A sustainability index for the micro-EDM drilling process

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Abstract

The increasing attention being paid to environmental protection has resulted in significant changes in all production systems. Moreover, system efficiency and productivity should be improved and manufacturing system design must take ecological constraints into consideration. Accordingly, the definition of an index of sustainability can help in assessing the different and sometimes conflicting aspects of a manufacturing process, such as manufacturing costs, energy consumption, waste management, personnel health, and operational safety. In this study, a sustainability index is defined and applied to a micro-electrical discharge machining (EDM) process in drilling operations. The index is composed of five sub-indices that evaluate a particular aspect: energy consumption, environmental impact, dielectric consumption, wear of electrode, and machining performance in general. Each sub-index is calculated by assigning an economic cost to the undesirable impact through a formulae of coefficients (weights) and variables (such as machining time and electrode wear). High index values mean that the process consumes a significant amount of resources and/or produces environmental pollution that is poorly sustainable. In contrast, lower values indicate that the process consumes fewer resources; therefore, it has a lower impact and is more sustainable. The developed sustainability index is applied to an experimental case: the drilling of micro holes in stainless steel (AISI 316L) and titanium alloy (Ti6Al4V) using two types of electrodes (brass and tungsten carbide). Several types of conventional and innovative dielectrics are used (both liquid and gas): kerosene, demineralised water, vegetable oil, compressed air, and oxygen gas. For each combination of workpiece, electrode material, and dielectric tested, the sustainability index is calculated and the outcomes are analysed. It is found that the dielectric plays a major role in the EDM process, because it significantly influences the machining performance. Moreover, it affects the environment in terms of the quantity of consumed resources and pollution created by the process. The type of electrode also affects the process. Within the limit of the present investigation, water and vegetable oil have the lowest environmental impact. For these dielectrics, brass electrodes halve the impact when stainless steel is processed, while tungsten carbide is better for

titanium sheets. The use of kerosene as a dielectric coupled with tungsten carbide as an electrode makes the process less green and should be avoided. The combination of air as a dielectric and tungsten carbide as an electrode proves interesting. Oxygen as a dielectric shows instabilities during the process, thus performing poorly in terms of the index. The proposed model for measuring the sustainability of the micro-EDM drilling process is designed to be useful in industrial applications and is easily computable. The index provides a tool that can assist in the decision-making stage of selecting conditions aimed at minimising environmental impact.

Keywords: micro-EDM, sustainability index, sustainable process, drilling, unconventional dielectric

1. Introduction

Recently, increasing attention had been devoted to the sustainability of both processes and products. The National Council for Advanced Manufacturing (2009) stated that sustainable production necessarily includes both sustainable products and processes. In many countries, governments are enforcing ever-stricter environmental regulations by promoting energy-saving and low-emission manufacturing activities. This guidance on environmental protection requires industrial actors to not only improve system efficiency and productivity, but also examine their manufacturing system design. Hence, they must take ecological constraints into account, and therefore incorporate environmental considerations into the design and operation of manufacturing processes or systems (Nujomm et al., 2016).

The concept of sustainability can be interpreted in many ways (Moldavska and Welo, 2017). In fact, several domains can be considered; therefore, as a function of these, the expression ‘sustainable manufacturing’ can assume different meanings. One of these is ‘*the creation of manufactured products by minimising the usage of energy and other natural resources and therefore the negative environmental impact*’ (Nujoom et al., 2018). Based on this definition, sustainable manufacturing processes should include several aspects (Figure 1) related to manufacturing cost, energy consumption, waste management, environmental impact, personnel health, and operational safety (Jawahir et al., 2006).

Figure 1. Sustainability elements of manufacturing processes (Jawahir et al., 2006)

A typical approach for the sustainability of machining processes (named Triple Bottom Line) was proposed by Elkington (1998), where three dimensions were considered: economic, ecological, and equity (3E). Alvarez et al. (2017) declared that several works on sustainability are present in the literature, but the majority of these do not simultaneously consider the three dimensions mentioned previously, and they are very general.

From the perspective of the product, to achieve good results in terms of sustainability, the development of a product should take into account the entire life cycle (incorporating the end-of-life stage considerations) at the design stage. A novel design for end-of-life methodology was developed by Lee et al. (2014), elaborating a quantitative indicator (end-of-life index) considering disposal, recovery, and disassembly aspects. This index enables designers to reach maximum product sustainability by selecting from available alternatives.

Sustainable manufacturing may be improved by several strategies, such as re-designing or even changing manufacturing practices, when designing new products (Dassisti et al., 2019). Another approach for improving product sustainability involves optimisation of the process in terms of energy, quality, and productivity by selecting suitable process parameters. An example was reported by Pereira et al. (2017), where the helical milling process of aluminium alloy was taken into account. The machining process can be optimised by also considering the tool geometry, as presented by Cui et al. (2019), who investigated the effect of cutting tool geometry on the energy consumption of a micro-machining process.

Based on these considerations on the sustainability of both processes and products, the main question is how to evaluate sustainability. Assessments can be made using sustainability indicators that evaluate sustainability performance in a quantifiable way. The indicators can be classified into quantitative (calculated by formulae such as the energy consumption and CO_2 emissions) and qualitative (quantified by means of surveys or based on experience such as health risks).

Nevertheless, these indicators for the manufacturing industry must satisfy the following criteria: measurable (the indicator must be able to measure in a quantitative way the aspects related to sustainability), relevant and comprehensive (the indicator must provide useful sustainability information on the manufacturing process), understandable and meaningful (the indicator can be easily understood by the community), manageable, reliable, cost-effective data access (based on accessible data), and timely (Che-Bong et al., 2013).

Several works concerning the definition of sustainable indicators are available in the literature. However, most of them are not related to products and processes but are concerned with sustainability of a company or a sector and environmental indicators of a region or country (Bordt, 2009).

Studies concerning the measurement of sustainability for manufactured goods are also available in the literature, in which some authors developed indicators of product sustainability (e.g. Fiksel et al., 1998). A sustainability index (SI) of a product as a management tool for the sustainability assessment of the development of Ford products was adopted by Schmidt and Butt (2006). Another developed method correlates the economic value of a manufactured product with its environmental impacts (Dickinson and Caudill, 2003; Gao et al., 2003) without considering the post-use phase and social aspects. In the study conducted by Bork et al. (2016), all pillars of the production processes were considered in developing a tool for assisting industrial decision makers. This tool uses individual metrics of a production process (both qualitative and quantitative) when generating an SI. Most of the manufacturing sustainability assessment studies focus on the product rather than on the process (Saad et al., 2019), although the manufacturing processes contribute significantly to the consumption of resources as well as the amounts of hazardous and toxic waste.

The manufacturing process can be assessed using six sustainability indicators: personnel health, safety, environmental impact, cost, material and energy consumption, and waste management (Feng et al., 2016). While such an approach is comprehensive, it is not applied by all authors (who prefer to focus on a particular aspect).

An effort to consider all such aspects was made by Linke et al. (2013), who presented a method for assessing the sustainability of a discrete manufacturing process through a total indicator. This indicator considers the three pillars of sustainability and the method was applied to a grinding technology. Through the index, it was possible to compare two different technological solutions.

In the study performed by Schuch Bork et al. (2016), a methodology for assessing an SI of industrial production processes was presented using a hierarchical structure of three levels: individual metrics, sub-index, and SI. The sub-indices represent the aspects of sustainability (economic, technological, environmental, and social), whose individual metrics are aggregated to compose the observation of its influence on the aspect of sustainability that it belongs. Individual metrics can be divided into objective (directly measured) and subjective (in this case, the score is assigned by subjective opinions of industrial research experts or academic researchers). This methodological tool allows the identification of critical variables, facilitating the implementation of actions that aim at improving the level of sustainability in different technological situations. A sustainability indicator for optimising a grinding process was developed by Priarone (2016), taking into account the process efficiency of industrial operations. The process efficiency is a trade-off between process sustainability (energy savings) and product requirements (machined part quality). With different combinations of weighting factors of the two aspects, the optimisation target may move to maximise the surface finish or energy saving or intermediate conditions. However, product sustainability and process sustainability are highly correlated: the evaluation of product sustainability cannot be separated from the sustainability of manufacturing technologies.

In general, the use of conventional mineral-based fluids as coolants and lubricants is a critical aspect common to many manufacturing technologies, especially for material removal processes such as metal cutting. Actually, these cutting fluids cause many environmental and biological problems. To improve the sustainability of the cutting process, an alternative is to use other fluids assumed totally biodegradable and eco-friendly, such as vegetable oils, liquid nitrogen, or compressed air (Chetan et al., 2015; Tan et al., 2002). In the study conducted by Liang et al. (2019), the dry turning process of Ti6Al4V was investigated and an effort to develop a sustainability quantitative index, namely product SI, was made. This index considers several factors such as environmental effect, operator health, processing efficiency, energy consumption, workpiece quality, tool cost, and coolant recycling and disposal. The scores of each impact factor were ranked from the worst to the best standard based on experimental results.

Electrical discharge machining (EDM) is a non-conventional technology used to machine any conductive material (including high-strength metals) that are considered difficult to cut with conventional techniques. EDM removes material by a series of rapidly recurring electric arc discharges between the electrode (the cutting tool) and the workpiece, in the presence of an energetic electric field. The electrode is guided along the desired path, very close to the workpiece but without contact. Consecutive sparks produce a series of micro-craters on the workpiece and remove material along the cutting path by melting and vaporisation.

