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ORIGINAL ARTICLE

Real time power consumption monitoring for energy efficiency analysis in micro EDM milling

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Abstract Sustainability has become a major concern in many countries and is leading to strict regulations regarding the impact of products and services during their manufacturing, use, and disposal. Power consumption monitoring in manufacturing companies can lead to a reduction of machine tools energy wastes and consequently to lower expenses. To this end, a complete transparency of energy usage among the entire manufacturing facilities is required. Despite the small volume of material processed, micro manufacturing processes are energy intensive and the optimization of energy usage becomes critical for manufacturing sustainability. Electrical discharge machining (EDM) is considered an attractive solution for the manufacturing of microcomponents. In this paper, a low cost and modular data acquisition system, based on open-hardware and open-source software, for online energy consumption monitoring, is presented. The system described is applied for energy efficiency analysis of the micro EDM milling process by using a state of the art commercial machine tool. A number of sensors is connected to the data acquisition system to measure the energy consumption of the main sub-systems of the machine tool, data is recorded through a microcontroller, and sent to the main computer via Wi-Fi for data storage and analysis. Results show that the process efficiency depends on machine parameters but it is always far below 0.01 %. Solutions are suggested to improve the energy efficiency of the machine tool considered in this work.

Keywords Micromachining · EDM · Electrical discharge machining · Energy · Monitoring · Efficiency · Sustainability

1 Introduction

Sustainability has become an important issue in all spheres of life as it focuses on safeguarding natural resources against exploitation in the name of productivity and competitiveness by manufacturing and service organizations. In many countries, it is leading to strict regulations regarding the impact of products and services during their manufacturing, use, and disposal. As a consequence, the interest in environmentally friendly manufacturing is increasing [9].

Anastas et al. define green chemistry as the design, development, and implementation of chemical products and processes to reduce or eliminate the use and generation of substances hazardous to human health and the environment [1]. According to [7], it is possible to define green manufacturing, green marketing, and green supply chain in a similar way.

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Sustainability can be pursued at different levels: business, product design, supply, production, distribution, remanufacturing, and/or recycling. A sustainable production is achieved by managing the processes with sustainable inputs such as energy, people, equipment, and machines with the objective of reducing waste, rework, and carbon footprint.

Accordingly to recent studies [18], electricity monitoring in manufacturing companies should be performed in three levels: factory, department, and unit process. Examining the lower level, energy bills can be sensibly eased by reducing machine tools energy wastes. To accomplish this task, different approaches are available, from product design optimization and life cycle management to production plant scheduling and tool machine ecodesign. What all these approaches have in common is the requirement of complete transparency of energy usage. To this end, it is necessary to implement a detailed grid of meters to characterize energy consumption over time, plus an information system capable of logging data from such meters, process it and visualize human readable results in support to management and decision making.

In this paper, a mini framework for developing intelligent energy management in manufacturing systems through online energy consumption monitoring is presented. The development of the system for the online energy consumption monitoring of electric units is presented and exploited to analyse the power consumption of a micro EDM milling machine and its most relevant subsystems (Fig. 1, Table 1). The data acquisition system is described in detail, so that it can be easily replicated and adapted to monitor the energy consumption of any kind of machine. The system was employed to acquire data and gain a better understanding not only of the total amount of energy involved in the process, but also of the quota dissipated by each sub-system of the machine. The results obtained from the data analysis were used to suggest strategies to increase the energy efficiency of the micro EDM milling machine considered in this work.

Fig. 1 Sarix SX-200 micro EDM milling machine used in the experiments

Table 1 List of the main subsystems of the micro EDM machine (Fig. 1) that were considered for the energy consumption evaluation

Unit	Code	Description
Control	MC	Main of control unit
Control	C1	On-board computer
Control	C2	Micro pulse shape generator
Control	C3	Erosion power supply
Control	C4	Motors control unit
Control	C5	X and Y axes power supply
Control	C6	Z axis power supply
Control	C7	C axis power supply
Dielectric	MD	Main of dielectric unit
Dielectric	D1	Low pressure flushing pump
Dielectric	D2	Cooling and filtering pump
Dielectric	D3	Dielectric unit ancillaries

1.1 Energy efficiency in micro EDM

Electrical discharge machining (EDM) is an electro-thermal process where material is removed from the workpiece electrode by means of recurring electrical discharges [15]. Given its peculiar characteristics, EDM is considered an attractive solution for the manufacturing of microcomponents [19]. In order to machine microparts by EDM, it is necessary to increase the accuracy and the resolution of the process in terms of minimum machinable feature size and surface roughness. For this reason, in micro EDM, the minimum achievable material removal per single discharge, which is proportional to the discharge energy [14], is lower than in conventional EDM.

