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Article

Experimental Investigation of Stability of Vegetable Oils Used as Dielectric Fluids for Electrical Discharge Machining

Maria-Crina Radu [1,*], Raluca Tampu [2], Valentin Nedeff [1,3], Oana-Irina Patriciu [2], Carol Schnakovszky [1] and Eugen Herghelegiu [1]

[1] Department of Industrial System Engineering and Management, Faculty of Engineering, Vasile Alecsandri University of Bacau, Calea Marasesti 157, 600115 Bacau, Romania; vnedeff@ub.ro (V.N.); scarol@ub.ro (C.S.); eugen.herghelegiu@ub.ro (E.H.)
[2] Department of Chemical and Food Engineering, Faculty of Engineering, Vasile Alecsandri University of Bacau, Calea Marasesti 157, 600115 Bacau, Romania; tampu.raluca@ub.ro (R.T.); oana.patriciu@ub.ro (O.-I.P.)
[3] Gheorghe Ionescu-Sisesti Academy of Agricultural and Forestry Sciences, B-dul. Marasti Nr. 61, Sector 1, 011464 Bucuresti, Romania
* Correspondence: caxinte@ub.ro

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Abstract: One main drawback of electrical discharge machining (EDM) is related to the dielectric fluid, since it impacts both the environment and operator health and safety. To resolve these issues, recent research has demonstrated the technical feasibility and qualitative performance of vegetable oils as substitutes for hydrocarbon-based dielectric and synthetic oils in EDM. However, due to the higher content of unsaturated fatty acids, vegetable oils lose their stability, due to several factors such as heating or exposure to light or oxygen. The present study is a first attempt to analyze the extent to which the physic-chemical properties of vegetable oils change during EDM processing. Refractive index, dynamic viscosity and spectra analyses were conducted for sunflower and soybean oils. The results revealed that, under the applied processing conditions, no structural changes occurred. These findings are very promising from the perspective of EDM sustainability.

Keywords: vegetable oil; EDM; refractive index; viscosity; UV/Vis; FTIR

1. Introduction

Electrical discharge machining (EDM), nowadays the fourth most popular machining process after milling, turning and grinding [1], is used in many industrial sectors due to its ability to process, through the three existing variants (ram EDM, wire EDM and small hole EDM drilling), a large variety of materials (hard and soft, conductive and even nonconductive materials) into complex geometrical shapes, providing fine finishes and excellent geometrical accuracy (up to ±0.0025 mm) [2–5].

