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RESEARCHES ON THE BEHAVIOR OF ECOLOGICAL DIELECTRIC LIQUIDS AT CLASSIC AND ULTRASONICALLY AIDED EDM

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ABSTRACT: The paper deals with the behavior of environmentally friendly dielectric liquids: rapeseed and sunflower oil, compared to an usual hydrocarbon based dielectric liquid. Experiments have been performed with these dielectric liquids, using them at classic electrical discharge machining (EDM) and ultrasonically aided electrical discharge machining (EDM+US). The results concerning productivity and the roughness of machined surface under these same working conditions were compared. Computerized models have been developed, using the finite element method for material removal mechanisms related to these processes. The aim was to explain the behavior of dielectric liquids under specific conditions of EDM and EDM+US.

KEYWORDS: dielectric liquids, environmentally friendly, electrical discharge machining, ultrasonic.

1. INTRODUCTION

The study related to behavior of environmentally friendly dielectric liquids is justified by the increasing demands regarding the elimination of the pollutant character of these liquids at EDM.

This kind of nonconventional technology is applied on an increasingly large scale, in the various fields of activity, where it is required to achieve surfaces of high complexity and precision, associated with great quality of the machined surface.

The dielectric fluid has the following functions: restoring the electrical isolation (deionization) of the working gap, after a discharge is produced, the evacuation from the working gap of the particles removed from the machined material, the decrease of the temperature within the working gap, decreasing also the temperature of the part and the tool and implicitly their thermal deformations. Based on these considerations, it can be observed that appropriate flushing of working gap with dielectric liquid has the same importance at EDM as any input working parameter [1].

Dielectric liquids based on rapeseed and sunflower oils were used for EDM, but also for ultrasonically aided EDM, hybrid machining, in the present work. Given the using growth of ultrasonic assisted hybrid technologies, it was considered justified to extend these experimental research concerning vegetable dielectric fluids in ultrasonic field conditions. The ultrasonic assistance variant also involves phenomena of ultrasonically induced cavitation in the working gap, which may affect the composition, physical properties and implicitly, the behavior of dielectric liquids during machining process. In order to better understand these complex phenomena, computer models of material removal mechanisms using element finite method were also developed.

2. STATE OF THE ART ASPECTS

There are studies in the current state of the field that emphasize the highly polluting character of dielectric liquids based on aromatic hydrocarbons and the harmful effect on the human body (EDM operator). Satyarthi analyzed the degree of pollution of the dielectric fluid on the human operator during its working hours, and the results of his research have been really worrying [2]. Some experiments were carried on by combining mineral oils with water, but the influence of water could not to greatly reduce the harmful character of the dielectric fluid [3].

There are also researches concerning the replacement of pollutant dielectric liquids by using environmentally friendly liquids, especially vegetable oils, such as cottonseed oil, coconut oil, sesame oil, in the current state of the art. Vegetable oils used as dielectric liquids must have a relative high inflammable point, excellent biodegradability, higher oxygen content, high viscosity, lower toxic emissions and low volatility. Coconut oil enjoys a great deal of these properties, followed by cottonseed oil [4, 5].

Since the dielectric fluid plays an important role in the electric discharge material removal mechanism at both EDM and EDM + US, the functions, which the dielectric fluids perform, can affect the productivity, quality of EDM products and cost.

Beside these, the health, safety and environment of the EDM operator are critical too.

The dielectric fluid loses his properties: the dielectric resistance, the semiconductor capacities and the electrical thresholds change, while the fluid spins and decomposes. It can no longer ensure consistent or repeatable semiconductor control at the spark gap, as it degrades. If over time the liquid breaks down and loses its resistance characteristics, the EDM process becomes more unstable and slower [6].

There are several types of fluids for EDM: petroleum, synthetic, water and vegetable based. Table 1 presents the main characteristics of the dielectric liquids according to the category they belong to. Fluid properties play an important role in EDM and for safe processing, the dielectric strength and the ignition point of the dielectric fluid should be higher [7].

Oil-based liquid it's the most widespread and is 30% less expensive than full synthetic liquids. The lifetime of this fluid is the smallest of all fluids. Kerosene is among the first dielectric materials used in the EDM process, having a major benefit, namely low viscosity. Unfortunately, it has many negative properties: low ignition point, high volatility, unpleasant odor. The use of kerosene has produced numerous incidents including explosions and fires, but also incidents that have affected the health of human operators. The increase of sensitivity to the problems that this dielectric has created is reflected in the strict increasing legislation requirements and in the national and international standards, being excluded from the category of dielectric liquids.

EDM being a thermal process, the hydrocarbon dielectric liquid vaporizes and the toxic emissions affect the human operator causing headaches, dizziness, skin irritation, eyes and even memory difficulties. Being in the position where it serves the machine tool, the operator can easily inhale the vaporized dielectric, being impossible to avoid these emissions, unless using air purification systems with activated carbon installations are used in order to retain them. This efficiency proved to be more than 99% for adsorption of harmful compounds from hydrocarbons cracking in dielectric mineral oil [9].

Synthetic liquids haven't need replacement, because their dielectric resistance properties don't change or decompose over time. These fluids are also less irritating to the skin than oil-based fluids. The biggest harmful effect came from oil products. The plant fluid was developed based on the requirements of the medical industry. The processed parts no longer need sterilization based on acid softening or passivation and in this way the human operator is protected [3].

Lifetime of the dielectric fluid depends on: the type of liquid, the type of EDM works performed (higher power for machining will affect the oil faster), the type of processed materials also the quality of the filtration of the liquids used in the process. The physico-chemical phenomena that appear under the action of the electric shock in the dielectric are the electric piercing, mechanical shock wave formation, the circulation of erosion products.