In micro EDM milling, a cylindrical rod is used as tool electrode and it is guided along the toolpath in order to remove the material from the workpiece layer-by-layer [22], where layer thickness can be as low as 0.1 μm. The diameter of the tool, instead, can vary from few microns to few millimeters.

Online energy monitoring [2, 11, 16, 21] and modeling of energy consumption of industrial processes at macro scale [4–6, 10, 12, 20] have already been studied and a number of works have already been published on this topic. At micro scale, instead, and in particular in micro EDM, there are only few investigations reported [13, 17]. Kellens et al. presented a preliminary environmental assessment of wire EDM, die-sinking EDM, and micro EDM [13] using the CO_2PE!-methodology. However, for the micro EDM machine, the power consumption of the two main units of the machine tool was measured as a whole, relatively to roughing and finishing operations only. In this work, instead, a detailed quantification of the energy use in micro EDM milling is carried out considering the most relevant machine tool subsystems and a wide range of process parameters.

The energy efficiency of the micro EDM machine considered in this work can be evaluated by comparing the total energy of the discharges (process energy), which are instrumental in material removal, and the overall energy consumption of the machine tool including all the necessary auxiliary equipment. The total energy of the discharges involved in a micro EDM operation can be evaluated experimentally by multiplying the number of discharges counted during the machining process by the mean discharge energy that can be considered a statistical characteristic of the population relative to the selected set of process parameters [3].

Although only a small percentage of the discharge energy is effectively spent to remove material from the workpiece, because energy is converted into heat and then almost completely dissipated by conduction into the electrodes and dielectric fluid [15], total discharge energy will be considered in this work.

In order to perform a micro EDM process, a number of auxiliary components are required and it is expected that the energy consumed by these auxiliaries is dominant, since the amount of material that is removed in micromachining processes is very small. Nevertheless, an estimation of the energy consumption of the machine subsystems is valuable because it can suggest procedures and strategies for the optimization of machining procedures and improvements of the machine hardware, oriented to the reduction of the overall energy consumption of the micromachining process.

2 Micro EDM machine

The machine tool selected for the energy efficiency investigations that are reported in this work is a Sarix SX-200 (Fig. 1), state of the art in micro EDM and capable of performing micro EDM milling, micro EDM drilling, micro EDM die-sinking, and micro EDM grinding operations.

The machine consists of four main sub systems with different electrical elements: the main structure which includes the spindle, motors, actuators, and other equipment to perform machining, the control unit with generators and logic boards to drive the process, the human-machine interface, and the dielectric unit for filtering, cooling and pumping the dielectric liquid. The flushing of dielectric liquid, which in this case is a low viscosity hydrocarbon oil, is provided by a pump directly on the machining area through a hose.

The electrical components in the main structure and the human-machine interface are controlled and powered by the control unit. As a consequence, the control unit is composed of many electrical components and the most important ones are (Table 1): a number of power supplies (C5, C6, C7), a motor control unit (C4) that drives the motors of the axes, the erosion power supply (C3) that generates the power required for the material removal process, the micro pulse shape generator (C2) that modulates electrical discharge pulses and monitors in real-time machining parameters, process performance, and short circuits.

The dielectric unit, instead, is connected to the control unit only for communications purposes and sources the power from the grid through a dedicated plug. The dielectric unit is equipped with two electrical pumps necessary for flushing (D1) and for cooling and filtering (D2) the dielectric fluid, and a number of auxiliaries (D3) such as power supply, electro valves, temperature and pressure sensors, logic boards, communication interface board, relays, safety switches, circuit breakers.

The micro EDM machine is also using compressed air for the functioning of the high pressure dielectric pump, pneumatic actuators, and cleaning of the tool electrode before the measurements at the laser micrometer. A water cooler is used to provide water at 20.0 °C to the heat exchanger of the dielectric unit and thus to control the temperature of the dielectric fluid. The power related to the air compressor and water cooler was not considered in this work.

3 Measuring the electrical energy consumption

Most of the production machines consist of several subsystems with resistive, capacitive, and inductive loads. In this case, the energy consumption at a given time can be calculated by measuring the electric instant power $P(t)$ over the observed period of time T:

$$E = \int_0^T P(t)\mathrm{d}t \tag{1}$$

Instant power $P(t)$ is the product between instant voltage $U(t)$ and instant current $I(t)$:

$$P(t) = U(t) \cdot I(t) \tag{2}$$

In this way, real power and not apparent power was measured.

The following paragraphs are dedicated to the description of the monitoring system. Hardware, software, data recording, and calibration process are explained in detail.

3.1 Modular energy monitoring system

The experimental setup that is necessary to perform the energy consumption analysis of the micro EDM machine and its main subsystems with real-time data processing and visualization has to perform the following tasks: measure potential difference and current intensity related to at least 12 different components (Table 1), read the analog signals from sensors, and convert it to digital values, perform data processing in real-time, show to the operator a visual indication of the measured parameters while the machining process is running and store the data in a non-volatile database.