An important sector where the EDM technology is commonly used is micro-manufacturing. Micro-EDM is one of the most effective methods for producing micro deep holes in metals used for several purposes in many products, such as inkjet printer nozzles, spinner holes, turbine blade cooling channels, diesel fuel injection nozzles, and drug delivery orifices (Diver et al., 2004). The material removal mechanism of micro- and macro-EDM is the same; however, in the case of micro-EDM, each discharge conveys less energy, and the discharge frequency and specific power consumption are higher (Gutowski et al., 2006; Kellens et al., 2011). In these conditions, the system is able to realise very small features (less than 1 mm) affecting the energy effectiveness that in general is lower because the fraction of energy used for vaporising the dielectric is relatively higher (Liu et al., 2016; Qian et al., 2015).

Evaluation of the sustainability of the EDM process is another important aspect to be considered. Currently, there are many studies on EDM that are aiming to improve process efficiency and minimise environmental impact (Singh and Sharma, 2017). The sustainability is often associated with the optimisation of process performance (Modica et al., 2011). Shen et al. (2017) assumed that the material removal rate (MRR) and power consumption significantly affect the process sustainability. Consequently, optimising the process parameters makes the process more sustainable.

Recently, the energy efficiency was investigated and an energetic model was implemented to both predict the energy consumption and identify the machine components that have more impact on the overall energy consumption (Marrocco et al., 2017). It was demonstrated that the majority of the energy (up to 80%) is absorbed by the auxiliary units (air compressor, filters, chiller unit, etc.). The micro-EDM process itself requires only 1% and the rest is for the control and supply units.

The sustainability of the EDM process is particularly influenced by the type of dielectric. The common dielectrics used for industrial applications are hydrocarbon oils or water-based solutions (Abbas et al., 2012; Chakraborty et al., 2015; Niamat et al., 2017). However, the use of these types of dielectrics causes some problems such as electrolysis corrosion with water as a dielectric and toxic hydrocarbon disposal when a kerosene-based dielectric is used (Yeo et al., 1998; Leppert, 2017). Operator risk potential is high due to possibilities of fires and explosions and formation of toxic and hazardous substances in the working area (Valaki et al., 2015). The effects of kerosene as a dielectric was investigated by Abbas et al. (2012), and they concluded that using water or dry EDM is a possible solution for preventing environmental pollution. Kerosene may release vapours and fumes that may present health hazards for operators. It has been pointed out that a quantitative assessment of health impacts requires more data about pollutant concentration in fumes, which is heavily dependent on the dielectric type (Singh and Sharma, 2017; Evertz et al., 2006).

Alternative dielectrics have been evaluated. Valaki and Rathod (2016) and Valaki et al. (2016) successfully tested waste vegetable oils as alternative to conventional dielectric fluids. The use of biofluids permits increasing the sustainability of the process to ameliorate environmental friendliness, operational safety, and personnel health issues. A variant of the process uses a gaseous dielectric (instead of a liquid) such as oxygen, nitrogen, argon, or compressed air (dry EDM), which is channelled to the machining area by means of appropriate pipe and pressure control systems. The gas cleans the machining zone, prevents debris attachment on the electrode, and enables reintegration of the dielectric strength in the gap after formation of the plasma channel. This machining technique has lower manufacturing process costs, dielectric medium costs, and pollution compared with that using a liquid dielectric (Pandey and Singh, 2010; Paul et al., 2013). However, it has the following disadvantages: the surface finish is generally poor due to debris reattachment, the MRR is low, there is odour of burning, and cooling of the machining area is slower. However, the tool wear rate is lower, owing to the unwanted attachment of the debris on the workpiece and consequent 'shielding effect' on the tool electrode (Zeng et al., 2012). To overcome the above-mentioned drawbacks, near-dry solutions were tested (Tao et al., 2008) by applying a liquid–gas mixture as the dielectric medium.

Environmental problems using the EDM technology are not only due to the dielectric nature. In fact, the process in general is characterised by a poor MRR, the electrode is subject to erosion, and the process is characterised by high specific energy consumption (Gutowski et al., 2006; Tristo et al., 2015), there are hazardous emissions near the operator breathing zone during machining, and the possibility of fires and explosions is high (El-Hofy and Youssef, 2009). A study on the environmental impact of the EDM process was reported by Kellens at el. (2011), while the effect of process parameters on the breathing zone concentration of gaseous hydrocarbons was shown by Sivapirakasam et al. (2011).

The optimisation of the EDM process parameters for green manufacturing using a combination of grey relational analysis associated with principal component analysis had been developed by Jagadish and Ray (2016). In the study conducted by Sivapirakasam et al. (2011), a systematic framework for EDM parameter optimisation was developed, to minimise degradation of the environment. Wang et al. (2018) evaluated the EDM process from the green manufacturing point of view using an integrated approach, which is a combination of decision-making trials, laboratory evaluations, and analytic network processes.

Table 1 provides brief information of the papers available in the literature on the sustainability of the EDM process.

Table 1. Brief information on sustainability of EDM process from the literature

Micro-machining	Parameter optimisation	Experimental research	Dielectric type	Social aspects	Elaboration of index	
	X	X	X			Valaki and Rathod, 2016; Valaki et al., 2016; Shen et al., 2017
				X	X	Wang et al., 2018
X	X	X				Modica et al., 2011
X		X			X	Kellens et al., 2011
X		X				Marrocco et al., 2017
	X	X		X	X	Sivapirakasam et al., 2011
			X	X		Valaki et al., 2015; Leppert, 2017
			X			Srinivas et al., 2017; Chakraborty et al., 2015
X			X			Chakraborty et al., 2015
	X	X		X		Jagadish and Ray, 2016
				X		El-Hofy and Youssef, 2009
X		X				Tristo et al., 2015
		X	X			Tao et al., 2008
X	X	X	X			Zeng et al., 2012
X		X	X			Paul et al., 2013; Niamat et al., 2017
		X		X		Evertz et al., 2006
			X			Abbas et al., 2012
		X	X	X	X	Yeo et al., 1998

Based on this literature analysis, it can be asserted that many studies dealt with the topic of EDM sustainability. However, very few tried to evaluate the sustainability of the process (and how it is affected by some variables) in an effective and quantitative way (Srinivas et al., 2018). The reason could be due to the intrinsic complexity of the process, which is characterised by many parameters that have interactions between them (Aide et al., 2014).

The present study proposes a model for evaluating the sustainability of the micro-EDM process in drilling operations through the elaboration of an SI, taking into consideration all the aspects related to sustainability. This index represents the environmental impact in terms of the quantity of consumed resources and pollution effects created by the process. In the case of the micro-EDM drilling process, the aspects considered are the energy consumption, environmental impact, dielectric consumption, wear of electrode, and machining performance in general. This approach provides a tool that permits the evaluation of the environmental impact of a machining operation, evaluating several aspects that can then be summed up in a single comparable value. A similar approach by Singh et al. (2009) claimed to be effective in focusing attention and simplifying the problem. The index was implemented in an experimental case: the drilling of micro holes on stainless steel (AISI 316L) and titanium alloy (Ti6Al4V) using two types of electrodes (brass and tungsten carbide) and several types of dielectrics (both liquid and gas): kerosene, demineralised water, vegetable oil, compressed air, and oxygen gas. For each combination of workpiece and electrode material, a comparison between the different types of dielectrics and an analysis of the critical aspects related to the sustainability were conducted. The proposed index is simple, practical, and can be easily implemented, as suggested by Schuch Bork et al. (2016). It can assist the decision-making stage of the selection of process conditions for micro-EDM, aiming at minimising the environmental impact.

2. Elaboration of sustainability index for micro-EDM drilling

The author's intent was to propose an index that can be applied to real practice in a simple and practical way as recommended by Schuch Bork et al. (2016). In this perspective, it was assumed that the economic value of the consumed resources could be represented by its environmental impact. A similar approach that links the economic value of a product with its environmental impact to provide a practical criterion for sustainability was already used (Dickinson and Caudill, 2003). The SI, expressed in euro [€], represents the environmental impact in terms of the quantity of consumed resources and pollution effects created by the EDM. High values of the index mean that the process consumes a significant amount of resources and produces high levels of environmental pollution; thus, it has poor sustainability. Low values indicate that the process consumes fewer resources and has a lower impact; therefore, it is more sustainable. The index comprises five sub-indices, and each of them involves coefficients (weights) and variables (i.e. machining time and electrode wear). For the determination of the coefficients, some easily accessible economic considerations were used except for some cases where simplifications were necessary. This choice makes the model very simple and easy to use. The values of the variables were obtained from experimental tests. Each sub-index evaluates the following particular aspects (Figure 2):

- *Energy consumption*. This represents the electrical energy consumption of the micro-EDM machine. The energetic sustainability (S_{energy}) is calculated as follows:

$$S_{energy} = E_{tot} \cdot c_{el} \qquad (1)$$

where E_{tot} represents the absorbed energy of the machine and c_{el} is the cost per unit of electricity.

- *Electrode wear*. The sustainability related to electrode wear (S_w) can be evaluated as

$$S_w = W \cdot c_e \qquad (2)$$

where W is the volume of the consumed electrode and c_e is the unit cost per volume of tool.

- *Dielectric*. To estimate the impact of the dielectric, the purchase cost of both the dielectric and filters and their disposal costs were considered.