Ram electrical discharge machining, which is the “conventional” version of EDM, is the most efficient solution when a complex blind cavity is required [1]. The process is based on material erosion caused by sparks occurring between two electrodes-i.e., the tool and the workpiece-immersed in a dielectric fluid, acting as an insulator, when a power supply provides electric current. Two phases of the process can be highlighted: (1) the “on time” phase, when a suitable voltage breaks down the insulating properties of the dielectric fluid and an electrostatic force develops between the electrode and workpiece, causing the electrons to move from the cathode to the anode. The kinetic energy of the accelerated electrons is converted into heat, reaching up to 8000–12,000 °C, which causes the fluid to ionize and allows sparks of sufficient intensity to melt or vaporize the workpiece material; (2) the “off time” phase, during which the dielectric fluid cools the vaporized material and removes the EDM chips. Thus, the machine parameters, i.e., peak current, pulse on time, pulse off time, peak voltage, the type and characteristics of the dielectric fluid and the material properties of the electrode and the workpiece are important inputs that affect the performance of the electrical discharge machining process [6,7]. However, in the current context of ensuring sustainable development [8], the performance of a manufacturing industrial process is not only expressed in terms of qualitative and quantitative output, but also in terms of environmental and social improvements [9–12]. One main drawback of electrical discharge machining is related to the dielectric fluid, since it impacts both the environment and the operators' health and safety. On the one hand, hazardous emissions are generated in the machine working area during processing; on the other hand, particles removed from the workpiece and electrode mix with the fluid and form an erosion slurry. In both cases, contact with the dielectric (airborne or direct) fluid may lead to health problems (e.g., dermatological problems, asthma and lung diseases, or even cancer) [13–15]. Besides that, due to the content of hazardous substances like chromium, lead and cadmium (depending on the processed material and the electrode material), the used dielectrics present environmental problems when they are disposed of, and special, expensive procedures are necessary to neutralize their harmful content. Consequently, recent research related to the EDM process has been focused on finding solutions to make it more environmentally friendly and less harmful to the operator. One such a solution consists of using vegetable oils as dielectric fluids instead of hydrocarbon-based or synthetic oils, without affecting the process performance in terms of quality and productivity. Different studies have been published on this topic. For instance Valaki et al. [16] investigated the technical feasibility of *Jatropha curcas* oil as an alternative to kerosene; they reported better performance in terms of the material removal rate (MRR), surface roughness (SR) and surface hardness (SH) compared to kerosene. Khan et al. [17] also recently showed that *Jatropha curcas* oil may be conveniently used as a dielectric to improve EDM sustainability. Singaravel et al. [18] conducted a study on *Jatropha curcas* oil, sunflower oil, canola oil, cotton seed oil and kerosene and assessed the process performance according to five parameters, namely: MRR, SR, SH, electrode wear rate (EWR) and relative wear ratio (RWR). They found that vegetable oils led to similar results as mineral oils when used as dielectrics in EDM. Ng et al. [19] compared canola and sunflower oils with a conventional dielectric in terms of MRR and tool wear rate (TWR). The conclusion was that both vegetable oils have the potential to replace conventional dielectric fluids. Palm oil was also shown to be a highly sustainable and technically feasible alternative to kerosene in EDM. A study conducted by Valaki et al. [20] highlighted increased MRR (with 38%) and similar SR and SH compared to those obtained with kerosene. Singaravel et al. [21] recently reported that vegetable oils (sunflower oil, canola oil and *Jatropha curcas* oil) showed similar dielectric properties and erosion mechanisms compared to kerosene when they were used for the electric discharge machining of a titanium alloy (Ti6Al4V), also providing a cleaner and safer machining environment. Das et al. [22] also carried out a study on *Jatropha curcas* oil, canola oil and neem oil as alternatives to conventional kerosene for EDM of Ti6Al4V alloy. The authors concluded that vegetable oils (especially *Jatropha curcas* and canola oils) lead to better output (i.e., MRR, SR, overcut and tapper cut) but mentioned that a specific range of flushing velocity should be used. Mishra and Routara [23] reported that *Calophyllum Inophyllum* (*Polanga*) vegetable oil showed lesser environmental impact and enhanced productivity and process quality compared to a conventional hydrocarbon oil for the processing of a through-hardening alloy steel.

In this work, the authors address the sustainability of the EDM process by seeking to answer the following questions: what happens when vegetable oils are used as dielectric fluids? Do they maintain their stability or undergo structural changes, and if so, to what extent? The findings should afford useful information to establish the lifespan of vegetable oils as dielectric fluids for EDM. To this end, the refractive index, dynamic viscosity and spectra analyses (UV/Vis and FTIR) corresponding to two vegetable oils, compared with the same properties of a mineral oil, were evaluated.

2. Materials and Methods

2.1. Electrical Discharge Machining Setup and Processed Materials

The experimental tests were carried out on a KNUTH FEM 110 CNC electrical discharge machine, using a 3^3 experimental setup (Table 1). A 3 L copper pot incorporated into the machine tank was used as a dielectric working tank. A 15 mm square electrode of electrolytic copper, serving as the cathode, was designed to machine blind holes of 3 mm depth in the workpiece material (Figure 1). The electrode material properties are presented in Table 2.

Table 1. Process variables and their control levels.