To this end, in addition to the current and voltage sensors, a data acquisition system provided with an analog to digital converter (ADC) and a personal computer to implement a graphical user interface and store the data are necessary.

In order to encourage the implementation in different settings of the method proposed in this work, only the most affordable among the different configurations of the structure outlined above were considered. For the same reason, the system had to be also easily adaptable to different machine tools, equipment, instruments, or production plants.

Affordability and adaptability led to a configuration composed of a number of microcontroller boards with embedded ADC for data acquisition and real-time data processing that are connected through an Ethernet network to a server where the live feed of data is displayed and stored in a database (Fig. 3). Indeed, such a system can be easily expanded as needed by adding more microcontroller boards, used to monitor components that are arranged over a large area by using a wireless connection, adapted to acquire data from other kind of sensors to measure also flow rate, temperature, pressure, and more.

In this case, two types of commercially available Hall-effect current sensors have been used, one with a range of 20 A for the main plugs (MC, MD) and one with a range of 5 A for the subsystems, plus voltage sensors that have been assembled in-house and are based on a voltage divider circuit. These sensors are able to scale down the voltage signal from 220 V AC to the $0 \div 5$ V range that is accepted by the microcontroller Analog-to-Digital Converter (ADC). All current and voltage sensors, as well as the microcontroller boards were powered by a dedicated 9 V power supply unit through a 5 V voltage regulator, in order to stabilize the DC voltage required by all the elements of the data acquisition system.

When possible the information sourced from a single voltage sensor has been shared with multiple current sensors, thus simplifying the system and reducing the amount of data that has to be processed by the microcontroller board.

3.1.1 *Microcontroller board*

The microcontroller board chosen for this work is an Arduino Uno (Figs. 2, 3 and 4), which is equipped with an 8 bit Atmel ATmega328 microcontroller with a clock rate of 16 MHz, 2 KB of SRAM memory and six analog inputs. An Ethernet shield has been added to each Arduino Uno board to be able to send data to the remote server through existing Ethernet network.

Theoretically, the microcontroller has enough computational power to sample current and voltage signals, to perform calculations and to send elaborated data to the server. However, it has some limitations that must be addressed in order to use it for this task.

The built in memory is not sufficient to store values for a long period of time, it can be used only as a small buffer for a limited number of samples.

Since the microcontroller is not capable to perform multiple operations in multitasking, the time spent to send data to the remote server corresponds to a pause in the operation of sampling the signals from sensors. As a consequence, it is important to maximize the data transfer speed. To this end, UDP was selected among the existing data transfer protocols over Ethernet but then it is necessary to provide every microcontroller board with an Ethernet Shield because Arduino Uno has not a built in Ethernet adapter.

The analog to digital converter (ADC) of the microcontroller is capable to convert analog signals at a rate of about 10 kSa/s, which is sufficient in sampling a voltage/current signal characterized by a frequency of 50 Hz. However, the six analog inputs/outputs of the microcontroller board are multiplexed and thus the sampling rate of the system is

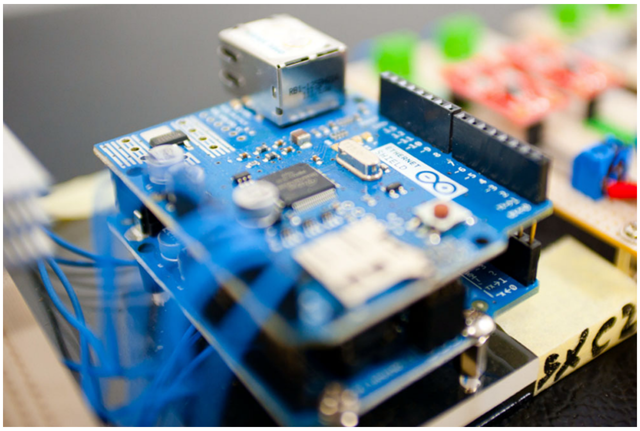
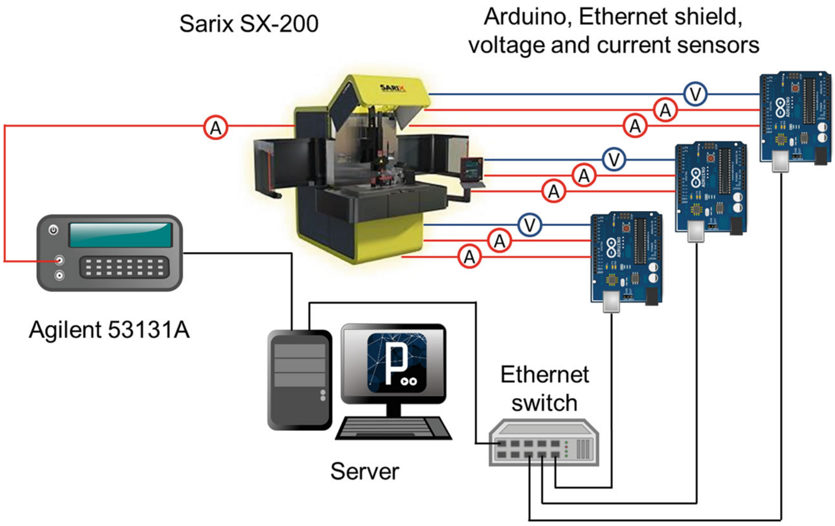