The purchase cost of a dielectric (C_d) charged to the EDM operation having a time duration of t_e (erosion time) was evaluated as

$$C_d = \frac{c_{ad} \cdot V_d \cdot t_e}{L_d} \qquad (3)$$

where c_{ad} is the price per litre of the dielectric, V_d is the volume of the dielectric tank, and L_d is the lifetime of the dielectric.

The purchase cost of the filter (C_f) for the dielectric unit can be estimated as

$$C_f = \frac{c_{af} \cdot t_e}{L_f} \qquad (4)$$

where c_{af} is the cost of the filter and L_f is its lifetime.

The dismantling cost of the dielectric is defined as

$$C_s = \frac{c_s \cdot V_d \cdot t_e}{L_d} \qquad (5)$$

where c_s is the unitary dielectric dismantling cost per litre.

The dielectric sustainability includes the three above-mentioned elements:

$$S_{dielectric} = C_d + C_f + C_s = \left(\frac{(c_{ad} + c_s) \cdot V_d}{L_d} + \frac{c_{af}}{L_f}\right) \cdot t_e \qquad (6)$$

- *Process performance*. This factor is related to the geometric characteristics of the micro holes. The variability of the hole dimensions under the same experimental conditions must be taken into account. The selection of the EDM process parameters has influence on the diameter overcut. The process performance sustainability considers both the standard deviation of the top diameter and the economical value of the resources used to realise the hole. This economical value comprises the values of the consumed electrode, machine time, and workpiece. The sum of these three terms is multiplied by a coefficient (α) that represents the probability of producing a defective hole. In this work, a hole is assumed to be conforming when its top diameter is within tolerance. Under the hypothesis of normal distribution of the diameter, the percentage of experimental tests producing a diameter that is out of tolerance can be estimated. Its value is evaluated based on the standard deviation of the top diameter calculated using residuals from a linear regression model. Only the standard deviation of values was used to evaluate alpha, regardless of the mean value of their distribution that could be controlled by other means (i.e. by adjusting the electrode size). In other words, the experimental condition is fixed: as the geometric dimension variability increases, the process becomes less predictable, and the process performance negatively affects the SI. On this basis, the performance sustainability can be estimated as follows:

$$S_{performance} = (W \cdot c_e + t_e \cdot c_m + k) \cdot \alpha \tag{7}$$

where c_m is the hourly cost of the micro-EDM machine and k indicates the value of the workpiece. Several situations can occur when the top diameter is out of tolerance: in some cases, the entire workpiece is treated as waste; in other cases, the workpiece can be reprocessed. Moreover, the value of the workpiece depends on many factors such as material, dimension, and previous machining. Based on such considerations, it is very difficult to assign a general value of this parameter; therefore, for the sake of simplicity, its value was set as zero.

The electrode wear was used to calculate both the sub-index related to electrode wear and that related to performance. It is worth nothing that S_w refers to the production of conforming holes, while $S_{performance}$ takes into account operations unable to yield an acceptable hole, that is, resources used up to produce scrap. In fact, two situations can occur: when the hole is within tolerance, $S_{performance}$ is null and the electrode wear is computed only for S_w. When the hole is out of tolerance, $S_{performance}$ represents the penalty for the production of a defect.

- *Environmental impact*. This represents the environmental impact of the dielectric used. Several aspects were considered such as fire hazards, generation of fumes and vapours, possible skin irritation of operators, generation of toxic fumes, dust formation, possible re-use of the dielectric, and dielectric and filter dismantling. The pollution effects caused by the contamination of the electrode and workpiece during machining due to wear were assumed negligible. Most of these aspects were not directly measurable, but were estimated based on a subjective evaluation. It can be noted that a similar approach was adopted by Schuch Bork et al. (2016) and Wang et al. (2018). Each of these studies used a qualitative evaluation from 0 to 3 based on literature data (a larger value means that the environmental impact is more severe). The penalty coefficient k_i was defined as the ratio between the sum of these evaluations and the maximum achievable points. The environmental sustainability (S_e) was evaluated as follows:

$$S_e = (1 + k_i) \cdot \beta \cdot t_e \qquad (8)$$

where β represents the unitary environmental cost caused by using the technology. Its numerical value determination cannot be performed in a simple way but, at least, the order of magnitude of β can be gathered from industrial insurance premiums. It was assumed that the premiums consider both the probabilities of risks and their extents connected with the industrial activities.

Based on the above description, the SI was calculated as

$$SI = S_{energy} + S_w + S_{dielectric} + S_{performance} + S_e \qquad (9)$$

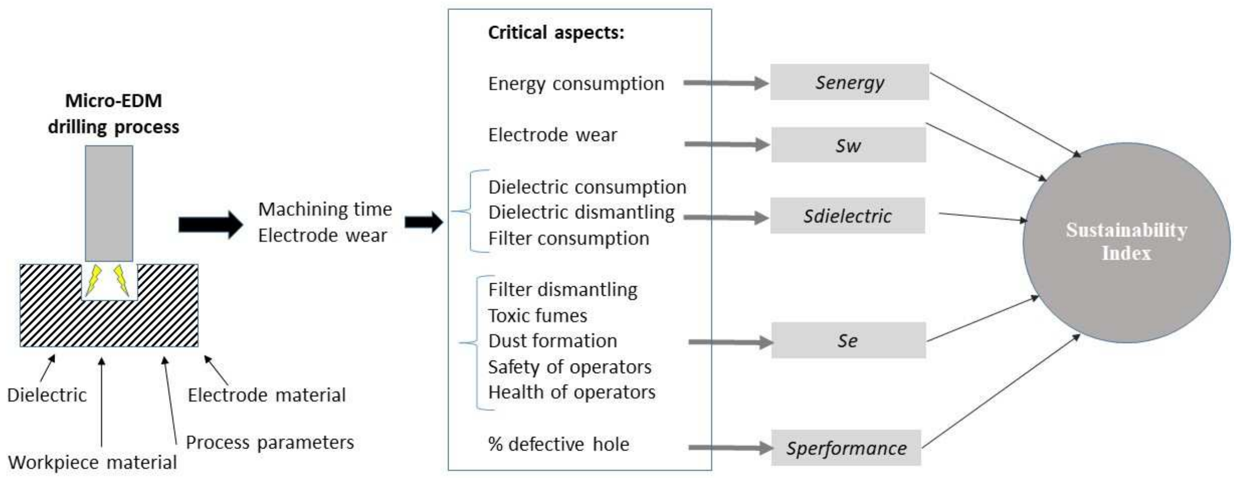

Figure 2. Factors considered for the development of sustainability index (SI) of micro-EDM technology

Although the values are expressed in euro, the indices try to measure the sustainability of the manufacturing operation. Some other cost items (such as lighting and air conditioning costs) could be related to sustainability issues. In this work, their effects were neglected for simplicity. The effects of the working conditions of the micro-EDM drilling on the process sustainability are evaluated in the succeeding sections. The working condition includes the electrical process parameters, tool type, dielectric, and workpiece materials.

3. Experimental tests

The SI described above was calculated for a micro-EDM drilling application. Micro holes were drilled in stainless steel (AISI 316L) and titanium (Ti6Al4V) plates having a thickness of 0.5 mm using the Sarix SX-200 machine. Table 2 lists the properties of the two workpiece materials. Tubular electrodes made of two different materials, i.e. tungsten carbide (WC) and brass, having an external diameter of 0.3 mm and internal diameter of 0.12 mm, were used. Both liquid and gaseous dielectrics were tested, namely kerosene (HEDMA 111), demineralised water, vegetable oil (soya bean), air (10 bar), and oxygen (9.5 bar). The dielectric properties are presented in Table 3. The gaseous dielectrics were injected in the machining zone through the tubular electrode (Figure 3).

Figure 3. Implementation of dry EDM

For each hole, the machining time, electrode wear, energy consumption, and top diameter were measured correspondingly. A program for the automatic drilling of holes using different process parameters was implemented into the Sarix EDM machine. This program permits recording the machining time and the frontal electrode wear for each micro hole. The time starts when the clamp begins its stroke along the Z-axis over the position where the micro hole will be drilled. The clock stops after a few seconds from the workpiece piercing. After drilling each hole, the electrode clamp was moved to a specific reference point to measure the electrode wear by an electrode touching operation. The frontal tool wear was calculated as the difference between the initial and final length of the electrode. Then, the electrode was cut using the wire EDM unit to restore the same initial electrode conditions for each hole. The absorbed energy of the EDM machine during the drilling operation was measured using a watt meter with an acquisition rate of 0.2 Hz (Christ Elektronik, CLM1000 Professional), located at the main energy supply (Figure 4). When using gaseous dielectrics, the dielectric unit was switched off and for compressed air, only the absorbed energy of the compressor was assessed. The top diameter of the micro holes was measured using a coordinate measuring machine, Zeiss O-Inspect 543. In this study, it is assumed that the quality requirement regards only the top diameter. If the top diameter is within tolerance, the hole is assumed to be good. When the hole is out of tolerance, the process sustainability is penalised. The hole diameter is influenced by both the electrode diameter and electrical process parameters. Based on the consideration that the tests were performed using the same electrode diameter (0.3 mm), only the standard deviation of diameter was used to evaluate the probability of producing a defective hole (called alpha in equation 7), regardless of the mean value of the distribution, which could be controlled by other means (i.e. by adjusting the electrode size).