The EDM technology is analyzed from the point of view of the extremely harmful aspects on the environment and of the human operator's body, the environmental and health aspects shouldn't be neglected. In the last fifty years, numerous researches have been carried out to replace hydrocarbon dielectric liquids with other environmentally friendly dielectric liquids. Particular attention is paid to vegetable oils. They don't contain harmful organic substances due to the fact the degradability is significantly increased. A vegetable oil can be identified as a dielectric liquid if it has optimum values of the following properties: viscosity, electrical conductivity, high flash point, low density and evaporation during heating.

Experiments are performed on coconut oil, whose physico-chemical properties are compared with the properties of a mineral dielectric liquid (IEC 60296) [8]. After complete analysis, it was found that coconut oil can replace the reference dielectric fluid. It also meets the requirements for the safety of the environment and the human operator through: biodegradability due to the organic composition, non-toxicity and ease of use. Another vegetable oil tested was cottonseed oil, the experiment being conducted by Karaosmanoglu. Oils were also chosen according to an important criterion, namely the degree of total unsaturation as low as possible [10].

Table 1. Characteristics of the types of dielectric fluids

Dielectric liquid	**Relative permeability to 25 ºC**	**Viscosity [mm*s^{-1}]**			**Flash point [ºC]**	**Fire point [ºC]**	**Density at 20 ºC [kg/dm^3]**
		0°C	**40°C**	**100°C**			
Mineral	2,1-2,5	<76	3-16	2-2.5	100-170	110-185	0,83-0,89
Silicone	2,6-2,9	81-92	35-40	15-17	300-310	340-350	0,96-1,10
Synthetic ester	3,0-3,1	26-50	14-29	4-6	250-270	300-310	0,90-1,0
Vegetable	3,1-3,3	143-77	16-37	4-8	315-328	350-360	0,87-0,92

3. EXPERIMENTAL DATA

During this research, the usual dielectric liquid P3 was replaced with vegetable oils: rapeseed oil and sunflower oil. P3 dielectric fluid is a hydrocarbon-based liquid having optimal physico-chemical properties that allow it to act as a dielectric medium [8]. Its characteristics are presented in table 2.

Table 2. Properties of P3 dielectric liquid

Properties		P3 dielectric liquid
Density at 15°C [kg/m^3]		840
Flash point [°C]		104
Amount of aromatic hydrocarbons [%]		22
Kinematic viscosity	at 37.8°C	(2.2…3) x 10^{-6}
	at 22°C	(2.2…4.5) x 10^{-6}
Mineral acidity and alkalinity		no

Two essential properties of the dielectric fluid have been determined, namely: kinematic viscosity and electrical conductivity, in order to replace the classic dielectric liquid with the two vegetable oils. Kinematic viscosity was determined using the Engler viscometer at temperatures of 20, 40, 60 and 80 °C, its values being presented in table 3.

Table 3. Values of the cinematic viscosity of vegetable oils

Vegetable oil	Temperature [°C]	Kinematic viscosity [m^2*s^{-1}]
Sunflower oil	20	1,40x10^{-6}
	40	6,77x10^{-6}
	60	2,93 x10^{-6}
	80	0,16 x10^{-6}
Rapeseed oil	20	2,59x10^{-6}
	40	10,31 x10^{-6}
	60	5,42 x10^{-6}
	80	1,93 x10^{-6}

Figure 1 shows the variation of the kinematic viscosity as a function of temperature for the studied dielectric liquids.

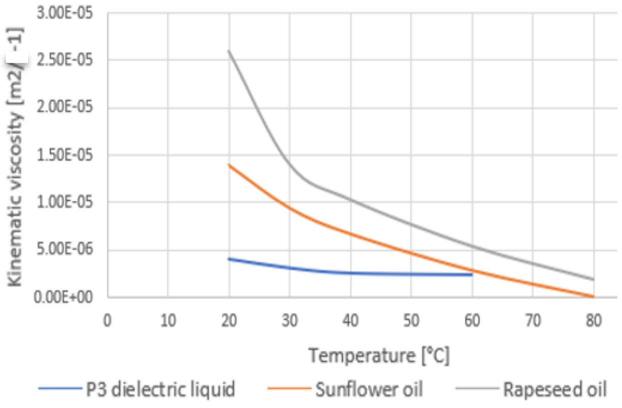


Figure 1. The variation of the viscosity of dielectric liquids as function of temperature.

As it is expected, the kinematic viscosity of vegetable oils and P3 decreases by increasing the temperature.

The rapeseed oil has a viscosity of 10.31 x10^{-6} m^{2}s^{-1}, a high value, comparing with the dielectric liquid P3 of 2.5 x10^{-6} m^{2}s^{-1} at 40 °C, usual for EDM process. Therefore it's found experimentally that this oil can produce instability during EDM (tendency to short-circuit between tool and workpiece). From the point of view of kinematic viscosity, sunflower oil is more suitable for EDM than rapeseed oil – see figure 1. Both vegetable oils are more appropriate for roughing modes.

Electrical conductivity is another property needed for the two vegetable oils to replace mineral oil. This was determined using the MeterLab CDM210 conductometer. The results are presented in table 4.

Table 4. The electrical parameters of dielectric liquids

Dielectric liquid	Electrical conductivity [µS/cm]	Resistivity [kΩ·cm]
P3 dielectric liquid	235,0	4255,3
Cut-Max SE2 dielectric liquid	234,2	4269,8
Distilled water	240,2	4163,2
Sunflower oil	227,0	4405,3
Rapeseed oil	227,5	4395,6

It's observed that all the dielectric liquids in the table 4 meet the operating condition for the EDM process, the resistivity > 100 kΩ · cm [11]. Figure 2 illustrates the experimental values. Sunflower oil and rapeseed oil have close electrical conductivity values, lower than the other two studied.