Fig. 2 Image of the acquisition system, which is composed of an Arduino Uno microcontroller board and Ethernet Shield, plus voltage and current sensors

Fig. 3 Arduino-based framework for the remote and online energy consumption monitoring of the micro EDM process



affected also by the number of channels that are read and the computational load between subsequent analog channel readouts. As a consequence, when the signals from multiple sensors are read successively the sampling rate decreases to a fraction of the nominal conversion rate of the ADC. Moreover, since channels are not read simultaneously, there is a short time interval between each channel readout. For this reason, the ADC clock speed was set at 500 kHz, thus making it possible to acquire from 850 to 1150 samples per second, depending on the number of channels and the complexity of calculations.

The nominal resolution of Arduino Uno internal ADC is 10 bit, which corresponds to 1024 levels on a measured range, and the accepted voltages at the input ports are in the range of 0 ÷ 5 V. Thus, the resolution of voltage sensors is about 0.6 V, given that the amplitude of the voltage signal is $\pm 220\sqrt{2}$ V, while the resolution of current measurements is 0.014 A for 0 ÷ 5 A current sensors and 0.055 A for 0 ÷ 20 A current sensors.

3.1.2 Microcontroller software

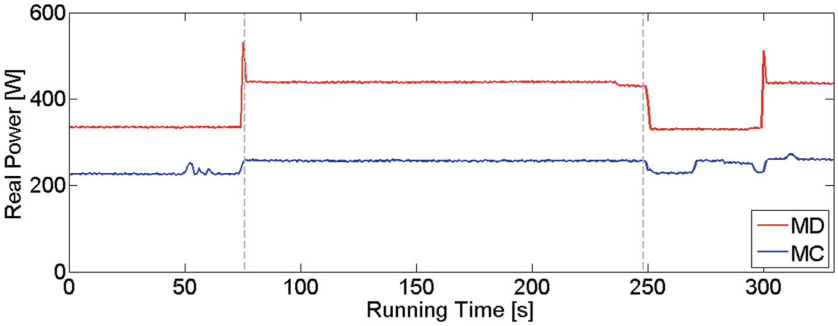
As it is with every software in general, the script developed for the microcontroller board accepts some values as inputs, processes them and provides the results at the output.

In this case, the input are voltage signals originating from current and voltage sensors that are connected to the analog input/output pins and transduced by the ADC into digital values ranging from 0 to 1023. The software has to accomplish the following tasks repetitively: to read the analog values as fast as possible, to perform the necessary calculations to obtain the desired results, and finally to send them to the server over Ethernet.

As discussed in Section 3.1.1, the analog inputs are multiplexed and as a consequence they are not read simultaneously but successively. However, if the analog channels are read fast enough relatively to the frequency of the input signal, then the resulting time gap between readouts can be neglected. To this end, all the analog channels that are connected to a sensor are read subsequently, values are just stored into variables until all the signals have been acquired and only then calculations are performed. Values of real power, RMS of voltage, and RMS of current are calculated with running algorithms [16] at every iteration.

Other values that are calculated are size of the sample (number of inputs contributing to the calculation of the mean value), microcontroller time reference at the beginning of the sampling, and number of periods of the sampled sine wave signals. The values that are temporarily stored in memory are converted with a predefined pattern into a

Fig. 4 Real power data relative to the main plugs of the control (MC) and dielectric (MD) units, as recorded by the data acquisition system during an experiment



binary packet that is then sent to the server, with a time interval of one second. Regarding the data transmission, it was possible to achieve a data transfer time shorter than 5 ms by using UDP data transfer protocol.

3.1.3 Server

Since raw data is processed directly by the microcontroller and results are transmitted to the server only once per second, data throughput and server hardware requirements are moderate. A laptop with a 2 GHz Intel Core2Duo processor and 4 GB of RAM was more than sufficient to run the server application and record the data incoming from the acquisition system.

Data is sent by the four microcontroller boards to the server through Ethernet connection using UDP protocol. The software on the server that manages the incoming data is continuously listening to the predefined UDP port and once a packet of binary data is received the variables are decoded, the graphical user interface is updated with the latest results, which are also stored in a database.

