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# Evaluation of the sustainability of the micro-electrical discharge milling process

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**A B S T R A C T**

The sustainability evaluation of an industrial process is an actual issue: a process should not only grant part quality and high production rates at the lowest cost, but it should minimize its impact on the environment as well. Micro-EDM (Electrical Discharge Machining) is widely used in micro machining for its small force and high precision and environmental aspects related this technology are taken into account. In this paper, an evaluation of the micro-ED milling process concerning the sustainability manufacturing was made. For this purpose, a method to assess the sustainability process was developed, taking into account the energetic consumption, the environmental impact, the dielectric consumption, the wear of the electrode and the machining performance. This method was applied for the execution of micro-pockets using two workpiece materials, two types of electrode and five types of dielectric, both liquid and gaseous. This analysis permits the identification of the critical aspects of the micro-ED milling process form the point of view of the sustainability. The comparison between the different solutions in terms of electrode material and dielectric underlines interesting considerations about the usage of non-traditional dielectrics. As regards electrode material, the environmental impact process when brass electrode is adopted is lower than tungsten carbide electrode. As concerns dielectric, water reveals to be the most sustainable dielectric; vegetable oil and oxygen, proved to be valid substitutes to traditional dielectrics under several viewpoints, including sustainability.



**A R T I C L E   I N F O**

*Keywords:*
Electrical discharge machining (EDM);
Micro-electrical discharge machining (micro-EDM);
Micro-electrical discharge milling (micro-ED milling);
Sustainability;
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## 1. Introduction

When dealing with process selection, sustainability issues are achieving increasing importance. A process should not only grant part quality and high production rates at the lowest cost, but it should minimize its impact on the environment as well. Whereas quality, productivity and cost can be evaluated using accepted techniques, sustainability evaluation is still matter of research. The simplest way of assessing sustainability is through indicators [1], although a more complex method of life cycle assessment has been proposed by international standards [2, 3]. In both cases, data collected from either production practice or experimental tests are supplied to a model which makes them dimensionally homogeneous and then aggregates them, generally by means of weighting factors. A scalar value (index) is then evaluated and used to rank different process conditions. To define a process index, knowledge about the subject is necessary to identify the factors [4]: in general, energy requirements (for both the main process and auxiliary actions), material usage (for both work and consumables), process fluids management (such as coolants, lubricants and dielectrics), waste production, health and safety issues should be taken into account. Among many other processes, sustainable production through electrical discharge machining (EDM) has been studied [5-7]. Albeit a relatively small number of parts are currently produced via EDM, when compared to metal cutting operations, EDM is one of the most energy intensive processes [8]. Similar considerations can be extended to micro-EDM, by which small but increasing volumes are processed and the high specific power consumption is higher [9, 10].

In EDM, material removal is effected by a sequence of electrical discharges between workpiece and a conductive tool (electrode), removing small portions of material from both sides, i.e. from both work and tool. To improve the process, such discharges take place in a dielectric medium, whose purpose is reducing the spark size, localizing the energy supply, contributing to end the spark and to remove the vaporized material [11]. Two main EDM techniques became popular, namely die-sink EDM (often simply quoted as EDM) and Wire EDM (WEDM).

EDM processes show many interesting properties, since they are able to produce complex shapes and they are not affected by the mechanical strength of the workpiece. On the other hand, some negative factors limit the field of application of such technique. First, the material removal rate (*MRR*) is critically low: for this reason, a good deal of research has been focused on improving the *MRR* [12, 13]. Moreover, tool wear rate (*TWR*) is always non negligible if compared with *MRR*, affecting material consumption and geometrical accuracy. Then, the process output depends on several parameters; process optimization is required to achieve good results but it is often nontrivial. As said, when assessing process performance for EDM operations, *MRR* and tool wear are mainly taken into account. Other important facts are geometrical accuracy and surface integrity. Recently, energy consumption and health impact are considered as well [14].