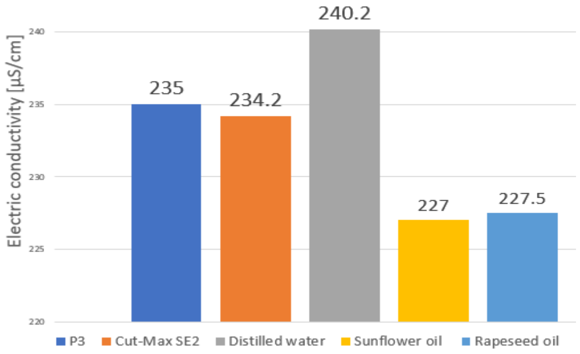


Figure 2. Electric conductivity of studied dielectric liquids

Machining by replacement of P3 dielectric liquid with vegetable oils was performed on the ELER01 Romanian machine with 50 A generator shown in figure 3. Three dielectric media were used to machine samples of laminated steel through EDM, but also EDM+US.

The components of the experimental stand are shown in figure 4. The machine was programmed with the following set of values: 12 µs commanded pulses, pause time 6 µs, intensity 6A, flushing pressure 1 bar, copper electrode at negative polarity, positioned at the end of ultrasonic chain for comparison between EDM and EDM+US.

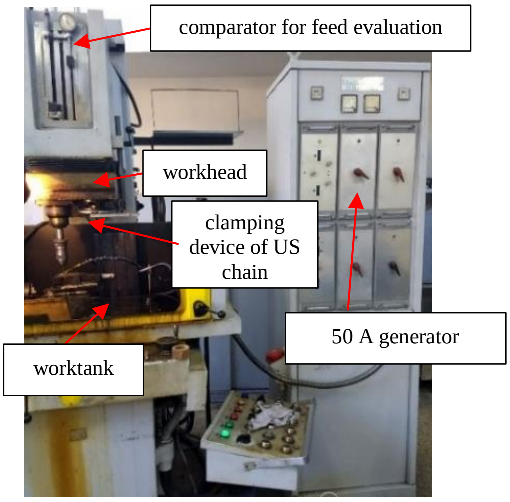


Figure 3. Electrical discharge machine ELER01 G50

In the second case, for EDM+US, the GUS-20-E ultrasonic generator was connected to ultrasonic chain, which provided 1200 V with 20 kHz ultrasonic nominal frequency and consumed power of 100 W.

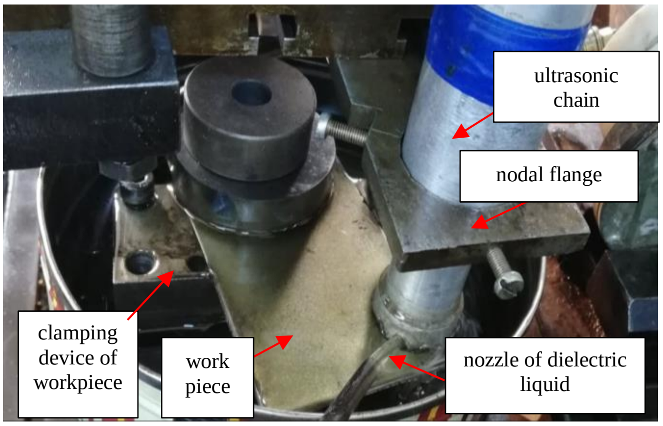


Figure 4. The components of the experimental stand

The results from six machining tests, using the three dielectric liquids are presented in table 5.

The productivity with the three dielectric liquids in descending order was: P3, rapeseed, sunflower. It is observed during the experimental machining by classic EDM that the highest stability of material removal process was recorded at using the P3 dielectric, and apparent instability was recorded at using sunflower and rapeseed oils.

By instability we mean repeated phenomena of withdrawal, caused by the short-circuits produced between the tool and the machined surface. The instability was visually assessed by following the obvious variations of a comparator apparatus mounted on the machine by which the machining depth is determined during the process.

The phenomena mentioned above could be explained by the fact that dielectric fluids based on vegetable oils have a relatively high viscosity, which created difficulties to penetrate in the working gap and therefore to evacuate the particles removed during machining.

Productivity increased at EDM+US in all three variants of dielectric liquids through the additional effect of ultrasonic cavitation within the working gap. Thermal removal increases because the ultrasonic action removes material in liquid state, its volume being much larger, bounded by the melting isotherm than at classic EDM, where is margined by boiling isothermal. This is the case of overlapping the pulse time on cumulative microjets stage. The gas bubble formed around the plasma discharge channel breaks much faster at each end of the ultrasonic period *Tus* = 50µs at the frequency of 20 kHz.

On the contrary at the classic EDM, the gas bubble collapses at over 150 µs after pulse end at such working modes. Therefore at pure EDM, the molten material is 90% resolidified and consequently cannot be removed by dielectric liquid when the gas bubble collapses, and so productivity decreases [1].

Taking account of higher viscosity of the rapeseed oil, a pulsating mode was chosen to improve gap flushing and EDM stability. In case of classic EDM, some instability was produced at using vegetable oils, which were eliminated at EDM+US.

The machined surfaces were studied by QUANTA INSPECT F50 electron scanning microscope (SEM), with a field emission electron gun and 1 nm resolution electron. The roughness of the machined surfaces was determined using the roughness ruler. The Rz roughness is equal with craters depth. The images of machined surface are presented in figures 5-7, with some dimensions of the craters determined by SEM software, and their corresponding profiles drawn by averaged dimensions.