3.2 Calibration of the sensors

Alternating current (AC) in general is varying through all the sensor range and depending on the setting of the trimmers on sensor breakout can show a response curve that is not perfectly linear at the extreme values. For this reason, current sensors have been calibrated in direct current (DC) but at different values within the sensor range. A calibration circuit was made with a variable 0 to 12 V power supply capable to provide up to 6 A and a suitable high power resistor in order to dissipate from 0 to about 5 A, which is the range of currents sensed during experiments.

Calibration of voltage and current sensors was performed using a multimeter as reference and dedicated software for both server and microcontroller board. Firstly, the offset of the analog signal was measured in open circuit conditions. Then, the desired flow of current in the test circuit was set by adjusting the potential difference provided by the power supply, and the gain compensation value was estimated by matching the RMS values read from the multimeter and the ADC value read by the microcontroller board.

This procedure was applied at different current values for each sensor, with ranges of nominal current values that depends on sensor application, and repeated five times. In Fig. 5 an example of data from calibration is reported relative to the sensor connected to the cooling and filtering circuit pump (D2) that was tested in a range from −4 to +4 A and shows an almost linear response curve. In this case, the coefficients of the calibration function were obtained by fitting the data with a one degree polynomial function.

4 Experiments

The system described in the previous section was applied to measure the energy consumption of the micro EDM machine while performing a pocketing operation of a circular cavity having a diameter and depth of about 530 and 30 μm respectively (Fig. 6), on a block of Uddeholm Stavax ESR tool steel by using a tungsten carbide tool electrode and hydrocarbon oil as dielectric fluid.

The power consumption of the machine tool and its main subsystems was tested on a wide range of process parameters (Table 2), ranging from fine-finishing (exp. index A) to pre-roughing (exp. index H). The energy efficiency performance of each set of process parameters was tested with a dedicated experiment, that was repeated three times to evaluate the reliability of the process efficiency estimation. The experiment index H was repeated ten times to evaluate the

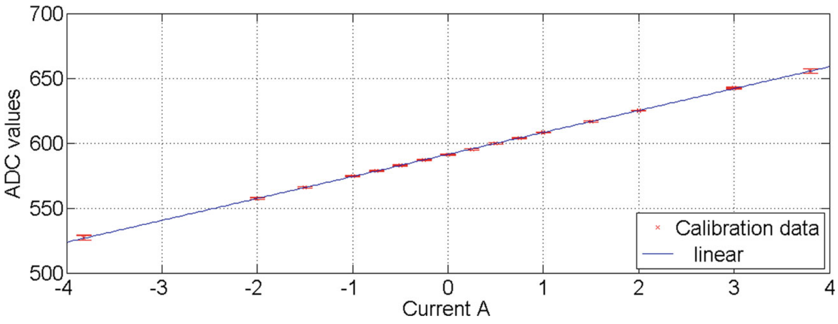


Fig. 5 Average values with relative standard deviations of the data acquired during the five repetitions of the calibration procedure of a current sensor. From these values, the calibration curve for current sensor is obtained by performing a polynomial fit in Matlab software

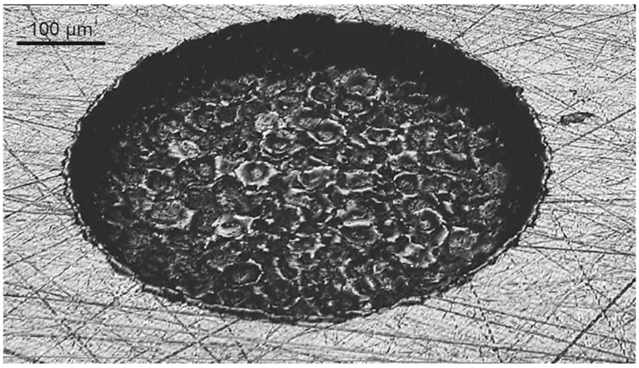


Fig. 6 Confocal image of a blind hole machined by micro EDM with a set of process parameters typically used in roughing operations (exp. index H), having a diameter of about 530 μm and a depth of about 30 μm

repeatability of the operation, while the acquisition system accuracy was tested by means of a digital multimeter and a oscilloscope.

The energy consumed by the discharges for the removal of the material from the workpiece electrode was evaluated by counting the number of discharges occurring during the machining process with an Agilent 53131A frequency counter, and then multiplying the resulting number of discharges by the value of average energy per discharge relative to the process parameters settings used in the experiment.

The average energy per discharge was measured in preliminary experiments by using an oscilloscope to acquire voltage and current signals of a relevant number of discharges, with the procedure that is described in [3].