Process Variables	Control Levels		
	Level 1	**Level 2**	**Level 3**
Working regime	E1161	E1181	E1191
Workpiece material	17–4 PH stainless steel	AZ31B magnesium alloy	AA 7075-T7351 aluminum alloy
Dielectric fluid	sunflower oil *	soybeans oil *	mineral oil

* Both oils were purchased from a local producer.


(**a**) (**b**)

Figure 1. EDM set-up: (**a**) Copper pot incorporated into the machine tank; (**b**) Copper electrode.

Table 2. Properties of electrode's material [24].

Melting Point (°C)	Resistance (Ωmm^2/m)	Density (g/mm^3)
1083	0.0167	0.0089

The working regimes were chosen from the preset regimes of the electrical discharge machine. Their specific parameters are presented in Table 3. These regimes are within the five most intensive working regimes allowed by the EDM machine, and were selected based on the following two considerations: (1) to assure consistency with the used electrode (according to the technical specifications of EDM machine [24]); and (2) to provide a high level of productivity, which, in industrial practice, results in lower manufacturing costs. The chemical composition of the processed materials is presented in Tables 4–6.

Table 3. Specific parameters of the working regimes [24].

Working Regime	Peak Current (I_p), (A)	Pulse on Time (T_{ON}), (μs)	Pulse off Time (T_{OFF}), (μs)	Mode
E1191	57.3	1250	420	00: the erosion time of each erosion impulse is equal
E1181	40.4	1000	380	
E1161	20.8	320	90	

Table 4. Chemical composition of the 17–4 PH stainless steel [25].

C (max)	Mn (max)	P (max)	S (max)	Si (max)	Cr	Ni	Cu	Nb
0.07%	1.00%	0.04%	0.03%	1.00%	15.00–17.50%	3.00–5.00%	3.00–5.00%	0.15–0.45%

Table 5. Chemical composition of the AZ31B magnesium alloy [26].

Mg	Al	Zn	Mn	Si	Cu	Ca	Fe	Ni
97%	2.50–3.50%	0.60–1.40%	0.20%	0.10%	0.05%	0.04%	0.005%	0.005%

Table 6. Chemical composition of the AA 7075-T7351 aluminum alloy [27].

Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Ti	Other	Al
0.00–0.12%	0.00–0.15%	2.00–2.60%	0.00–0.10%	1.90–2.60%	0.00–0.04%	5.70–6.70%	0.08–0.15%	0.00–0.06%	0.00–0.15%	balance

2.2. Dielectric Fluids

Two vegetable oils-sunflower oil and soybean oil-were chosen for this study for the reason that they can be easily purchased from local producers and are among the most important edible oils worldwide [28,29]. The oils were unrefined, obtained by cold pressing.

The mineral oil was the usual dielectric of the KNUTH FEM 110 CNC EDM machine (OEST FE FLUID 2460).

2.3. Determination of the Dielectric Fluid Properties

Determination of the dielectric fluid properties was made both before and after machining. After each test, the dielectric was replaced so that the oil properties would not be influenced from one processing to another. The utilized dielectric was then filtered using two layers of filter paper to remove the impurities.

2.3.1. Determination of the Refractive Index

The refractive index of each oil sample was measured using an AR4 Abbe refractometer. The apparatus measuring range was 1.3000–1.7000 nD. The optical system relative to the refractometer was based on the measurement of the refraction limit at the interface between the prism, having a refractive index of 1.7, and a liquid, having a refractive index less than that of the prism. The refractometer has LED illumination at a wavelength of 590 nm. All measurements were realized at room temperature.