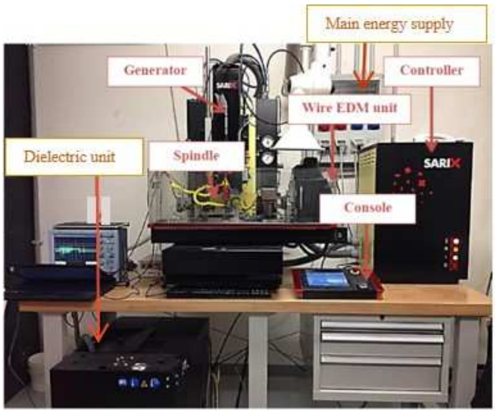

Figure 4. Components of the EDM machine and location of the energy measurement point

Table 2. Properties of workpiece materials

	AISI 316L	Ti6Al4V
Density [kg/m^3]	8000	4420
Melting temperature [°C]	1375–1400	1634–1664
Specific heat [J/kg·K]	500	560
Thermal conductivity [W/m·K]	16.3	21.9
Electrical resistivity [Ω·mm^2/m]	0.714	0.554

Table 3. Properties of the dielectrics

Type of dielectric	Dynamic viscosity [g/m·s]	Density [g/dm^3]	Breakdown voltage [kV/mm]	Thermal conductivity [W/m·K]	Specific heat [J/g·K]	Dielectric constant
Kerosene	1.64	781	14–22	0.14–0.149	2.1–2.16	1.8
Demineralised water	0.92–1	1000	65–70	0.606–0.62	4.19	80.4
Vegetable oil	48.4	915–925	62–65	0.14–0.16	1.67	2.86
Air	0.019	1.205	3	0.016–0.026	1.005	1.000536
Oxygen	0.021	1.43	0.92–2.6	0.026	0.92	1.00049

The variables used in the sub-index formulae are the machining time, electrode wear, and coefficient alpha, which are influenced by the electrical process parameters (peak current and voltage). The type of dielectric influences the selection of process parameters. For the conventional dielectrics, their selection was supported by literature data and by recommendations from the manufacturer. However, this was not possible for the unconventional dielectrics. Gaseous dielectrics have been already tested but only for some conditions; furthermore, there is some degree of disagreement among the results. For the vegetable oil dielectric, the literature does not fully support the parameter selection. For this reason, the ranges of peak current and voltage for the unconventional dielectrics were defined through a preliminary experimental campaign aiming to achieve feasibility first, then optimisation of machining time. Moreover, to investigate the range of peak current and voltage where drilling can occur, for each combination of workpiece material–electrode material–dielectric, a central composite design (CCD) 2^k with central point was used to plan the tests. Experiments with gaseous dielectrics were not complete, because not all treatments proved to be feasible. Each experimental condition was repeated twice except for the central point, which was replicated 10 times. Table 4 presents the various process parameters for each combination of workpiece, electrode, and dielectric. It can be noted that in the Sarix EDM machine, the peak current is expressed as an index, and there is no direct correlation with the actual value of current expressed in amperes. The pulse characterisation of the Sarix machine through the comparison of voltage and current waveform with varying input parameters can be found in the literature (Liu et al., 2010).

Table 4. Process parameters varied for each workpiece, electrode, and dielectric combination

			Type of dielectric									
			Kerosene		Demineralised water		Vegetable oil		Compressed air		Oxygen	
Material	Electrode		I	V [V]	I	V [V]	I	V [V]	I	V [V]	I	V [V]
AISI 316L	WC	min	49	79	49	79	78	98	-	-	78	78
		med	70	100	70	100	90	110	90	100	90	90
		max	100	121	100	121	102	122	-	-	102	102
	Brass	min	49	79	49	79	78	98	91	91	-	-
		med	70	100	70	100	90	110	100	100	-	-
		max	100	121	100	121	102	122	109	109	-	-
Ti6Al4V	WC	min	49	79	49	79	78	98	-	-	68	88
		med	70	100	70	100	90	110	80	100	80	100
		max	100	121	100	121	102	122	-	-	92	112
	Brass	min	49	79	49	79	49	79	-	-	-	-
		med	70	100	70	100	70	100	-	-	-	-
		max	100	121	100	121	100	121	-	-	-	-

When the value is omitted in Table 4, it means that the corresponding experimental condition did not work. In particular, in many tests performed using gaseous dielectrics with a brass electrode, the drilling operation took an excessive time; moreover, the deposition of a non-conductive material occurred on the electrode surface, compromising the electrode wear measurement. An image of this phenomenon is shown in Figure 5.

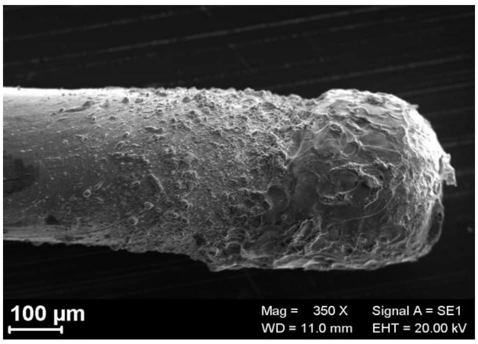

Figure 5. Brass electrode tip at the end of the drilling operation of AISI 316L using oxygen as dielectric

The fixed process parameters are presented in Table 5. Width is the time at which the transistor remains active. The generator turns the erosion circuit on and off at regular intervals with a frequency equal to the value set with the frequency parameter. Gain is a parameter that controls the gain of the reaction block, and gap is a value proportional to the distance between the electrode and the workpiece during erosion. The energy parameter establishes the shape of the pulse. Finally, regulation identifies a certain regulation management algorithm defined by the machine manufacturer. To guarantee suitable technological conditions, both the variable and fixed process parameters differ for each workpiece–electrode–dielectric combination. Further, within each combination, the execution order of the experiments was randomised to avoid possible systemic errors. When it was possible to realise the complete CCD, such as for the liquid dielectrics, 26 micro holes were drilled for each workpiece–electrode–dielectric combination.

In Table 6, the values of the coefficients used in the equations in Section 2 are summarised.

Table 5. Fixed process parameters

	Kerosene/Water/ Vegetable Oil/Air	Oxygen on AISI 316L	Oxygen on Ti6Al4V
Polarity	-	+	-
Width [μs]	3	4	3
Frequency [kHz]	146–150	100	150
Gain	20	20	20
Gap	30	30	30
Energy	365	365	365
Regulation	03–01	03–01	03–01

Table 6. Values of coefficients

c_{el} [€/kWh]	0.156
c_e [€/mm]	Brass: 0.024362
	WC: 0.1054
c_{ad} [€/L]	Kerosene: 9.63
	H_2O: 0.25
	Vegetable oil: 1.4
	Air: 0
	Oxygen: 1.05
V_d [L]	Kerosene, H_2O, veg oil: 25
	Oxygen: 40
L_d [h]	Kerosene, H_2O, veg oil: 1000
	Oxygen: 33.33
c_{af} [€]	117
L_f [h]	1000
c_s [€/L]	Kerosene: 0.215
c_m [€/h]	40

For each dielectric used in the experimental investigation, Table 7 provides the evaluation of all aspects considered for the determination of the penalty coefficient. This coefficient was used in the formula for environmental sustainability (S_e).

Table 7. Determination of penalty coefficient

	Kerosene	Demineralised water	Vegetable oil	Compressed air	Oxygen
Fire hazard	3	0	0	0	2
Fume production	3	3	3	0	0
Skin irritation	3	0	0	0	0
Toxic fumes	3	0	1	0	0
Dust production	0	0	0	3	3
Dielectric re-use	1	2	1	0	3
Dielectric dismantling	3	1	3	0	0
Filter dismantling	3	3	3	0	0
Total	19	9	11	3	8
$\boldsymbol{k_i}$	**0.79**	**0.37**	**0.46**	**0.12**	**0.33**

4. Calculation of sustainability index for the tested conditions

In the following sections, the proposed SI was applied for the tested conditions. Figure 6 displays the investigated conditions: the micro holes were drilled on stainless steel and titanium plates using both tungsten carbide and brass electrodes, varying the type of dielectric. The electrical process parameters (peak current and voltage) were varied to determine the region where the machining can occur.

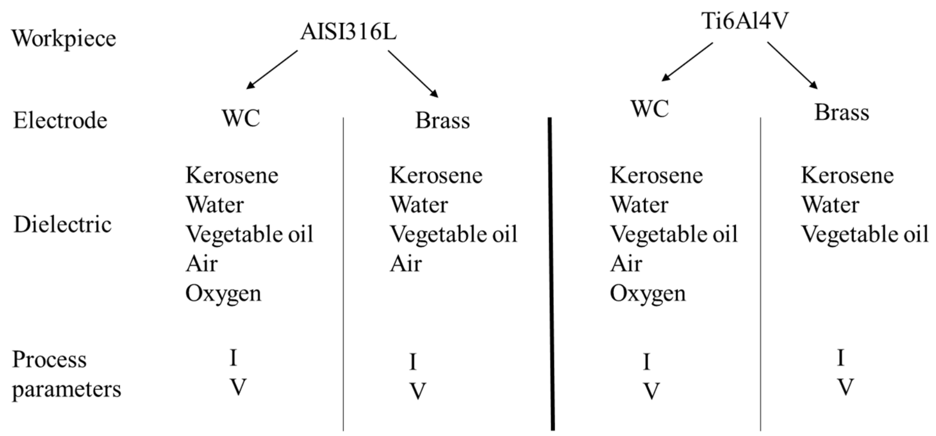

Figure 6. Schematic of the tested conditions

The most important variables in the SI formula are the machining time and electrode wear. The data were already presented and discussed before.