EDM can be used to machine small features (having characteristic size of about 1 mm or less), in this case the term *micro-EDM* is often used. Micro-EDM is based on the same physic principle as all EDM operations, yet each discharge conveys less energy and the discharge frequency is higher [15]. In this way, improved accuracy (small gaps are mandatory for small parts) is reached and the energy effectiveness is generally smaller, since the fraction of energy used for vaporizing the dielectric is relatively higher [16, 17].

Several types of operations are used in micro-EDM: micro-die sink and wire EDM are similar to their macro-scale counterpart, whereas some specific processes include micro-ED drilling, micro-ED milling, micro-ED grinding and micro-wire ED grinding (micro-WEDG). In micro-ED milling a rotating tool (of simple geometry) is moved with respect to the work as in traditional end milling, such as pocket milling or contouring applications. Compared with other micro-EDM processes, it achieves better flushing and tool stability [18]. In micro-ED milling, machining times are often quite long, but machining performance may be improved by either optimizing process parameters [19-21] or exploiting other techniques, as it has been reported in [22].

For both EDM and micro-EDM, process optimization may be carried out in several ways, by considering machining parameters or by selecting suitable materials for either electrode or dielectric fluid. Electrical parameter optimization involves the selection of current, voltage, spark time and spark interval. For this purpose, regression techniques are often used [23]. In general, commercial EDM devices are provided with *machining programmes*, including an optimal combination of parameters as a function of materials (for both work and tool) and of the surface requirements (either roughing or finishing); thus, fine tuning of electrical parameters is seldom feasible by the end user, who can only select among a set of machining programmes. In case of micro-EDM, a RC generator is very often employed: due to the physics of the power circuit, discharge current and duration cannot be independently chosen, so further reducing the degrees of freedom for optimization [8].

Further chances for optimization are provided by the selection of process materials, for both the dielectric and the electrode. Dielectric selection is dealt with in many studies [24]. At present, kerosene and deionized water (especially for WEDM) are mainly used [14, 25]. Desirable properties for a dielectric fluid are low specific gravity, high flash point and oxygen content, low viscosity and toxicity, high breakdown voltage and biodegradability [26].

Other solutions include organic oils, aerosols and gases [27, 28]. The use of a vegetable oil proved to achieve significant improvements with respect to kerosene in terms of *MRR*, surface finish and integrity, besides being more desirable for sustainability issues [6]. Gas assisted EDM (sometimes referred to as *dry* EDM) have been studied by several Authors. Both air [29] and oxygen [30] were studied, interesting findings have been reported in the last two decades. *MRR*, *TWR*, surface quality and integrity may be improved by using dry EDM [11].

When evaluating dielectric performances, health problems have been often considered. Dielectric fluids may release vapours and fumes; they may require a treatment (filtering, deionizing) and they become exhausted over time. It has been pointed out that a quantitative assessment of health impact requires more data about pollutant concentration in fumes that is heavily dependent on dielectric type [31, 32].

Dielectric circulation and filtering generally use a significant fraction of the overall power consumption [10]. In this way, both sustainability and process cost are affected. It is worth noting that energy consumption in EDM is reported to be the main source of both cost and sustainability issues. A relevant part of energy consumption is independent from machining parameters [33], so the main impact on both cost and sustainability is due to machining time; thus, *MRR* consideration are of primary relevance.

The sustainability evaluation of the micro-EDM process is a complex task because several aspects have to be taken into account. Sustainability assessment through indexes may be the simplest way, yet it requires knowledge about process data. In the present paper a sustainability index is presented for micro-ED milling and used to compare different choices of dielectric fluids, both liquid and gas. An experimental campaign was carried out to supply data to the model. Five dielectrics, two work materials (titanium and stainless steel) and two electrode materials (brass and tungsten carbide) were taken into account for the study.

## 2. Materials and method

### 2.1. Development of the Sustainability Index

The idea of *sustainable manufacturing* is not yet fully defined due to the presence of several interpretations of the *sustainability* concept [34]. In fact, several domains can be considered so, as a function of these, the expression *sustainable manufacturing* may assume different meanings. In this paper, the concept of sustainability is strictly connected to the manufacturing operations and the aspects related to stakeholders, technologies, services, supply chain are not included. In this view, the issues that are taken into account to evaluate the overall environmental impact are: the energy consumption, the materials requirement, the waste management, the process safety and the staff health (Fig. 1).