In order to compare the results relative to different working conditions and process parameters, or even different processes, the energy required by the machine tool during the material removal operations has been related to the effective volume that was removed from the workpiece. The quantity of material removed has been measured after the experiments with an optical profilometer.

Table 2 Process parameters used during the experiments: Energy index, pulse width, frequency, current, voltage, and layer thickness

Exp. index	Energy index	Width index	Freq. kHz	Curr. A	Volt. V	Layer μm
A	15	6.0	100	70	80	0.5
B	105	6.0	100	65	100	0.9
C	206	5.0	130	50	130	2.5
D	250	5.0	130	50	130	2.0
E	300	4.6	130	50	130	2.5
F	305	4.6	130	50	130	2.5
G	315	4.6	130	50	130	2.5
H	350	4.6	130	50	130	2.5

5 Results

3D images of the microfeatures machined during the experiments (Fig. 6) were acquired with a Sensofar PLμ Neox confocal microscope, and then the diameters and depths were measured with Image Metrology SPIP software. The volume of material removed during the micro EDM process was calculated from diameter and depth values and results are reported in Table 3.

The data acquisition system was started before the machining process and was stopped after the end of each experiment. The data relative to the machining time, and consequently the time that was required to remove the material of the cylindrical pocket, were extracted by means of a script in Matlab by using the current signals as indicators of the status of the machine. As a matter of fact, the pulse generator, the spindle, and the pump for the flushing of dielectric on the workpiece are turned on just at the beginning of machining and then turned off exactly at the end of the operation. They are turned on again towards the end of the experiments to cut the tool electrode, as it is possible to notice in Fig. 4. The machining operations were lasting between 257 and 413 s, depending on the process parameters settings, as reported in Table 3.

Table 3 Average values (μ) and relative standard deviations (σ) of the geometrical characteristics of the features machined during the experiments and of the duration of the material removal operation (erosion time)

Exp.	No. of	Radius (μm)		Depth (μm)		Time (s)	
index	obs.	μ	σ	μ	σ	μ	σ
A	3	258.1	0.6	52.9	0.6	174	1
B	3	260.2	0.7	30.4	0.7	213	1
C	3	264.9	0.3	46.4	0.3	363	0
D	3	263.1	0.7	29.8	0.7	284	0
E	3	266.3	0.2	38.0	0.2	354	1
F	3	265.0	0.5	35.7	0.5	991	5
G	3	264.6	0.4	40.8	0.4	410	1
H	10	263.3	0.5	30.0	0.4	413	0

Table 4 Average values (μ) and relative standard deviations (σ) relative to the energy consumption per cubic millimeter of material removed during the micro EDM process for the different process parameter settings (Table 2)

MJ/mm^3	A		B		C		D		E		F		G		H	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
MC	4.0	0.02	8.3	0.03	9.0	0.04	11.0	0.05	10.5	0.06	31.7	0.10	11.6	0.05	15.8	0.04
C1	0.8	0.01	1.6	0.01	1.8	0.00	2.2	0.00	2.1	0.01	6.2	0.02	2.3	0.00	3.1	0.00
C2	0.3	0.00	0.5	0.00	0.5	0.00	0.6	0.00	0.6	0.01	1.9	0.01	0.7	0.00	0.9	0.00
C3	0.1	0.00	0.1	0.00	0.1	0.00	0.2	0.00	0.2	0.00	0.5	0.00	0.2	0.00	0.2	0.00
C4	0.6	0.00	1.3	0.01	1.4	0.00	1.8	0.00	1.7	0.02	5.1	0.01	1.9	0.00	2.6	0.00
C5	0.5	0.00	1.0	0.00	1.1	0.00	1.3	0.00	1.2	0.01	3.7	0.01	1.3	0.00	1.9	0.00
C6	0.3	0.00	0.6	0.00	0.7	0.00	0.9	0.00	0.8	0.00	2.5	0.01	0.9	0.00	1.2	0.00
C7	0.3	0.01	0.6	0.01	0.7	0.01	0.9	0.01	0.8	0.01	2.4	0.02	0.9	0.01	1.2	0.01
MD	6.8	0.01	14.3	0.11	15.3	0.06	18.8	0.06	18.1	0.11	54.3	0.25	19.7	0.13	27.1	0.16
D1	1.6	0.03	3.4	0.01	3.6	0.01	4.4	0.02	4.3	0.08	12.8	0.28	4.7	0.16	6.4	0.52
D2	4.6	0.03	9.7	0.03	10.4	0.08	12.8	0.13	12.3	0.20	37.1	0.77	13.7	0.63	18.9	1.65
D3	0.8	0.00	1.6	0.01	1.7	0.02	2.1	0.02	2.0	0.03	6.1	0.08	2.2	0.08	3.1	0.18

The values stored by the server in the database were processed in Matlab in order to compare the energy consumption of the different machine tool subsystems and machining operations. The average real power and energy consumption through the machining time have been calculated as described in Section 3, and then the energy consumption relative to each subsystem per unit of volume of material removed was obtained from the geometrical characteristics of the machined holes and energy consumption. Results are reported in Table 4. The values listed in the columns relative to the standard deviation in Tables 3 and 4 show a good repeatability of the measures.