Figures 7 and 8 show the machining time obtained for AISI 316L and Ti6Al4V, respectively, as a function of the dielectric and electrode material combination. Considering the relevant amount of data, the results are displayed through synthetic graphical representations that point out the minimum (grey triangle), maximum (grey square), and mean value (black circle) of the considered output variable varying the electrical parameters (peak current and voltage). High bars indicate that the process is affected by the parameters while low bars mean that the process parameters have a low or negligible influence. In some cases, the electrical process parameters severely affected the drilling time. This occurred in the stainless steel–tungsten carbide–kerosene (workpiece–electrode–dielectric), stainless steel–brass–air, stainless steel–tungsten carbide–oxygen, titanium–vegetable oil–brass, and titanium–tungsten carbide–oxygen combinations. For these combinations, the selection of the optimal process parameters is a crucial aspect for the process performance and therefore for sustainability. From the comparison between the two electrode materials, the brass electrode provides better results in general. In fact, it permits faster machining than the tungsten carbide electrode as already reported by D'Urso and Ravasio (2017) owing to its higher electrical conductivity. When stainless steel is processed, the machining using tungsten carbide electrode and kerosene as a dielectric is not competitive as regards machining time. Water is the dielectric that minimises the drilling time. Non-conventional dielectrics show interesting results representing a competitive solution in terms of machining time, except for compressed air.

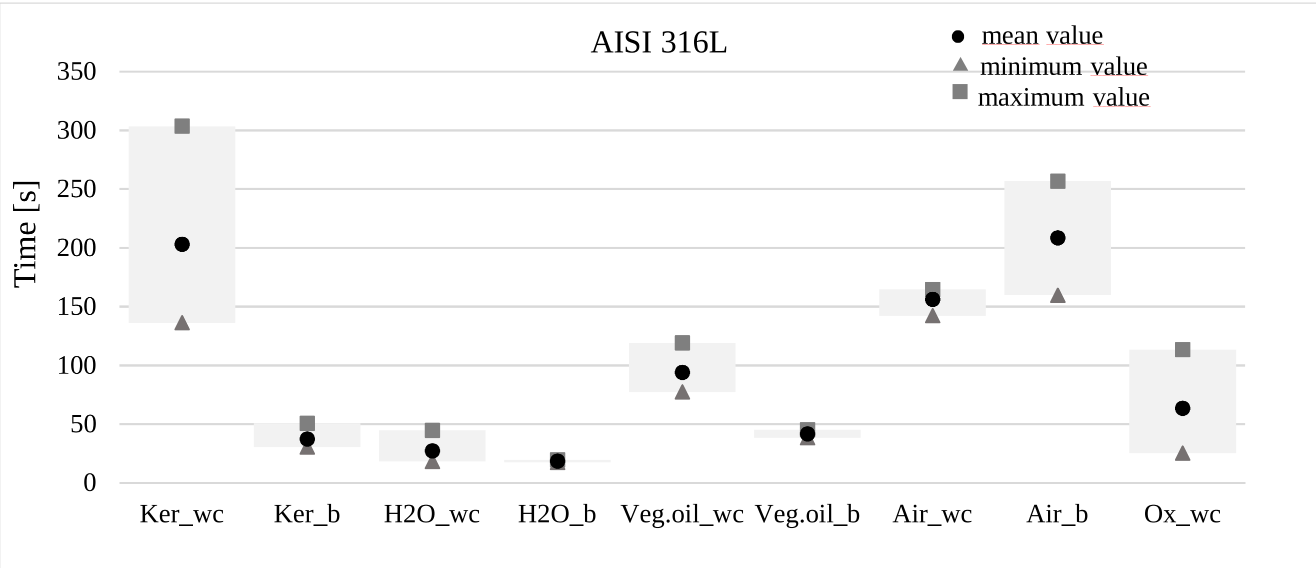

Figure 7. Machining time of AISI 316L for different electrode material/dielectric combinations

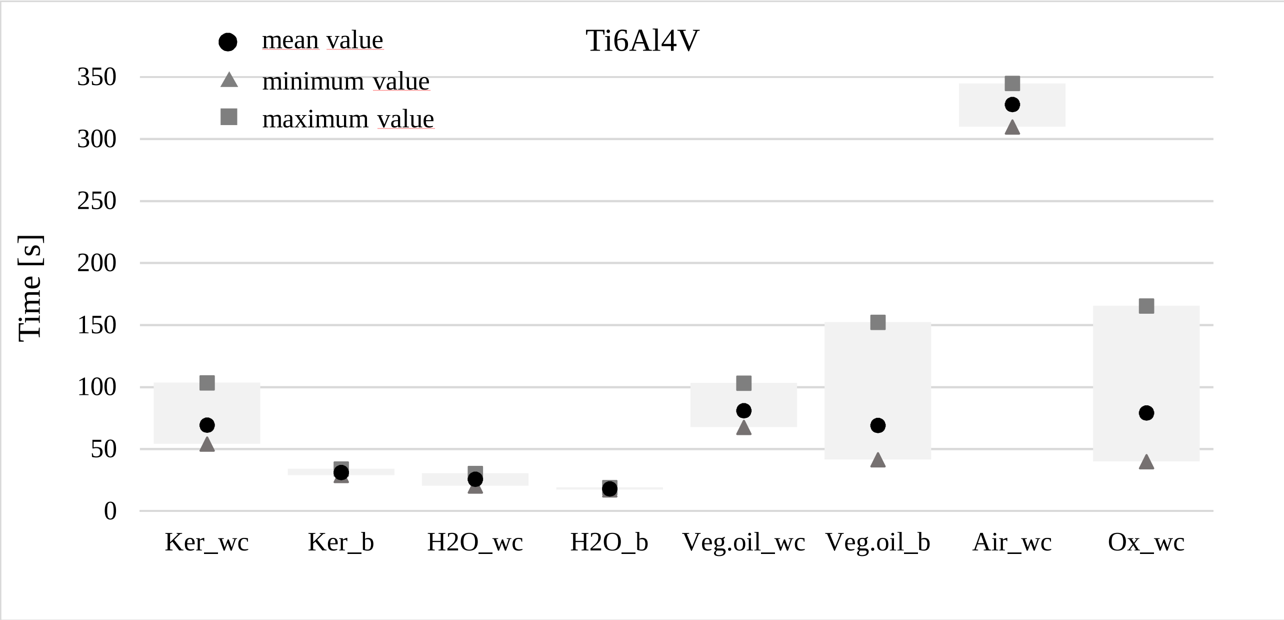

Figure 8. Machining time of Ti6Al4V for different electrode material/dielectric combinations

The electrode wear expressed in mm^3 is illustrated in Figures 9 and 10 for AISI 316L and Ti6Al4V, respectively, as a function of the dielectric and electrode material combination. In some conditions, the electrical process parameters play a major role while in other cases their influence is minor. In general, the brass electrode displays a higher level of wear than the tungsten carbide one due to its thermal and electrical characteristics as already reported by D'Urso and Ravasio (2017). For each electrode material, it can be noted that there is a relationship between the machining time and electrode wear: in general, in the conditions where the machining occurs slowly, the electrode wear is faster. However, this is not true for the combination of air as a dielectric and tungsten carbide as an electrode for both workpiece materials, which represents the solution that minimises the electrode wear to the detriment of machining time. It is noted that by using gaseous dielectrics with titanium plates, the deposition of some chemical composites on the electrode tip causes a shielding effect, which decreases the progress of machining (resulting in high machining time) but enhances the electrode life (low electrode wear). This phenomenon should be investigated more fully in future works.

The use of vegetable oil with the brass electrode is not an optimal combination from the point of view of electrode wear, while it appears to be a valid choice with the tungsten carbide electrode. In general, water as a dielectric is the best solution for both machining time and electrode wear.

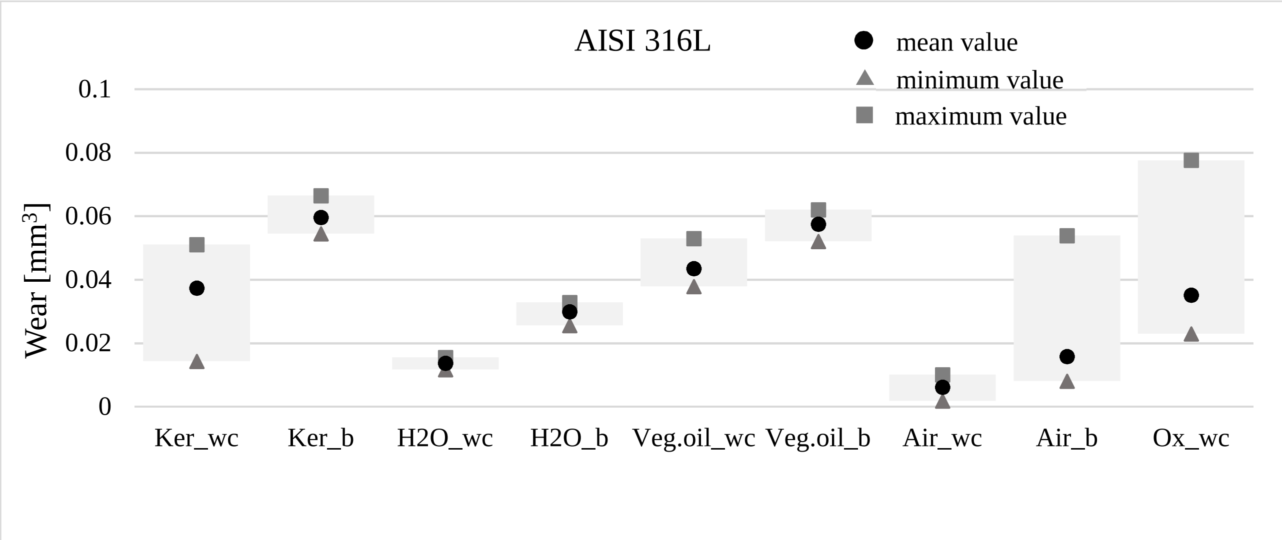

Figure 9. Electrode wear of AISI 316L for different electrode material/dielectric combinations