A Sustainability Index (*SI*), expressed in euro, was developed representing the environmental impact in terms of quantity of the consumed resources and pollution effects created by the EDM machining. In this way, when the index assumes high values, the process is poorly sustainable, while for low values the process has a lower impact and therefore is more sustainable.

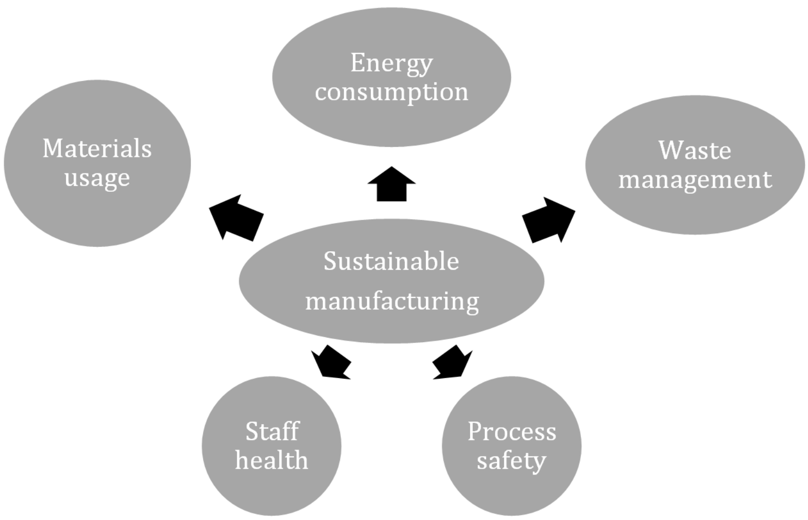


**Fig. 1** Sustainable manufacturing issues

The elements taken into account to formulate *SI* are:

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

$$S_{energy} = E_{tot} \cdot c_{el} \tag{1}$$

where $E_{tot}$ represents the absorbed energy of the machine expressed in [kWh] and $c_{el}$ the cost per unit for the electricity in [€/kWh].

*Electrode wear*: The sustainability related to the electrode wear ($S_w$) can be evaluated as:

$$S_w = W \cdot c_e \tag{2}$$

where $W$ is the volume of the consumed electrode in [mm$^3$] and $c_e$ is the unit cost per volume of the tool expressed in [€/mm$^3$].

*Dielectric*: To estimate the impact of the dielectric, the purchase cost of both the dielectric and the filters and the costs for its disposal were taken into account. The purchase cost of the dielectric ($C_d$) expressed in [€], charged to an EDM operation having a time duration of $t_e$ (erosion time), was evaluated as:

$$C_d = \frac{C_{ad} \cdot V_d \cdot t_e}{L_d} \tag{3}$$

where $C_{ad}$ is the price per litre of the dielectric in [€/l], $V_d$ is the volume of the dielectric tank [l] and $L_d$ is the lifetime of the dielectric in [h]. It must be noted that the erosion time, expressed in [h], is time interval from the start to the end of machining cycle and therefore includes time period in which the machine does not erode (for example the time used to control the level of wear of the tool). Strictly speaking, only the active time should be taken into account but considering that the duration of the milling operation is much longer than the passive time, assuming that this latter is negligible leads to an acceptable approximation. This information is in agreement with [10] found for die-sinking EDM of macro components.

The purchase cost of the filter ($C_f$) in [€] for the dielectric unit can be estimated as:

$$C_f = \frac{c_{af} \cdot t_e}{L_f} \tag{4}$$

where $c_{af}$ is the cost of the filter in [€] and $L_f$ is its lifetime expressed in [h]. It is worth noting that filter management involves the use of significant amount of energy; in this model, however, such value has already been included in overall energy consumption and therefore is not accounted here.

The dismantling cost of the dielectric in [€] is defined as:

$$C_s = \frac{c_s \cdot V_d \cdot t_e}{L_d} \tag{5}$$

where $c_s$ is the unitary dielectric dismantling cost for liter in [€/l].