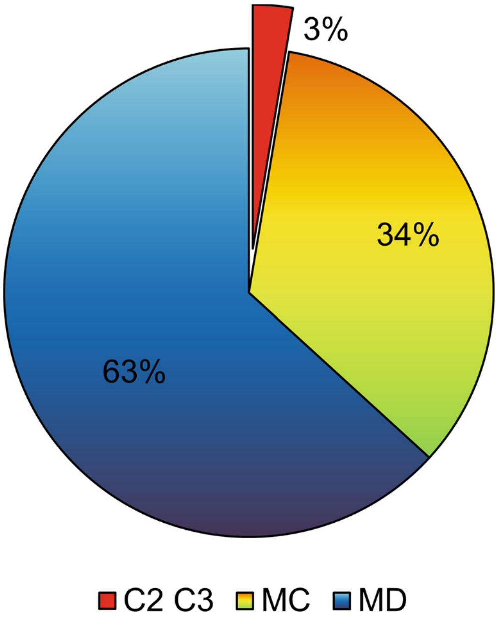


Fig. 7 Energy consumption distribution between the control unit, the dielectric unit and the discharge generator during a pre-roughing machining process (exp. index H)

The average power consumption recorded during the experiments was compared with the specifications declared by the manufacturer. For example, in the case of the circulation pump (D2), the measured average real power is 292 W and is compatible with the manufacturer specifications, which rate the power consumption to 300 W.

From the data reported in Table 3, it is possible to calculate that the average specific energy requirement is $1.7e^7$ J mm^{-3}, which is close to the value reported in [8] for the drilling EDM process.

The data visualization as represented in Fig. 4 was available for all the subsystems during the machining process, enabling online analysis and providing valuable information about the ongoing machining operation. For instance, a machine malfunction can be promptly identified and eventually prevented by searching for anomalies in the signals, such as large deviations from standard values.

The pie chart in Fig. 7 shows that the quota of energy consumed by the pulse generators during the process is almost negligible when compared to total machine energy. In particular, the dielectric unit is absorbing more than 60 % of the total energy consumption of the machine.

The column chart in Fig. 8 shows that the power required by the control unit for the machining operations with different process parameters settings can be considered constant. There is a slight variation in the power absorbed by the dielectric unit between different experiment indexes, but this is not related to differences in process parameters because they have no effect on the dielectric unit performance.

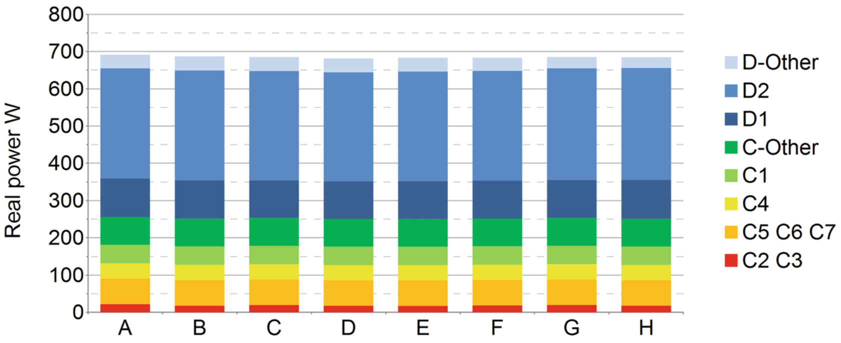


Fig. 8 Average values of power required by the main sub-systems of the micro EDM machine during the machining operation with different process parameter settings

This result can be explained by the difference between total discharge energy and total machine energy in Table 5. Total discharge energy is evaluated by multiplying the average discharge energy, relative to the process parameters settings considered, by the number of discharges counted during the experiments. Total machine energy, instead, is measured with the voltage and current sensors at the main plugs of control and dielectric units. The variation in total discharge energy due to different process parameter settings is several orders of magnitude smaller than total machine energy, and hence it is negligible.

For this reason, the differences of the results in Table 4 between process parameters settings are almost exclusively due to the difference in machining time (Table 3).

The Sankey diagram in Fig. 9 is based on the mean values relative to experiment index H and gives a clear overview of the energy losses through all the main subsystems of the micro EDM machine. The circulating (D2) and flushing (D1) pumps together require more than half of the total energy consumption of the complete micro EDM machine. Indeed, the dielectric unit is probably oversized. As a matter of fact, the flow rate of dielectric fluid, which is provided by the pump D1, is always more than sufficient to completely flood the working area and it has to be reduced by means of a ball valve, thus dissipating energy. The pump dedicated to the cooling and filtering of the dielectric fluid (D2), instead, is always on once the machine is armed, independently from the conditions of the dielectric fluid.