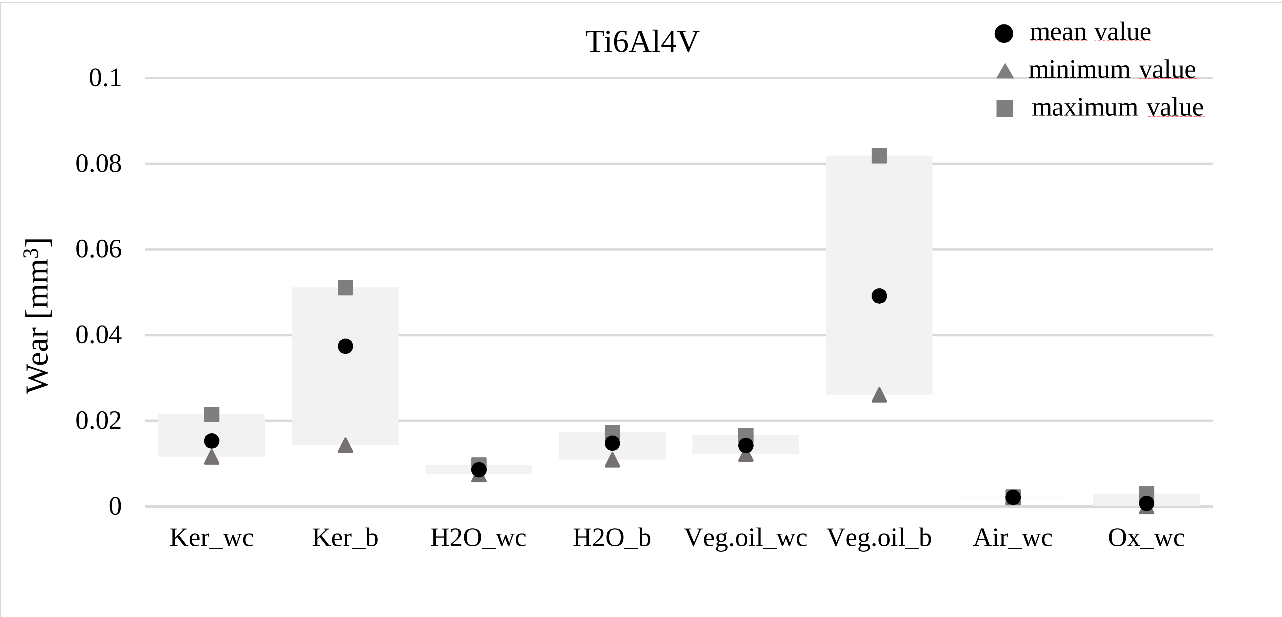

Figure 10. Electrode wear of Ti6Al4V for different electrode material/dielectric combinations

Regarding electrical energy consumption (which is another variable in the SI formula), this shows a linear trend as a function of time, and is insignificantly influenced by the EDM process parameters. The proposed SI was calculated using the data reported above for different experimental conditions. The results are shown through the box plot graphs (Figures 11–14). It is worth noting that the value represents the environmental impact in terms of the quantity of consumed resources and pollution effects created by the EDM for the drilling of a micro hole. High values indicate worse sustainability, while low values mean that the process has a low impact and is therefore more sustainable.

When stainless steel is processed, water and vegetable oil as dielectrics are the best solutions with regard to sustainability for both electrode materials. Air only achieves a good result for the tungsten carbide electrode, where the machining time is acceptable, while the performance deteriorates with the brass electrode, particularly in terms of machining time and geometric accuracy of the holes. Among the liquid dielectrics, kerosene appears to be the one with the lowest sustainability. From a comparison between the two electrodes, tungsten carbide approximately doubles the environmental impact. This result permits the assertion that when stainless steel is machined, tungsten carbide electrodes should not be used except when high-accuracy machining is required.

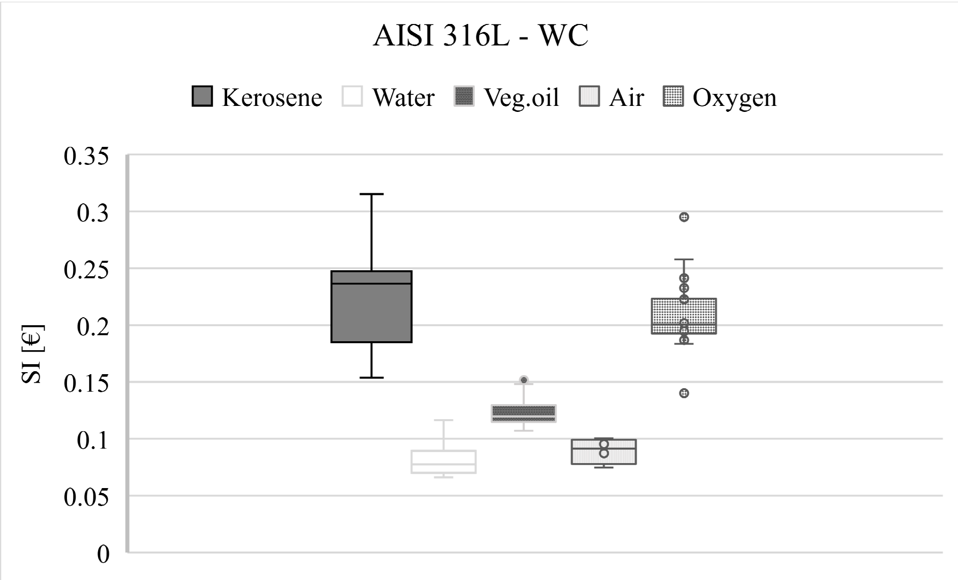

Figure 11. SI of AISI 316L using tungsten carbide electrode

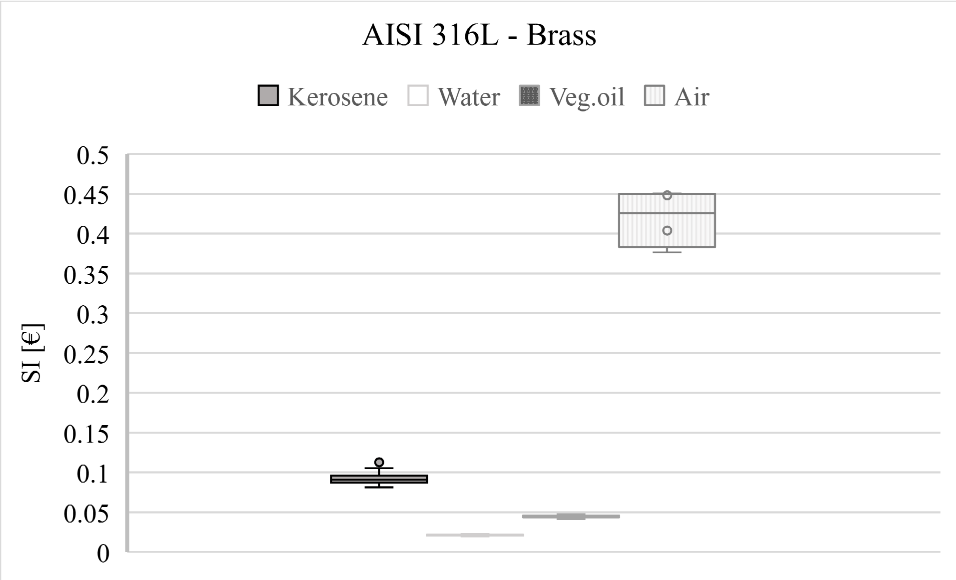

Figure 12. SI of AISI 316L using brass electrode

When titanium is processed (Figures 13 and 14), water and vegetable oil are hereby confirmed as the dielectrics that make the process more sustainable. The use of air with tungsten carbide electrodes provides a result similar to that of kerosene, while the index using oxygen becomes worse. With regard to the difference between the two electrodes, when kerosene is adopted the brass electrode reduces the environmental impact by half, as already demonstrated for stainless steel. In the other cases, the effect of the two electrodes seems to be almost negligible.