The dielectric sustainability takes into account the three over mentioned elements:

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

Noted that the total effect of dielectric on sustainability is proportional to machining time and therefore it is directly dependent on *MRR*.

*Process performance*: This factor is related to the sustainability impact of scrap production that can be evaluated by multiplying the scrap rate $\alpha$ (i.e. the probability of producing a non-conforming part) by the average cost of either disposing or repairing the part. If a part cannot be repaired, its disposal cost is evaluated by taking into account the cost of the electrode wear, of the machine time and of the raw workpiece. When a part can be repaired, the associated cost is lower than the disposal cost. On average, the cost for producing a nonconforming part (to be either scrapped or repaired) is a fraction $\gamma$ of the total disposal cost. Scrap rate should be estimated through a statistical analysis; for the reported experiments, however, a simplified technique, based on deviations of the machined slot depth from its nominal value, was preferred. A suitable smoothing function was used to link deviations to scrap probability.

On this basis, the performance sustainability can be estimated as follows:

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

where $c_m$ is the hourly cost of the micro-EDM machine, expressed in [€/h], and $k$ describes the value of the workpiece, for sake of simplicity, its value was set to zero.

*Environmental impact*: It represents an evaluation of the environmental impact of the used dielectric. Several aspects were taken into account such as the fire hazard, the generation of fumes and vapours, the possible skin irritation of the operators, the generation of toxic fumes, the dust formation, the possible re-use of the dielectric and, finally, the dielectric and filters dismantling. For each of them, a qualitative evaluation from 0 to 3 was made based on literature data [7, 35] (increasing the value, 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:

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

where $\beta$ is an unitary coefficient in [€/h].

In front of the above description, the Sustainability Index in [€] is calculated as:

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

The developed Sustainability Index is affected by the process performance, in terms of machining time and electrode wear, experimentally evaluating.

## 2.2. Experimental cases

A Sarix SX-200 machine was used to realize micro-milling tests. Micro-pockets on two types of workpiece materials and using two different electrodes were machined. Fig. 2 shows the dimensions of the pocket having depth 0.1 mm. The milling strategy was layer-by-layer and the depth of each layer was 0.003 mm, adopting a roughing energy. When dealing with milling, the machine builder allows to select among some built in sets of process parameters (machining strategy, i.e. roughing, finishing etc.). For the present case, the machining strategy labelled *roughing* was selected. It can be noted that within each strategy, the electrical parameters depend on the workpiece material, the electrode characteristics and the type of dielectric (only kerosene and water are included). The machining parameters affect strongly the machining performance in term of machining time, electrode wear and geometrical characteristics. In its turn, the sustainability index depends strongly on machining time and on electrode wear (see the equations of the sub-indexes).

The workpiece materials were stainless steel (AISI 316L) and titanium (Ti6Al4V); as regards the tool, tubular electrodes made of two different materials, tungsten carbide (WC) and brass, having external diameter of 0.3 mm and internal diameter of 0.12 mm, were used.

As regards the dielectric, five types of dielectric were used, both liquid and gaseous: Kerosene (HEDMA 111), demineralized water, vegetable oil (soya bean), air at 10 bar and oxygen at 9.5 bar. Their properties are reported in Table 1. The gaseous dielectrics were injected in the machining zone thorough the tubular electrode (Fig. 3). When the unconventional dielectrics were used, since they are not included in the software, kerosene data were selected.

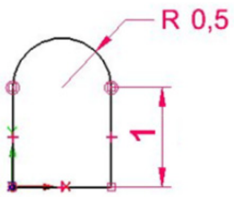


**Fig. 2** Geometry of the micro-pocket


**Fig. 3** Implementation of dry-EDM

For each pocket the energy consumption was measured using a watt-metro Christ EL-EKTRONIK (CLM1000 Professional Plus) placed in way to include the whole power usage. When gaseous dielectrics were used, the dielectric unit was disabled to measure the actual electrical energy adsorbed by the machining. In the case of compressed air as dielectric, the energy consumed by the compressor was measured and included. At the end of each pocket, the electrode was cut using the wire EDM unit to restore the same initial electrode conditions for each test. For each milling, the EDM machine records the machining time, the electrode wear, the mean erosion speed, the eroded volume and the actual depth of the pocket. Table 2 reports the values of the coefficients used in the equations to calculate the sustainability index.