Table 5. Experimental results

Dielectric liquid	Machining type	Machining depth [mm]	Machining time [min]	Productivity [mm^3/min]
P3	EDM	0.20	3min 22s	8.75
	EDM+US	0.26	4min 50s	22.01
Sunflower oil	EDM	0.10	3min 26s	1.975
	EDM+US	0.20	3min 09s	17.90
Rapeseed oil	EDM	0.16	3min 55s	7.03
	EDM+US	0.22	4min 50s	16.23

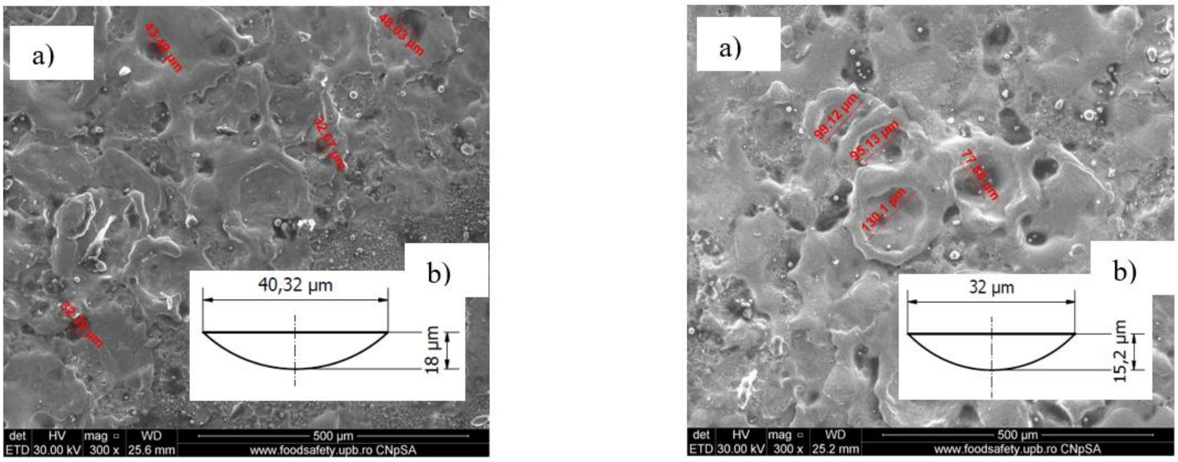


Figure 5. a) SEM images; b) craters averaged dimensions;
left EDM and right EDM+US, P3 dielectric fluid

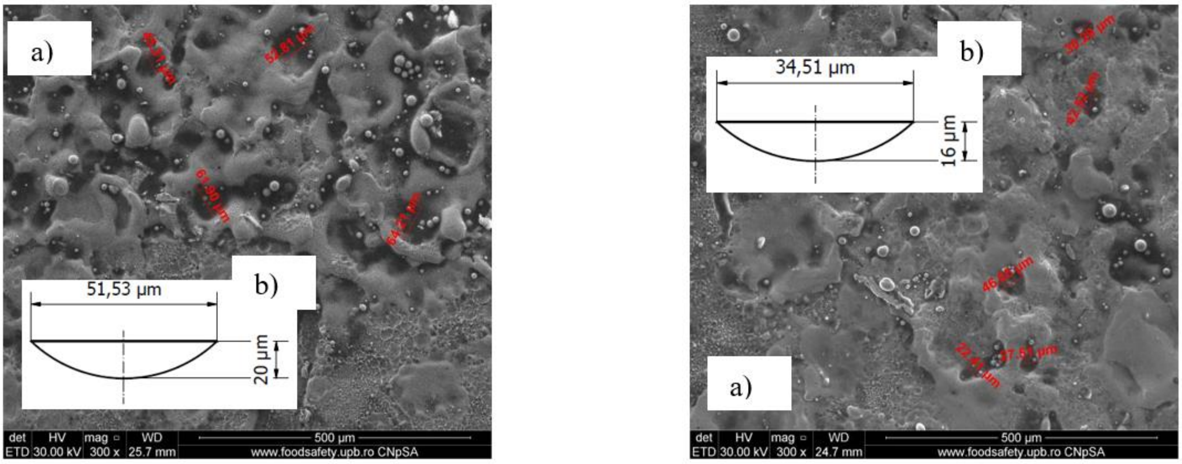


Figure 6.a) SEM images; b) craters averaged dimensions;
left EDM and right EDM+US, sunflower oil

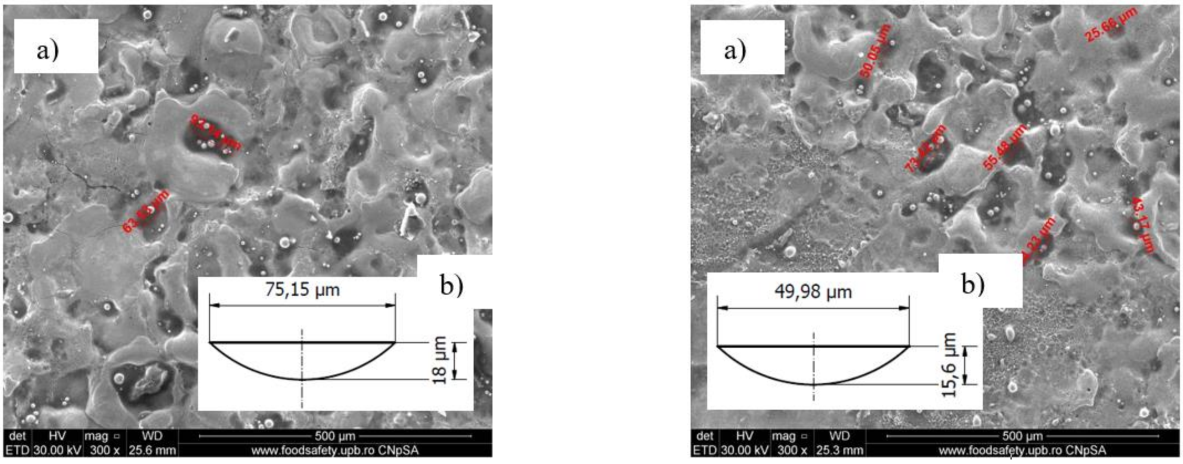


Figure 7.a) SEM images; b) craters averaged dimensions;
left EDM and right EDM+US, rapeseed oil

4. MODELING AND SIMULATION OF THE MATERIAL REMOVAL PROCESS

To increase the performance of the process, but also to understand it better, computerized models were created, using the finite element method (FEM).