The power required for any machining operation could be sensibly reduced by replacing pump D1 and ball valves in the flushing circuit with a variable speed pump and by turning on pump D2 only when the dielectric fluid stored in the tank effectively requires to be cooled or filtered.

Table 5 shows that the set of process parameters identified by experiment index C is the most efficient despite having less than half the average discharge energy of the most aggressive set of machining parameters (exp. index H). This result can be explained by considering that the process efficiency strongly depends on the energy consumed by the machine subsystems, which is proportional to the operational time. Therefore, the overall process efficiency depends not only on the energy provided in the discharge, but also on the stability of the machining operation and the successful occurrence of discharges.

Table 5 Efficiency, energy required for the material removal calculated as average discharge energy multiplied by the number of discharges and total energy consumption of the micro EDM machine, relatively to different process parameters settings

Exp. Index	Number of discharges $\cdot 10^3$	Average discharge energy μJ	Total discharge energy J	Total machining energy kJ	Specific energy MJ mm^{-3}	Energy efficiency %
A	11464	0.2	2.8	120.0	10.8	0.002
B	522	11.6	6.1	146.4	22.6	0.004
C	247	64.5	16.0	248.9	24.4	0.006
D	71	108.5	7.7	193.6	29.8	0.004
E	54	168.5	9.2	241.6	28.5	0.004
F	45	98.7	4.4	676.8	86.0	0.001
G	43	149.4	6.5	281.0	31.3	0.002
H	79	193.8	15.3	281.7	43.0	0.005

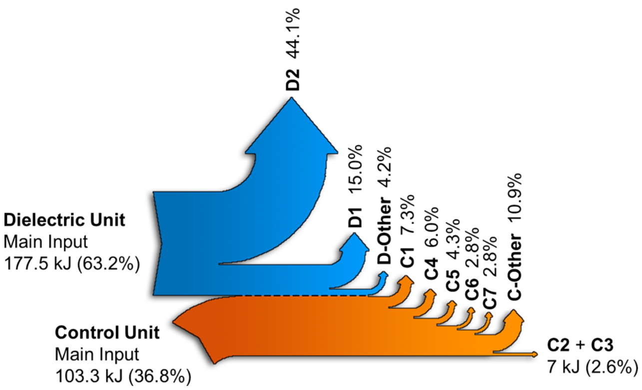


Fig. 9 Sankey diagram illustrating the distribution of energy in a pre-roughing micro EDM operation (exp. index H)

6 Conclusions

In this paper, the design, implementation, and application of a modular framework for the online and remote energy monitoring of industrial manufacturing systems has been described in detail. The monitoring system was implemented by employing open-hardware and open-source software and was applied to the energy efficiency analysis of a micro EDM machine. In order to validate the applicability of the proposed framework, machining conditions were varied from fine-finishing to roughing, through eight different sets of process parameters.

The analysis of the energy consumption in micro EDM using the developed framework showed that the energy that is strictly necessary for material removal is always less than 3 % of the total energy consumption of the machine tool, while the process efficiency is always below 0.01 %.

The overall energy consumption of the system is almost completely determined by the power absorption in the auxiliary sub systems such as pumps, heat exchanger, and motion drive units. It is also observed that such auxiliary systems do not need to run continuously throughout a machining operation.

On one hand, these results imply that the overall power consumption is almost insensitive to process parameters settings and thus an effective process optimization for energy efficiency maximization can be achieved, whenever possible, by reducing the duration of the machining operations.

On the other hand, the results above explain why the efficiency of micro machining systems is very low when compared to conventional machine tools. In fact, energy consumption of auxiliary sub systems, that are often a minor contribution in larger machine tools, become dominant in micro machining.

From another point of view, this also means that there are large margins for improvement. Indeed, the application of the proposed monitoring framework to general manufacturing systems enables the collection of detailed power consumption information for all the relevant sub systems. On the basis of such information, during the design phase, optimal sub system selection can be performed for minimal energy consumption. Furthermore, as highlighted by this study, several sub systems in a general machining system are often continuously running while their function might be required for defined time intervals during operation. The information gathered by application of the proposed framework enable highlighting such efficiency mismatch and calls for the implementation of intelligent energy management systems for all subsystems of a general machine tool.

As an example, when applying the proposed approach to the specific micro EDM machine tested in this work, the two pumps used for flushing, filtering, and cooling the dielectric fluid are consuming together more than all the other components of the machine. These should be the first subsystems of the machine to be taken into consideration for an energy efficiency optimization.

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