Table 3 reports, for each dielectric used in the experimental investigation, the evaluation of the all the aspects taken into account for the determination of the penalty coefficient ($k_i$). This coefficient was used in the formula of the environmental sustainability ($S_e$). For each aspect, a ranking index from 0 to 3 was evaluated. Coefficient $k_i$ is the ratio between the sum of all indexes and the worst possible score (all indexes equal to 3).

**Table 1** Properties of the dielectrics

| Type of dielectric | Dynamic viscosity [g/(m·s)] | Density [g/dm³] | Dielectric rigidity [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 |
| 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 |

**Table 2** Values of the coefficients

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

**Table 3** Determination of the penalty coefficient

| | Kerosene | Water | Vegetable oil | Compressed air | Oxygen |
|---|---|---|---|---|---|
| Fire hazard | 3 | 0 | 0 | 0 | 2 |
| Fumes 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 |
| Filters dismantling | 3 | 3 | 3 | 0 | 0 |
| Total | 19 | 9 | 11 | 3 | 8 |
| $k_i$ | 0.79 | 0.37 | 0.46 | 0.12 | 0.33 |

## 3. Results and discussion

Figs. 4 and 5 show the erosion time and the volume of the electrode wear obtained milling AISI304 and Ti6Al4V using brass and WC electrodes varying the type of dielectric. The bars for brass electrode using gaseous dielectrics are omitted since these conditions did not permit to realize the test as previously underlined. In general, water as dielectric offers an optimal solution for all the tested conditions when the objective is to minimize the machining time. When brass electrode is used, vegetable oil is comparable to kerosene especially for AISI304 while using WC electrode there is a remarkable difference on the performance between the oil-based dielectrics: the machining occurs in a faster way using vegetable oil than kerosene. As far as gaseous dielectrics are involved, some interesting results are obtained: while compressed air does not represent a valid alternative, the oxygen is one of the best solutions to minimize the milling time.

As regards the electrode wear, the gas dielectrics, especially the oxygen, minimize the wear. In general, the water as liquid dielectric obtains good results. It is hereby confirmed that vegetable oil is competitive with kerosene. Carbide electrodes show a lower electrode wear than brass [36].

Using these data, the developed Sustainability Index was calculated (Fig. 6). Several considerations can be made. First, the environmental impact process when brass electrode is adopted is lower than WC electrode. In fact, in three out of five sub-indexes of SI, machining time plays an important role and therefore the processes consuming lower time are more sustainable. Fixed the electrode, the dielectric that reveals to be the most sustainable is the water. In general, kerosene is less sustainable than the others liquid dielectrics. Vegetable oil is an appreciable dielectric in all the tested conditions. As regards gaseous dielectrics, compressive air gives worst results while oxygen is very interesting. On titanium sheets, oxygen is the best solution to minimize the sustainability index while on stainless steel gives good results.

Anyway, this analysis on the global *SI* does not allow identifying the problematic issues of each experimented conditions. For this reason, Figs. 7 and 8 show the contribution of the five sustainability sub-indexes to the global *SI*.