The COMSOL Multiphysics was used to simulate and visualize the phenomena that take place at machining.

Figure 8 shows specific phenomena related to the complex mechanism of material removal at classic EDM and ultrasonically aided EDM.

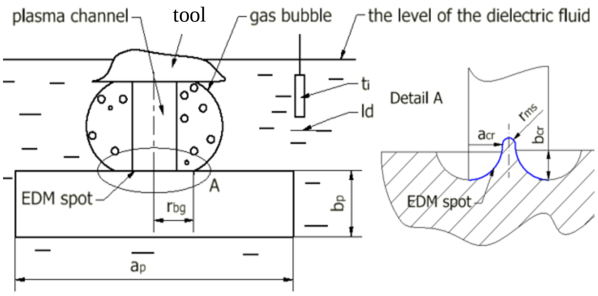


Figure 8. Specific phenomena of the computer model

FEM modelling comprises several steps. Firstly, due to the symmetry of the model, Space Dimension 2D was selected, and the mode of Heat Transfer in Solids, Time Dependent.

The parameters used for classic EDM modelling are shown in figure 9. Using the parameters defined above, the geometry of the workpiece was created. On machined surface, the microgeometry consists in initial craters with margins presenting resolidified material, specific to commanded pulses, according to the detail A shown in figure 8. The boundary conditions were established, figure 10 showing the temperature setup on EDM spot, as the boiling temperature and around 200 K over it, *tf*. According to the Van Dijck and Snoeys' overheating model, boiling is the main mechanism of material removal when the pressure drops after the pulse time [1, 11]. The gas bubble formed around plasma channel creates thermal insulation. The remaining uninsulated surface of the workpiece takes the temperature of the dielectric liquid, *tl*+273.15 [K].

The material used as a sample is laminated steel, equivalent to Swedish Steel AB from Comsol library.

When meshing the created geometry by finite number of elements, a satisfied quality as obtained, 0.96 on 0-1 scale. In the EDM spot zone, due to the connectivity property, the elements were much finer, figure 11.

The temperature distribution after a single discharge of 12 μs is shown in figure 12, and the position of boiling isothermal. From the temperature distribution, it appears that the single discharge produces effect only in the vicinity of the EDM spot, the rest of the sample, its volume being unaffected.

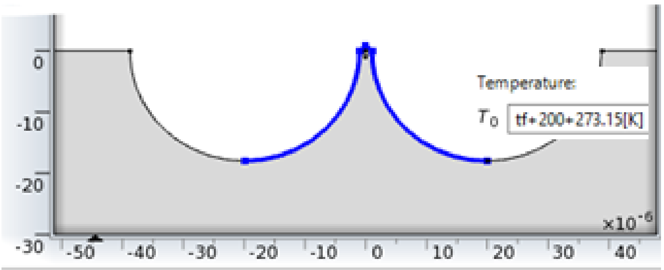
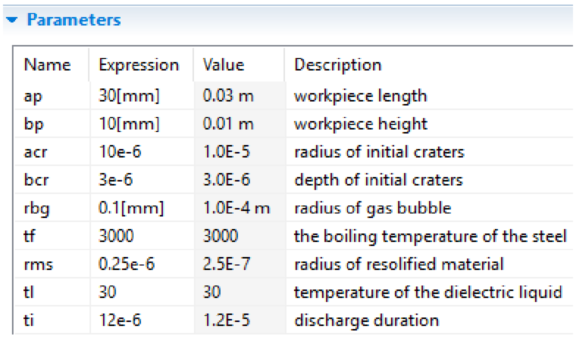

Temperature:
T_0 tf+200+273.15[K]

Figure 10. Temperature on the EDM spot



Name	Expression	Value	Description
ap	30[mm]	0.03 m	workpiece length
bp	10[mm]	0.01 m	workpiece height
acr	10e-6	1.0E-5	radius of initial craters
bcr	3e-6	3.0E-6	depth of initial craters
rbg	0.1[mm]	1.0E-4 m	radius of gas bubble
tf	3000	3000	the boiling temperature of the steel
rms	0.25e-6	2.5E-7	radius of resolified material
tl	30	30	temperature of the dielectric liquid
ti	12e-6	1.2E-5	discharge duration

