material was machined in distilled water. It was also noticed that the melted material removal process is very complicated and hard to define, thus more research in this area is needed. The type of dielectric liquid has a crucial influence on the technological material surface integrity during EDM machining, thus determining the operational properties of the machined element.

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