2.3.2. Dynamic Viscosity Determination

Oil viscosity was determined using a falling ball Hoppler viscometer. This apparatus is used to measure the viscosity of Newtonian liquids by measuring the time required for a standardized ball to fall under gravity through a tube filled with the sample that is inclined at a certain angle. The length of the measurement zone in the tube is of 100 mm. Ball number 3 was used for the determinations (see Ball Parameters in Table 7). The time was measured using a chronometer. All measurements were realized at room temperature. To calculate the dynamic viscosity, the following equation was used:

$$\eta = K\,(\rho_b - \rho_o)\,t\ (\text{cP}), \tag{1}$$

where K is the ball constant; t is the time required for the ball to travel the distance between the two marks (s); ρ_b is the ball density; and ρ_o is the oil density (g/cm^3).

Table 7. Viscometer ball parameters.

Ball Number	Diameter (mm)	Weight (g)	Density (g/cm^3)	Constant K
3	15.62	16.272	8.152	0.0757

The oils density was measured using a glass densimeter with a measuring range of between 0.860 and 0.930 g/cm^3.

2.3.3. Spectrophotometric Analysis

The UV/Vis spectra of oils were shown to be in the range of 190–600 nm using an UV 1900 UV-VIS spectrophotometer (Shimadzu, Kyoto, Japan) with quartz cuvettes (10 × 10 mm). The oil samples were diluted with analytical purity hexane (Chemical Company, Iasi, Romania) before analysis (8 mg of oil/5 mL of hexane).

The Fourier transform infrared spectra (FTIR) of oils were shown to be in the range 400–4000 cm^{-1} on a FTIR Spectrometer (VERTEX 70, Bruker, Billerica, Massachusetts, US), equipped with ZnSe crystal.

3. Results

3.1. Processing Time

The durations for the machining process for every working regime are presented in Table 8. We noticed that this varied considerably, i.e., from 1.16–16.2 min. Although some of these processing times were quite short, this was due to the fact that the working regimes used in the current study were much more intense than those presented in the literature (up to three times) [16,20–22]. The results showed a decrease in the processing time of stainless steel (up to 44% for the most intense working regime) when the mineral oil was replaced by edible oils. At the industrial level, this would be a gain both from an economic (higher productivity) and a social point of view (shorter exposure time of the operator to a potentially toxic environment).

Table 8. Duration for the EDM process for every working regime.

Dielectric Fluid	Processing Time (min)			
	Working Regime	17-4 PH Stainless Steel	AZ31B Magnesium Alloy	AA 7075-T7351 Aluminum Alloy
First press sunflower oil	E1161	12.23	4.48	5.1
	E1181	7.52	1.53	1.43
	E1191	4.49	1.22	1.22
First press soybeans oil	E1161	13.5	5.03	4.47
	E1181	7.59	2.09	1.46
	E1191	5.4	1.35	1.16
Machine's mineral oil	E1161	16.2	2.31	4.29
	E1181	8.17	1.37	2.08
	E1191	8.02	1.3	1.29

The following results were analyzed in the light of the above processing times.

3.2. The Refractive Indices

The refractive indices measured for the three types of oils, in the unprocessed state and after their use as dielectric fluids for the electrical discharge machining of materials, using different working regimes, are presented in Table 9. The results show insignificant variation of the refractive indices after processing, irrespective of the working regimes and processed materials, compared to those corresponding to the dielectric fluids in their unprocessed state.

Table 9. Refractive indices of the used dielectric fluids.

Dielectric Fluid	Before Processing	After Processing			
		Working Regime	17–4 PH Stainless Steel	AZ31B Magnesium Alloy	AA 7075-T7351 Aluminum Alloy
First press sunflower oil	1.4730	E1161	1.4730	1.4730	1.4730
		E1181	1.4725	1.4730	1.4725
		E1191	1.4725	1.4730	1.4725
First press soybeans oil	1.4730	E1161	1.4725	1.4730	1.4725
		E1181	1.4725	1.4730	1.4725
		E1191	1.4727	1.4725	1.4720
Machine's mineral oil	1.4445	E1161	1.4455	1.4460	1.4460
		E1181	1.4460	1.4460	1.4435
		E1191	1.4455	1.4460	1.4455

3.3. The Dynamic Viscosity

Determination of the dynamic viscosity according to the methodology presented in Section 2 was possible only for the vegetable oils. Six measurements were performed for each sample and the standard deviation was calculated. The results presented in Table 10 represent the averaged values.