Figure 9. Material modeling parameters

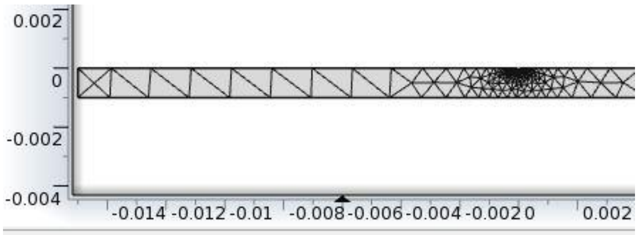
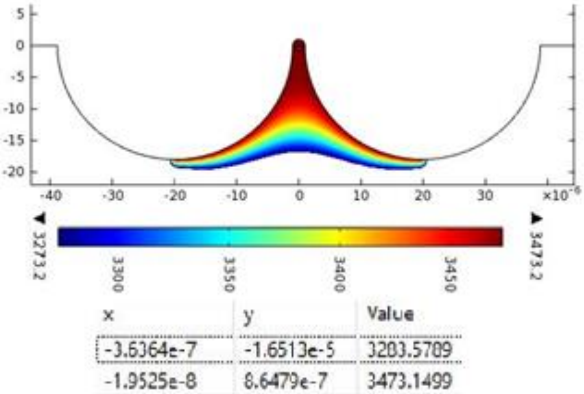


Figure 11. Meshing of the sample geometry much finer in the zone adjacent to EDM spot

In the case of FEM modeling of EDM + US material removal mechanism, the previous steps were covered, with several parameters being different. In order to compare the results of the modeling in case of classic and ultrasonic aided EDM, the geometry and the pulse time were kept the same. An additional mechanism for material removal occurs mainly, consisting in mechanical removal of micropeaks due the shock waves produces by ultrasonic cavitation. In the already existing model, the effect produced by the cumulative microjets and the mechanical-hydraulic removal of the workpiece material was studied, by calling Add Physics, the Solid Mechanics, and Time Dependent module. Some specific parameters to ultrasonic assistance, were added to the list from figure 9. These were the implosion time of the gas bubbles in the working gap, *tus* = 1μs, due to cavitation occurring at the final of each ultrasonic oscillation period, and the value of pressure applied of the microgeometry profile, *pus* = 60 MPa, due to cumulative microjets [1].



x	y	Value
-3.6364e-7	-1.6513e-5	3283.5709
-1.9525e-8	8.6479e-7	3473.1499

Figure 12. Temperature distribution after 12 μs pulse time, and boiling isotherm disposal at μm scale

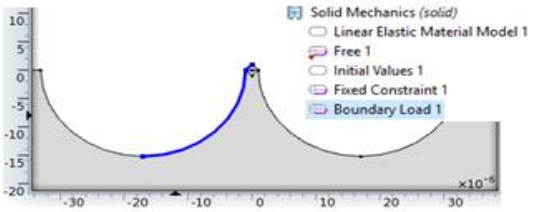


Figure 13. Cumulative microjets action as pressure boundary conditions at μm scale

The action of the cumulative microjets was assimilated as Boundary Load type on profile microgeometry, exerted on the x-axis, figure 13. The workpiece clamping was transposed by Fixed Constraints, selecting its base and lateral surfaces.

The distribution of Von Mises stress in the area adjacent to the EDM spot is shown in figure 14. It is considered that the action of the cumulative microjets at the end of each oscillation period is fatigue load with pulsating cycle. So the micro-peaks are removed by shearing, and the breaking resistance of material is determined by the relation [12]:

$$\tau_0 = 1.12(40 + 0.16\sigma_r) \qquad \text{MPa} \qquad (1)$$

where: σ_r is the static breaking resistance of the material. In this case, σ_r=650 MPa.
If the depth of the removed material is lower than the depth of the EDM crater, it is significant to approach the optimization of the working parameters, through the power applied on ultrasonic chain, key parameter.

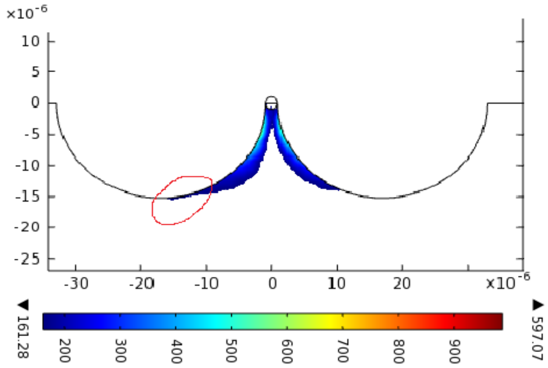


Figure 14. Von Mises stress due to cumulative micro-jets at ultrasonic pressure of 60 MPa at μm scale for P3 using

For validation of the modeling and simulation of machining process, it was necessary to compare its results with experimental reference data (figures 5-7), which were in good agreement.

5. MODELING RESULTS

The results obtained by modeling material removal mechanisms, using thermal heat transfer (specific to pure EDM) and mechanical hydraulic (specific to pure EDM) are presented below. Figures 15-23 show the temperatures, radius and depth of craters generated at the classic EDM by material boiling, at using the three dielectric liquids (P3, rapeseed oil, and sunflower oil).

The volume of removed material by the single discharge modeled at classic EDM is delimited by the boiling isotherm, defined by the temperature of 3473 K for all dielectric liquids – it depends on thermal physical properties of machined steel.

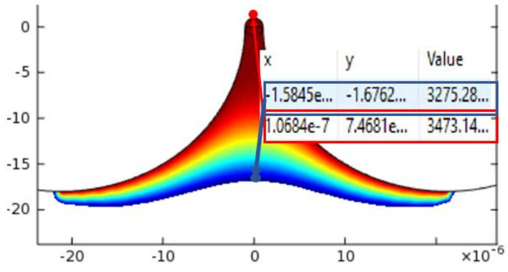


Figure 15. Temperature values at μm scale around EDM spot for P3 dielectric using