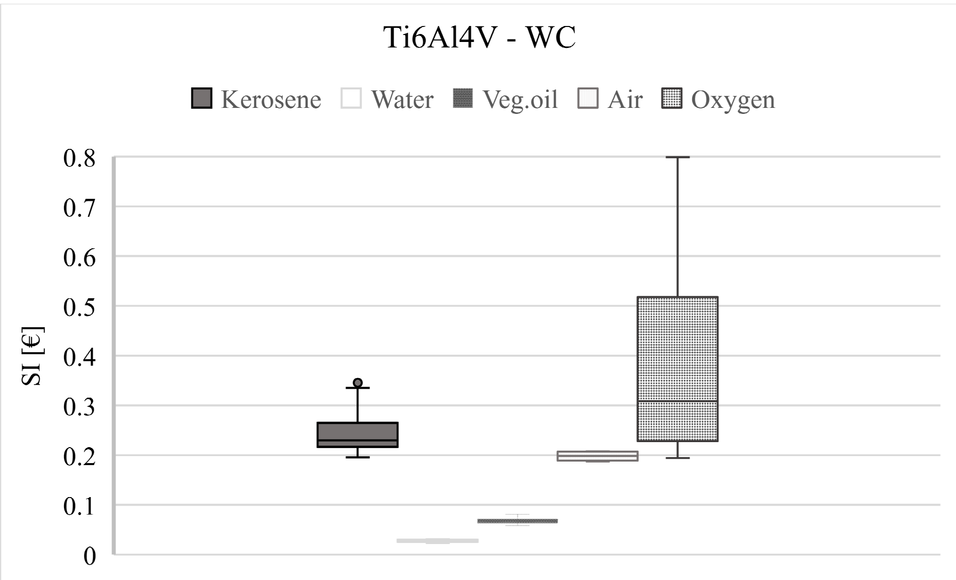

Figure 13. SI of Ti6Al4V using tungsten carbide electrode

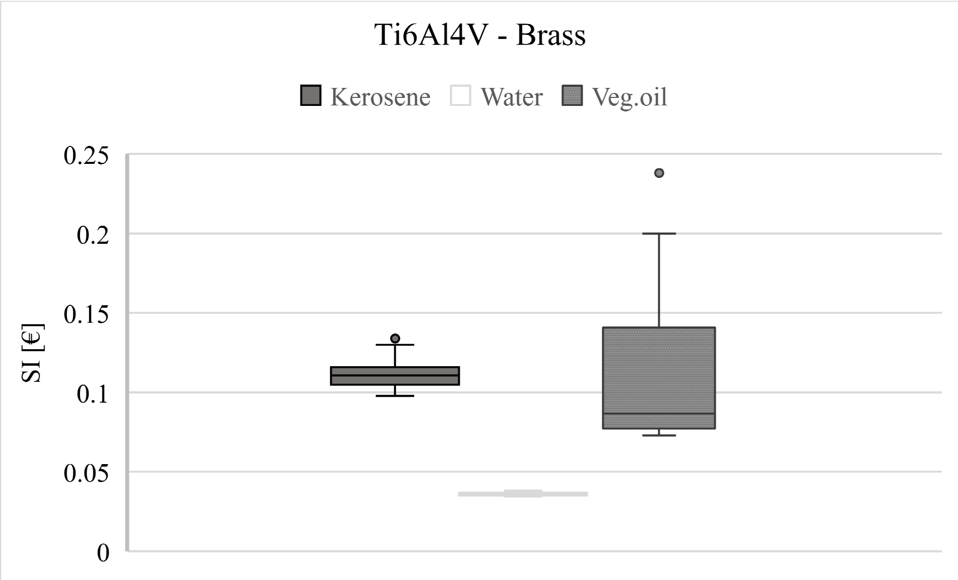

Figure 14. SI of Ti6Al4V using brass electrode

The overall SI is composed of five terms (see Equation 9), whose impacts are explored for each experimental configuration (workpiece–electrode–dielectric). This analysis allows the understanding of what actions must be undertaken to minimise the environmental impact of the process.

Figures 15–16 depict the weight of each sub-index on the composition of the overall SI for each experimental condition, when stainless steel is machined and when the central values of peak current and voltage are used. It can be asserted that the energetic component (S_{energy}) plays a minor role on the formation of the SI for all the tested conditions. The use of tungsten carbide electrode with kerosene as a dielectric is penalised by both wear and environmental components. The same critical aspects are found with vegetable oil but a lower value is reached. Water, which is found to be the best dielectric in this condition, shows some problems in the sub-index performance. Air as a dielectric is very interesting, but for the time being is penalised by the long machining time through the sub-index related to the environment. The sub-index performance reveals the low stability of the process when oxygen as a dielectric is used and with the air–brass combination. It is important to point out that the dynamics of the process using unconventional dielectrics are not well known and it is expected that there are many aspects that can be improved.

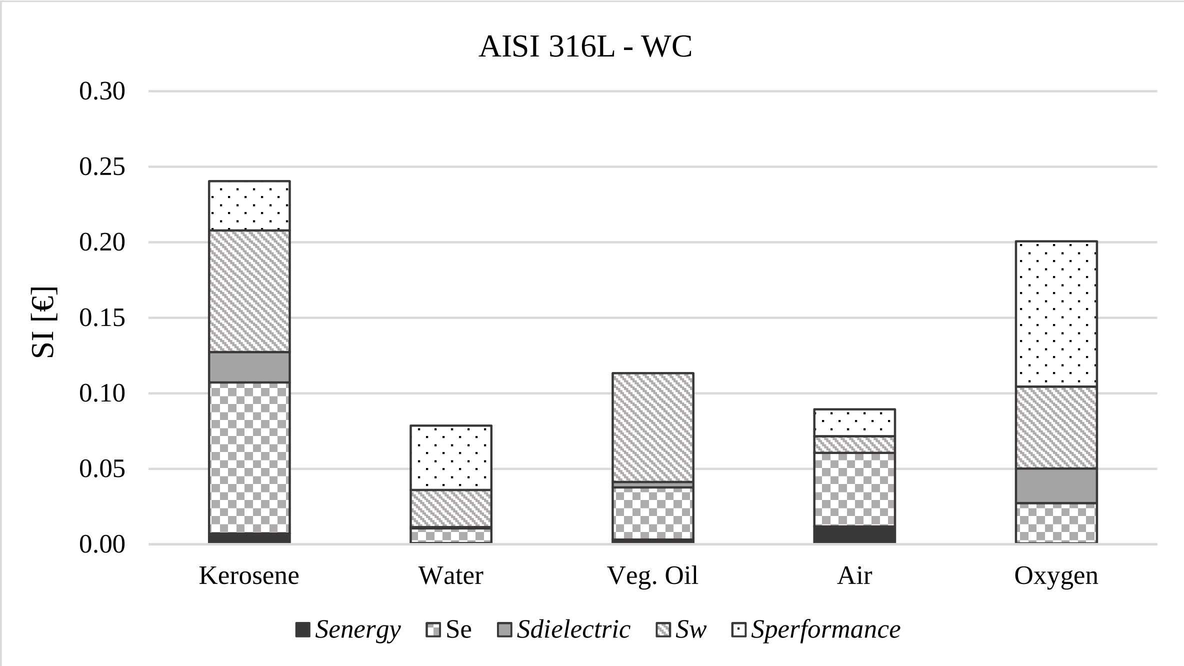

Figure 15. Composition of SI for AISI 316L using tungsten carbide electrode

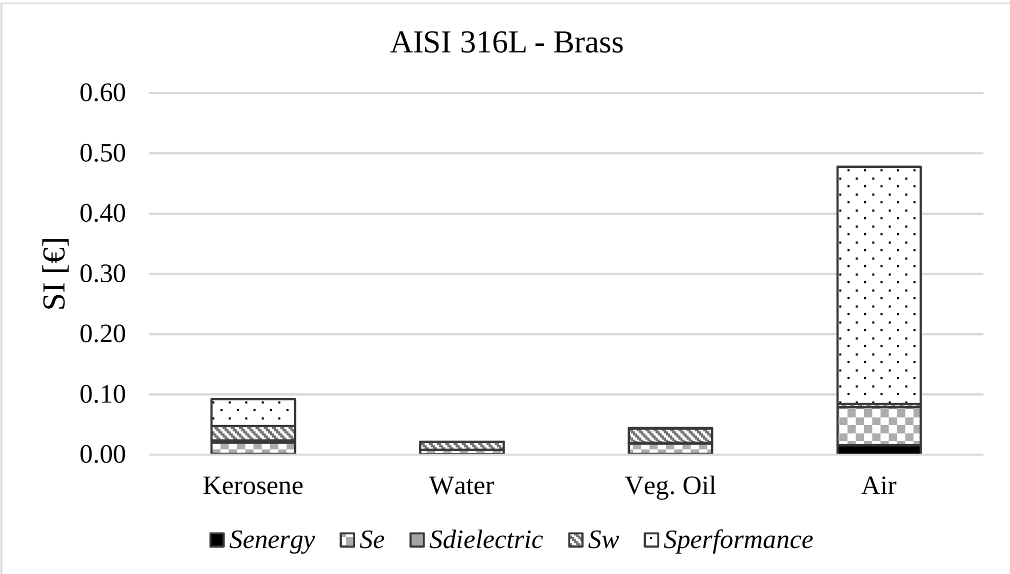

Figure 16. Composition of SI for AISI 316L using brass electrode

The analysis of the results obtained with titanium plates (Figures 17 and 18) confirms the evidences found for stainless steel. Term S_{energy} is always negligible with respect to the others terms. The major problems using gaseous dielectrics are due to the sub-index related to the performance (poor repeatability) and the environment (high machining time). Among the liquid dielectrics, the brass electrode shows a relatively worse sub-index performance, except for kerosene. For the liquid dielectrics, water is the choice that minimises the components related to both electrode wear and environmental impact.