Table 10. Dynamic viscosity of the vegetable oils, η (cP).

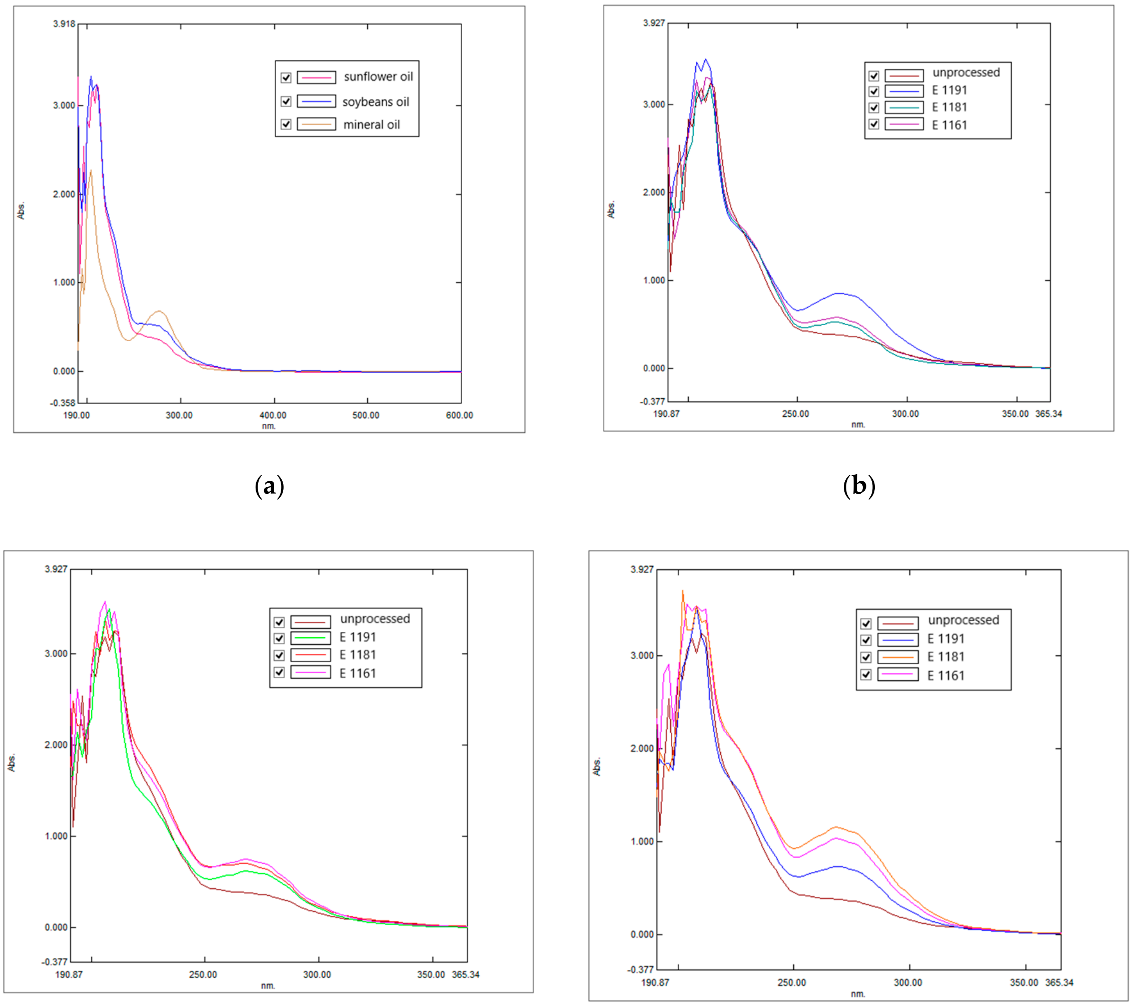
Dielectric Fluid	Before Processing	After Processing			
		Working Regime	17–4 PH Stainless Steel	AZ31B Magnesium Alloy	AA 7075-T7351 Aluminum Alloy
First press sunflower oil	50.70 ± 0.27	E1161	54.57 ± 0.44	51.18 ± 0.17	51.80 ± 0.15
		E1181	51.97 ± 0.19	51.15 ± 0.32	49.68 ± 0.29
		E1191	52.66 ± 0.18	52.47 ± 0.31	49.39 ± 0.10
First press soybeans oil	49.74 ± 0.18	E1161	51.33 ± 0.31	50.45 ± 0.27	49.86 ± 0.35
		E1181	51.04 ± 0.24	50.89 ± 0.30	49.47 ± 0.26
		E1191	50.12 ± 0.32	49.30 ± 0.25	50.40 ± 0.39