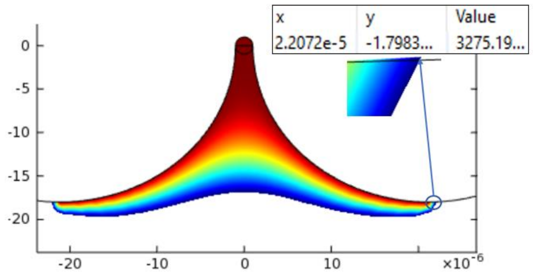


Figure 16. Crater radius at μm scale for P3 dielectric

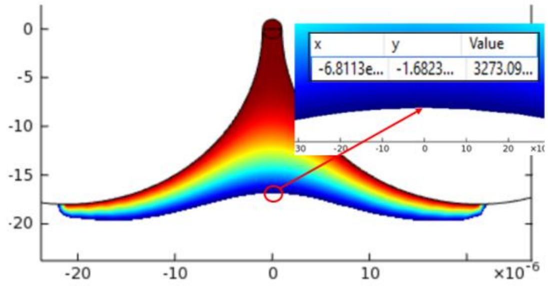


Figure 17. Crater depth at μm scale for P3 dielectric

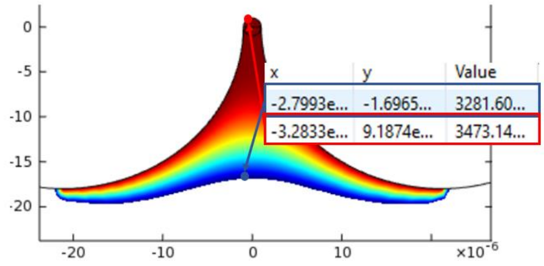


Figure 18. Temperature values at μm scale around EDM spot for rapeseed oil using

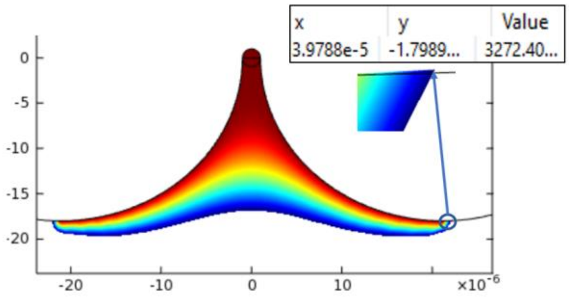


Figure 19. Crater radius at μm scale for rapeseed oil

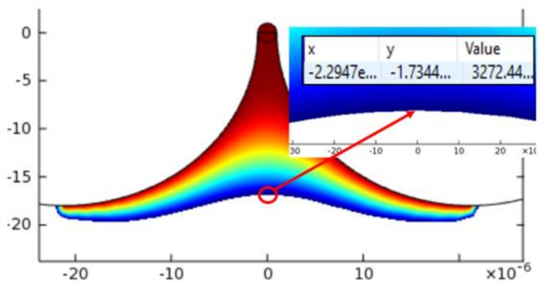


Figure 20. Crater depth at μm scale for rapeseed oil

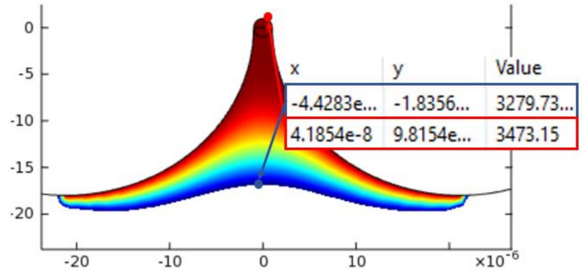


Figure 21. Temperature values at μm scale around EDM spot for sunflower oil using

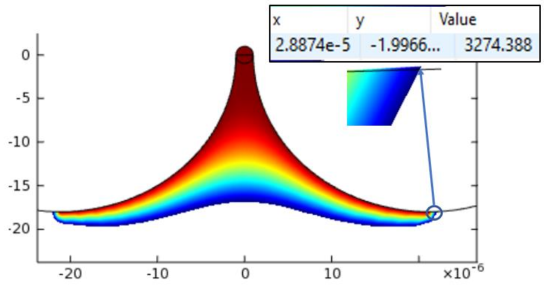


Figure 22. Crater radius at μm scale for sunflower oil

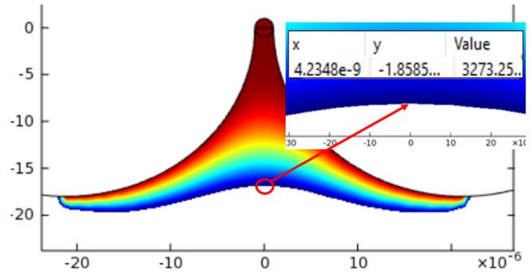
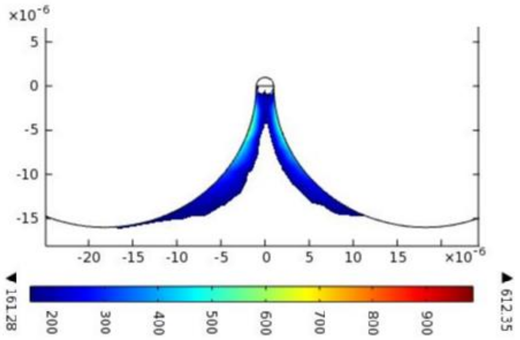
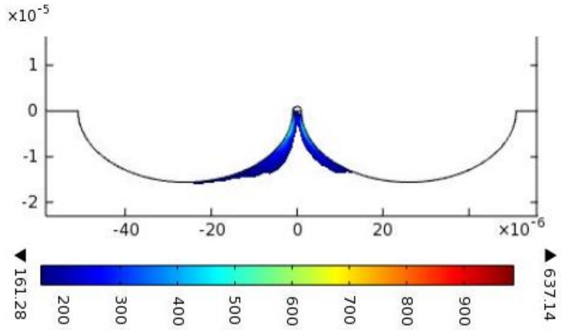


Figure 23. Crater depth at μm scale for sunflower oil

In order to minimize the roughness of machined surface, the power of the ultrasonic chain was taken into account in terms of ultrasonic pressure applied on profile microgeometry. Therefore attempts were made by changing the pressure parameter, until favorable results were observed concerning the depth of removed layer, i.e. surface roughness. The results such as the volume of material removed by the ultrasonic shock waves, corresponding to the breaking resistance at fatigue load (see relation 1) are shown in figure 24. Figure 14 shows the similar results when using P3 liquid.



a) Sunflower - 60 MPa contour load



b) Rapeseed - 80 MPa contour load

Figure 24. Von Mises stress [MPa], exceeding breaking resistance, due to cumulative microjets at EDM + US

The experimental results for roughness were compared to those of computer modeling, which are presented in the table 6.