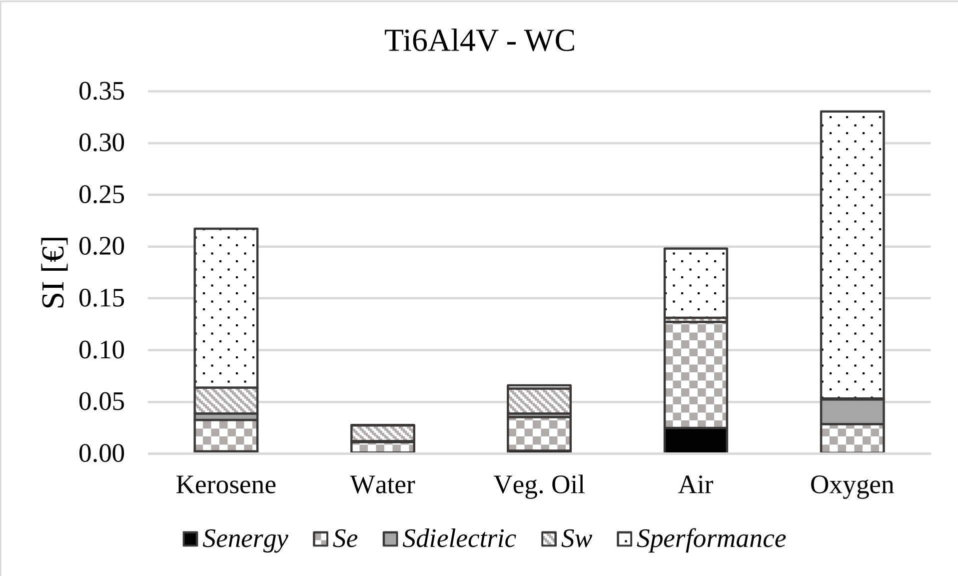

Figure 17. Composition of SI for Ti6Al4V using tungsten carbide electrode

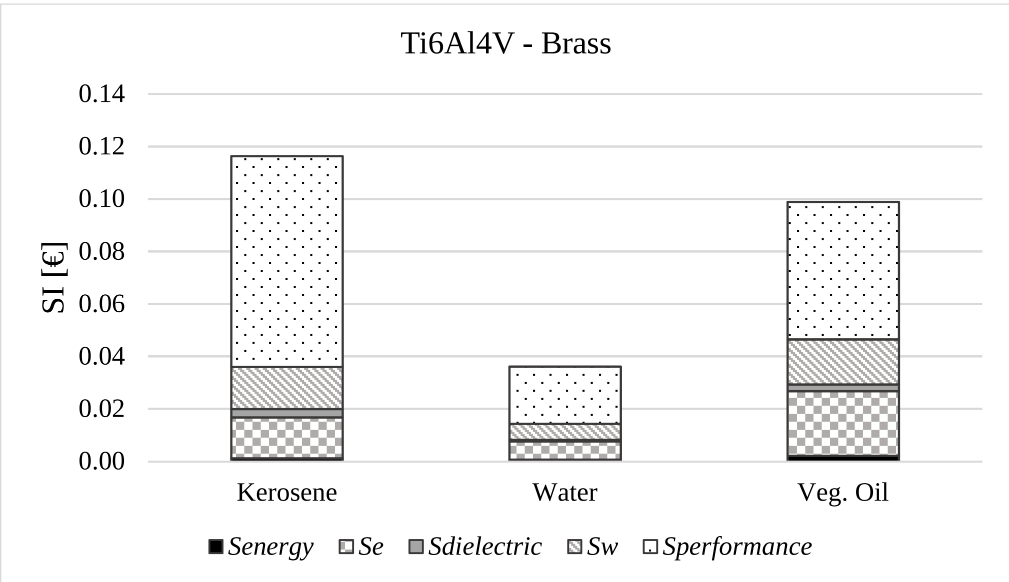

Figure 18. Composition of SI for Ti6Al4V using brass electrode

Table 8 summarises the results of SI for each combination of workpiece–dielectric–electrode, pointing out the sub-index that has the greatest impact (X). In some cases, when there is another sub-index that affects significantly the SI (higher than 30%), this is remarked with the symbol XX.

Table 8. Sub-indices with the greatest impact on SI at various experimental conditions

Workpiece	Dielectric	Electrode	SI [euro]	S_{energy}	S_e	$S_{dielectric}$	S_w	$S_{performance}$
AISI 316L	Kerosene	WC	0.240		X		XX	
		Brass	0.092					X

	Water	WC	0.079				XX	X
		Brass	0.021		XX		X	
	Vegetable oil	WC	0.113		XX		X	
		Brass	0.044		XX		X	
	Air	WC	0.089		X			
		Brass	0.478					X
	Oxygen	WC	0.201					X
Ti6Al4V	Kerosene	WC	0.217					X
		Brass	0.116					X
	Water	WC	0.027		XX		X	
		Brass	0.036					X
	Vegetable oil	WC	0.066		X		XX	
		Brass	0.099		X			X
	Air	WC	0.198		X			XX
	Oxygen	WC	0.330					X

The dielectric plays a major role in the EDM process because it greatly affects the performance. The dielectric also affects the environment in terms of the quantity of consumed resources and pollution created by the process. The type of electrode affects the process as well. These remarks are reflected in the proposed model.

It can be noted that the coefficients used in the formula for each sub-index influence the numerical values of the SI obtained in this study. It is reasonable to assume that the coefficients can change as a function of the specific parameter considered, e.g. the use of other EDM systems or different electrode sizes. Further works could include a sensitivity analysis of the model.

Within the limit of the present investigation, some guidelines can be identified. Under the hypothesis that the workpiece material is selected from manufacturing or design constraints, water and vegetable oil are the dielectrics with the lowest environmental impact. In general, for these dielectrics, the brass electrode halves the impact when stainless steel is processed, while the tungsten carbide one is better for titanium sheets. The use of kerosene as a dielectric makes the process less green and is not recommended when combined with tungsten carbide as an electrode. Finally, the combination of air as a dielectric and tungsten carbide as an electrode shows interesting results while the use of oxygen, at this time, is not recommended due to the instability of the process with its use. In general, the gaseous dielectrics make the process less stable probably due to a less effective washing of the machined zone than with liquid dielectrics. This causes a slowing down of the advancement of drilling, penalising the accuracy of the holes. Anyway, based on the growing interest on sustainability, it is expected that the knowledge of unconventional dielectrics in

the EDM process will be further improved and some operative conditions will be determined to overcome some of the critical aspects revealed in this study. For example, an increase in the gas pressure or hybrid solutions (near-dry) could overcome these limitations.
The most important sub-indices are often related to the environment and performance, while the terms associated with the energy and dielectric are always of minor significance.

Conclusion

Considering the importance of environmental sustainability for industrial manufacturing processes, an analysis of the micro-EDM drilling process was conducted. Further, a numerical method for evaluating the sustainability of the process was developed and a model for calculating the overall SI was presented. The index estimates the environmental impact in terms of both the quantity of consumed resources and pollution effects created by the micro-EDM drilling process. Under the assumption that the index must be applied in simple and practical ways, a link between the economic value of a product and its environmental impact was assumed. The index is composed of five sub-indices, and each of them evaluates a particular aspect. These sub-indices are energy consumption, environmental impact, dielectric consumption, wear of electrode, and machining performance in general. The proposed index was applied for a practical case: the drilling of micro holes on stainless steel (AISI 316L) and titanium alloy (Ti6Al4V) using two types of electrodes (brass and tungsten carbide) and (where possible) five types of dielectrics, both liquid and gas. For each combination of workpiece and electrode material, both a comparison between the different types of dielectrics and an analysis of the critical aspects related to the sustainability were performed. In general, water and vegetable oil are the dielectrics with the lowest environmental impact, but they need an appropriate electrode material in accordance with the workpiece material. Kerosene as a dielectric makes the process less green and the combination with tungsten carbide as an electrode is not recommended. The combination of air as a dielectric and tungsten carbide as an electrode shows interesting results while the use of oxygen, at this time, is not recommended due to the instability of the process. The most important sub-indices are often related to the environment and the performance while the terms associated with energy and the dielectric are always of minor importance.
The proposed model for measuring the sustainability of the micro-EDM drilling process meets the requirement of easy implementation in industrial applications. The index provides a tool that can assist the decision-making stage of the selection of conditions aiming at minimising the environmental impact. It can be further improved by detailing the sub-index performance, which

should include other product quality criteria (i.e. taper rate, roughness, and circularity). Moreover, pollution effects due to the contamination from dusts of both electrode and workpiece could be considered into the sub-index related to the environment. The implementation of the index into different technological situations (such as micro-EDM milling or wire EDM) can be made.

Nomenclature

α = top diameter scrapping rate coefficient [-]

β = unitary coefficient [€/h]

C_{ad} = price per litre of dielectric [€/L]

c_{af} = cost of filter [€]

C_d = purchase cost of dielectric [€]

c_e = unitary volumetric electrode cost [€/mm^3]

c_{el} = unitary electricity cost [€/kWh]

C_f = purchase cost of filter [€]

c_m = hourly cost of micro-EDM machine [€/h]

C_s= dismantling cost of dielectric [€]

c_s = unitary dielectric dismantling cost per litre [€/L]

E_{tot} = absorbed energy of the machine [kWh]

I = peak current [-]

k = value of workpiece [€]

k_i = coefficient penalty [-]

L_d = lifetime of dielectric [h]

L_f = filter lifetime [h]

S_e = environmental sustainability [€]

S_{energy} = energetic sustainability [€]

SI = sustainability index [€]

$S_{performance}$ = performance sustainability [€]

S_w = sustainability related to electrode wear [€]

t_e = erosion time [h]

V = voltage [V]

V_d = volume of dielectric tank [L]

W = electrode wear [mm^3]

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