As the results indicate, the oil viscosity after processing varied within very small limits. However, relating it to the processed materials, higher values were obtained for both the considered vegetable oils in the case of processing 17–4 PH stainless steel, irrespective of the applied working regime. The explanation for this could be stronger oxidation of the oils due, on the one hand, to the longer processing time (a longer air-contact period and a higher oil temperature) and, on the other hand, to the chemical composition of the material (stainless steel contains a higher percentage of copper and a significant amount of chromium, both of which act as extremely efficient catalytic converters of the oxidation process) [30,31].

According to the working regime, generally, the oil viscosity increased with decreased intensity of the machining regime (in the case of stainless steel and aluminum alloy processing). This can be attributed to the longer processing time specific to the less intense working regimes, which favors oxidation. However, when processing a magnesium alloy, this tendency was no longer observed for the three working regimes; rather, the opposite was observed, i.e., more viscous oils generally resulted in more intense working regimes. This may have occurred because the magnesium salts (solids) generated by electrolysis, in combination with the dielectric oil (the dispersion medium), led to the formation of a "grease" that increased the oils' viscosity.

3.4. Spectra Analysis of the Dielectric Fluids

The UV/Vis spectra of the dielectric fluids are shown in Figure 2, and the FTIR spectra in Figure 3. The UV spectra of the unprocessed vegetable oils were very similar to that of mineral oil (Figure 2a). The graphs emphasize that between 350–600 nm, the oils did not exhibit any absorption, which indicates that the spectra are less informative in this range. The absorption band was recorded in the 190–330 nm region, where two absorption peaks were present, i.e., one at ≈275 nm and a bigger one at ≈210 nm. After machining, the oils' spectra showed the same tendency of variation as that of the sunflower oil, as shown in Figure 2b–d.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. UV/Vis spectra of dielectric fluids: (**a**) Before machining; (**b**) Sunflower oil, before and after machining the 17–4 PH stainless steel; (**c**) Sunflower oil, before and after machining the AZ31B magnesium alloy; (**d**) Sunflower oil, before and after machining the AA 7075-T7351 aluminum alloy.