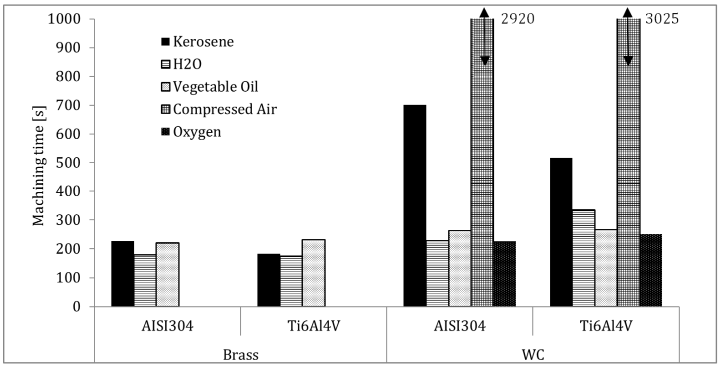


**Fig. 4** Machining time for AISI304 and Ti6Al4V using brass and WC electrode varying the dielectric

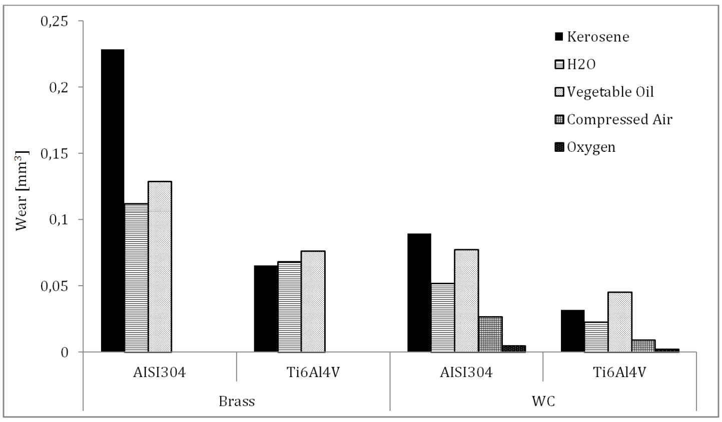


**Fig. 5** Wear of brass and WC electrode when AISI304 and Ti6Al4V is machined varying the dielectric

Using brass electrode, wear and environmental sub-indexes are especially relevant. The energetic component and that one related to the performance are almost constant for all the conditions. Regarding the others components, the dielectrics display the largest percentage variation, yet its contribution to *SI* is relatively small. The dielectric and environmental sustainability indexes are high for kerosene, medium for vegetable oil and low for water for both workpiece materials. Similar remarks are valid for electrode wear when AISI304 is machined, while electrode wear is almost the same for Ti6Al4V.

There is a different situation when WC electrode is used. The energetic component results always small except for air as dielectric. For liquid dielectrics, each sub-index can be ranked as follows: high for kerosene, medium for vegetable oil and low for water. The main components are wear and environmental sub-indexes. Overall performance of air dielectric is poor while oxygen proves to be competitive with liquid dielectrics especially because it allows low electrode wear.

Anyway, the critical aspects on the formation of the global *SI* varying workpiece and electrode material and dielectric type can be underlined though Figs. 6 and 7. In view of this analysis, it is possible to take actions aiming to reduce in general the sustainability index (and therefore to improve the sustainability level) focusing on the aspects causing more sustainability problems following a Pareto logic.