Table 6. Validation of computer modeling results

Dielectric liquid	Results of computerized modelling for roughness [μm]	Experimental results of roughness[μm]
P3	16.8	18
Sunflower oil	18.5	20
Rapeseed oil	17.3	18

The values are very close, validating the model. The recorded differences emphasize the potential of roughness improvement by optimization of the key-parameter, the power applied on ultrasonic chain that includes the tool-electrode, which can be adjusted from the user interface of ultrasonic generator.

6. COSTS

An important aspect of choosing those two vegetable oils was their costs. Rapeseed oil and sunflower oil are produced and marketed in Romania. Table 7 presents the prices of the three dielectric media used.

Table 7. The cost of dielectric liquids

Dieletric liquid	Cost [lei/liter]
P3	20
Sunflower oil	3,9-5,9
Rapeseed oil	5,5-6,6

As one can see, the two vegetable oils are very competitive from the economic point of view comparing to industrial synthetic oil.

7. CONCLUSIONS

1. Two usual nonpolluting, very price competitive vegetable oils of sunflower and rapeseed, found in Romania were studied concerning their behavior as dielectric liquids at EDM. These were compared to a reference mineral oil, P3 widely used. Their measured parameters of kinematic viscosity and electrical conductivity met the requirements for EDM.

2. The tests were made on usual carbon steel samples by machining them through EDM and EDM+US, taking into account the progressive spreading of this hybrid technology. The recorded values of productivity and surface roughness confirmed the possibility of using these vegetable oils as dielectric liquids. Nevertheless, some process instability were encountered at classic EDM, reflected by lower values of productivity than in case of P3. This was caused by higher values of viscosity of tested vegetable oils than in case of mineral reference oil. This instability was much improved at ultrasonic aiding EDM due to controlled cavitational phenomena induced in the working gap. This contributes efficiently to evacuation of the removed particles from the gap because of the pumping effect produced by the variation of the pressure in the working gap. The values of productivity with vegetable oils at EDM+US were comparable to those obtained with mineral oil.

3. The modeling with finite element method of the material removal process comprised two components: thermal one due to EDM and mechanical-hydraulic one due to the ultrasonic effect. The results obtained from the modeling, validated by the experimental data, pointed out that ultrasonic shock wave have the ability to remove the peaks of the microgeometry of the machined surface, resulting the roughness decrease. A key-parameter, the power applied on ultrasonic chain could be optimized in order to minimize the machined surface roughness.

Further researches will be extended to the modeling of the EDM process, taking into account the viscosity different values of the dielectric liquids, which implies the modification of the plasma channel radius and of the EDM spot size, depending on the viscosity parameter, and the working temperature.

Other nonpolluting vegetable oils will be tested in order to eliminate their impact on the human operator, analyzing them from technical and economical points of view.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Ghiculescu, D., *Computer aided engineering and machining in nonconventional processes field* (in Romanian), Printech, Bucharest, (2013).
2. Satyarthi, M.K, Bharti, S., A review of Impacts of EDM on Environment, Health and Safety, *International Symposium on „Fusion of Science & Technology",* New Delhi, India, January 18-22, (2010).
3. Sanghani, C.R, Acharya, G.D., Effect of Various Dielectric Fluids on Performance of EDM: A Review, *Trends in Mechanical Engineering & Technology*, volume 6 (issue 1), (2016).
4. Karaosmanuoglu, F. et al., Fuel properties of cottonseed oil, *Energy Sources*, nr 21, pp. 821-828, (1999).
5. Abeysundara, D.C et al., Coconut oil as an alternative to transformer oil", *ERU Symposium*, pp. 1-11, (2001).
6. Pfluger, B., Familiar With Your EDM Fluid?, *Canadian Industrial Machinery,* (2013), available at: https://www.canadianmetalworking.com/article/metalworking/familiar-with-your-edm-fluid, accessed at: 20.12. 2018
7. Davim, J. Paulo et al., *Microfabrication and Precision Engineering Research and Development*, Woodhead, (2017), available at: https://www.sciencedirect.com/topics/engineering/dielectric-fluid accessed at: 20.12. 2018.
8. Bashi, S.M et al., Review of advances in transformer dielectric insulating fluids, *Journal of Industrial Technology*, vol. 14, pp. 71-86, (2005).
9. Ghiculescu, D., Marinescu, A., Performances obtained with local air purification system with active coal at EDM", *Review of industrial ecology,* no.10, pp.12, (2000).
10. Dorobantu, P.I, Chemical analyses of some commercial oils, mix type and their importance in feeding (in Romanian), *Review of scientific papers, Agronomy series*, vol. 5, (2008).
11. Jahan, M.P., et al. *Electrical Discharge Machining (EDM), Types, Technologies and Applications,* Nova Publishers, New York, (2015).
12. Drobotă, V. *Resistance of materials* (in Romanian), Didactic and Pedagogical, Bucharest, (1983).