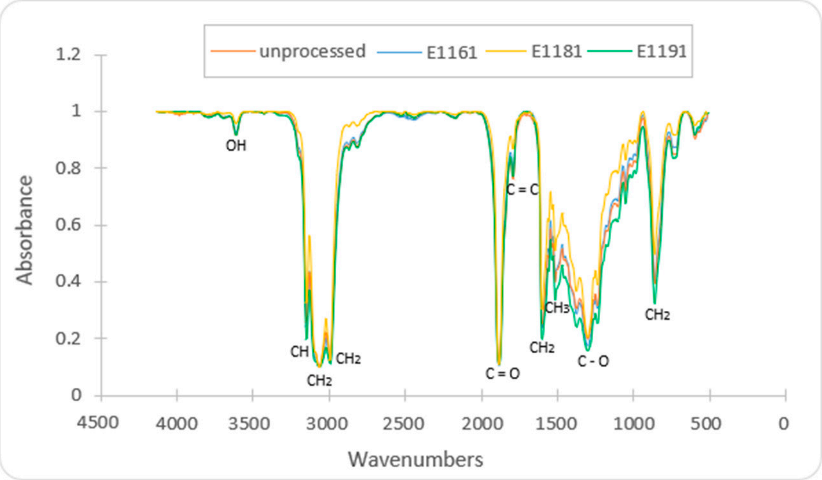


Figure 3. FTIR spectra of the sunflower oil.

The FTIR spectra registered for the sunflower oil revealed that there were no appreciable differences in the spectral features before and after processing, as well as between different working regimes, apart from changes in the intensity of some absorption bands; the most relevant change was within the range of 1465–721 cm^{-1}, where an increase in the absorbance of the oil corresponding to the middle intensive working regime (E1181) and a slight decrease of the absorbance of the oil corresponding to the most intensive working regime (E1191), were recorded. The obtained spectra are in very good agreement with those presented in the literature [32].

4. Discussion

The results presented in the literature demonstrate the technical feasibility and qualitative performance of vegetable oils as substitutes for hydrocarbon-based dielectrics and synthetic oils in EDM processing. However, due to the higher content of unsaturated fatty acids, one of the main issues related to vegetable oils is the loss of their stability, due to several factors such as heating, exposure to light or oxygen, etc. [33–36]. EDM processing may involve high processing times (depending on the complexity of part and the expected quality), and thus, long periods of light and oxygen exposure, as well as high temperatures (depending on the processed material and the applied working regime). In this context, the question arose as to whether vegetable oils were still effective as dielectrics after a certain number of usage cycles. The present study was a first attempt to analyze to extent to which the physic-chemical properties of vegetable oils change during EDM processing. Refractive index, dynamic viscosity and spectra analyses were conducted for sunflower and soybean oils. The results revealed that, for the applied processing conditions, no structural changes occurred. These findings are very promising from the perspective of EDM sustainability. From an economic point of view, electrical discharge machining would be cheaper, because soybean and sunflower oils are available worldwide, with an increasing trend in production (soybean oil production increased by ≈20% in 2019/2020 compared to 2013/2014, while sunflower oil production increased by ≈30% in 2019/2020 compared to 2013/2014 [37]) and are cheaper than mineral oils (the oils purchased for this study cost less than 1 euro/L). Additionally, it was reported that vegetable oils allow higher material removal rates compared to conventional hydrocarbon oils [17], which means increased productivity and lower production costs. From an environmental point of view, soybean and sunflower oils do not contain harmful substances, have a high biodegradability level (>95% compared to less than 30% for mineral oil [38,39]) and are renewable. And last but not least, sunflower and soybean oils are not toxic for the operator (although they do emit the smell of old kitchen grease, as a result of interactions with heat and agitation during processing; however, this may be effectively attenuated with different deodorants).

Finally, they have higher flash and fire points than conventional mineral oil (>300 °C [38,39]), and hence, present low explosion risk, which makes them safer for the operator and the environment.

In contrast, the slight increase in viscosity observed in the case of stainless steel processing compared to the other two softer materials could be an indicator that longer processing times may lead to structural changes in the oils, affecting their dielectric properties, with a direct impact on processing productivity. Thus, further research should be carried out to obtain more conclusive results, especially if we consider the need to use vegetable oils for several processing cycles. Also, the variation in the viscosity of oils observed when processing the magnesium alloy with three working regimes requires additional studies, to determine the extent to which the processing of such materials, whose compounds have lubricating properties, could affect the quality of vegetable oils used as dielectrics, over long periods of time and at high temperatures.

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