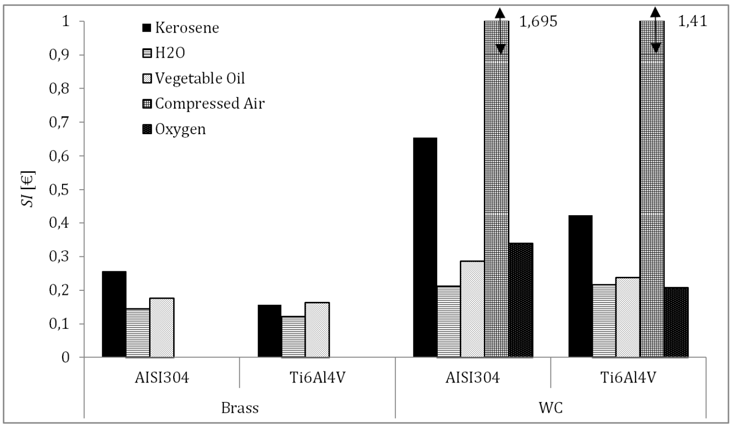


**Fig. 6** Sustainability index for AISI304 and Ti6Al4V using brass and WC electrode varying the dielectric

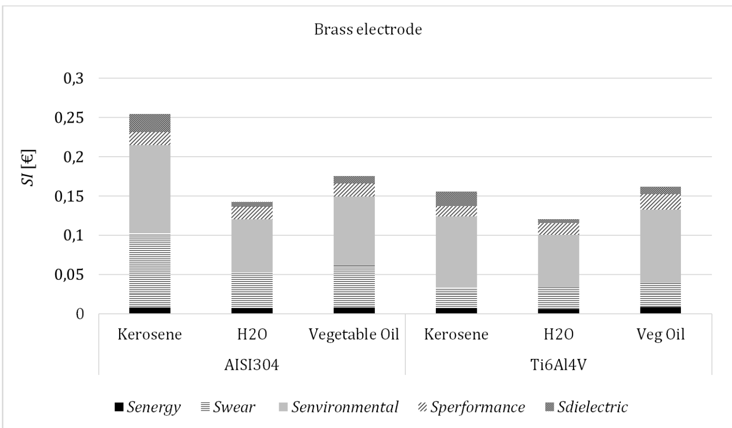


**Fig. 7** Composition of the sustainability index for AISI304 and Ti6Al4V using brass electrode varying the dielectric

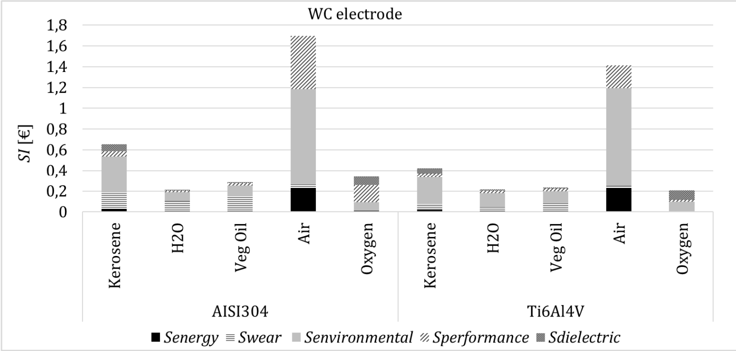


**Fig. 8** Composition of the sustainability index for AISI304 and Ti6Al4V using WC electrode varying the dielectric

A further comparison between working conditions (combinations of electrode material and dielectric) can be made by evaluating each single sub-index, normalizing the sum of all values corresponding to all working condition. The percentage distribution of each sub-indexes are reported in Figs. 9 and 10, showing a ranking of the experimental conditions for both work materials. Considering AISI304, in general the use of compressed air is not appreciable except for the indicator related to the dielectric sustainability. The combination kerosene as dielectric and tungsten carbide as electrode expends a lot of resources respect the others solutions. Oxygen as dielectric and WC electrode is the best solution for the sub-indexes regarding the energy consumption, the electrode wear and the environmental impact but need improvements for the performance and dielectric components. Water and vegetable oil always give good results.

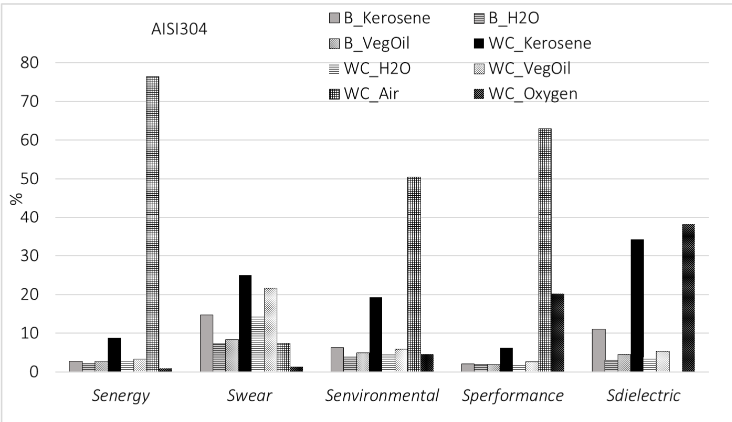


**Fig. 9** Percentage distribution of sub-indexes on different experimental conditions in terms of electrode material and dielectric for AISI304

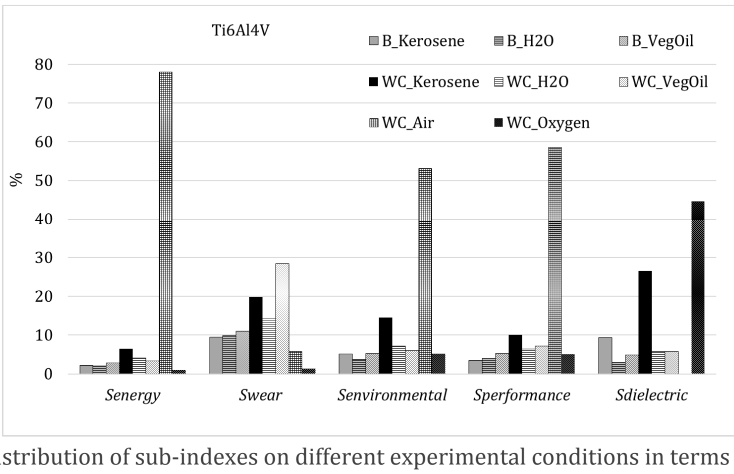


**Fig. 10** Percentage distribution of sub-indexes on different experimental conditions in terms of electrode material and dielectric for Ti6Al4V

Also for Ti6Al4V, water and vegetable oil show good performance from the point of view of the sustainability. It is confirmed that compressed air is not a competitive dielectric. As regards the combination oxygen as dielectric and tungsten carbide as electrode, the critical aspect is only the dielectric sustainability while the others sub-indexes are very interesting.

The advantage of the proposed index meets the requirements to be easily implemented in industrial applications. Anyway, the presented results in terms of the effect of the type of electrode and dielectric on the level of sustainability of the machining are influenced by the adopted parameters and by the choice of the values of the coefficients. The index could be improved taking into account other sustainability issues. For example, the pollution effects due to the contamination from dusts of both electrode and workpiece could be considered into the sub-index related the environmental. Moreover, other aspects related the quality of the machining could be taken into account such as roughness surface.

The proposed index can be implemented in different technological situations such as micro-EDM drilling or WEDM. In fact, these different applications of the same technology have in common the same physical principle of material removal based on the erosion thorough electrical discharges between the workpiece and the electrode tool that occur in a dielectric fluid. The aspects taken into account for the elaboration of the sustainability index are in general common to other EDM processes and therefore the model can support similar works on others applications. In fact, the main factors related to sustainability of EDM processes are the energetic consumption, the electrode wear, the usage of the dielectric, the effect of the dielectric on the environmental and the process performance in terms of the probability of producing a non-conforming part.

## 4. Conclusion

The micro-ED milling process was evaluated concerning the sustainability manufacturing. A global index, named Sustainability Index, taking into account the energetic consumption, the environmental impact, the dielectric consumption, the wear of the electrode and the machining performance (i.e. the scrapping/repairing rate) was developed. The index estimates the environmental impact in terms of both quantity of consumed resources and pollution effects created by the process. It was applied for an experimental case, in particular the execution of micro-pockets on stainless steel and titanium sheets using two types of electrode and five types of dielectric, both liquid and gaseous. For each workpiece material, the effects of both the electrode material and the type of dielectric on the sustainability process performance were analysed. In this way, for each condition in term of workpiece material/electrode material/dielectric the critical aspects related to the sustainability can be identified. Focusing on these aspects, actions of finding solutions minimizing the environmental impact of the process can be undertaken. Unusual dielectrics, such as vegetable oil and oxygen, proved to be valid substitutes to traditional ones under several viewpoints, including sustainability.

The proposed index to measure the sustainability of micro-EDM milling process meets the requirements to be easily implemented in industrial applications. The index provides a tool that can assist the decision-making stage of the selection of the product and process conditions aiming the minimization of the environmental impact. The obtained results can improve the knowledge of alternative dielectrics, not yet used in industrial applications. Finally, the aspects taken into account for the elaboration of the sustainability index are in general common to other EDM processes and therefore it can support similar works on others applications such as micro-EDM drilling or WEDM.

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