Modelling and optimization of energy intensity of an electrical discharge machine

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Abstract. Nowadays, high fabrication productivity and high-quality products are a matter of course. However, it would not be possible without the use of highly sophisticated progressive technologies in the production process. But many of these modern production technologies are characterized by high consumption of energy. Given the current energy prices, this is not an insignificant amount of money. It is also necessary to point out, that in many cases the rule concerning the mutual interconnection of the energy intensity of production technologies with the resulting quality of the machined area applies. These reasons led us to the optimization of energy consumption in the context of the required quality of the machined surface in terms of selected indicators. The paper aims to describe the results of the performed experimental measurements in order to create mathematical models with subsequent optimization of electricity consumption of an electrical discharge machine. Unlike many types of research conducted in the field so far, the results of the solution were based on determining the relationships between the energy intensity of the electrical discharge machine and its controllable outputs in terms of the final roughness of the eroded surface. The performed optimization based on experimentally obtained results was directed so that its results could be applied in real conditions of technical practice.

1. Introduction

The constant increase in requirements placed not only on quality but also on productivity of fabrication goes hand in hand with the implementation of modern production technologies into the production process. These modern production technologies are usually based on highly sophisticated production processes, of which progressive production technologies in many cases form an integral part [1]. In addition to meeting the quantitative and qualitative requirements imposed on the finished product, favorable economic efficiency is also an important criterion for the application of these modern technologies in the production process [2]. Therefore, several studies have been performed in the past, with a focus on understanding the interrelationships between the energy intensity of selected production processes and their resulting economic efficiency [3]. All these experimental studies, however, mostly targeted conventional production technologies, such as turning, milling, grinding, etc. Along with the introduction of new progressive technologies into production, research in this area gradually began to appear for these technologies as well [4]. Unfortunately, these studies have not been carried out to a sufficient extent just yet. Certain experiments have been performed with laser and water jets [5]. However, even with these technologies, a database of information concerning their economic efficiency has not yet been comprehensively processed. There is significantly more
information about the economic efficiency of the electrical discharge machining process [6]. EDM can generally be characterized as a machining process in which small particles of material are gradually removed through electric discharges between a tool and a workpiece. Although the EDM process itself does not consume a large amount of energy, other service processes executed on the electrical discharge machine during machining are energy-intensive [7]. These are mainly the transport of the wire electrode, the circulation and treatment of the dielectric fluid, the drives of the individual axes of the portals, and more. Therefore, electrical discharge machining is one of the most demanding production technologies in terms of energy requirements [8]. Another disadvantage of this progressive technology is the time-consuming nature of the operations performed. Although the instantaneous power consumption of an EDM machine is significantly lower compared to a lathe, laser, or water jet, its overall energy balance is not very favorable due to the application of long machining times. Consequently, this progressive technology is used in practice only as a marginal option, especially in cases where it is necessary to machine complicated workpiece shapes for which there are no better production alternatives [9]. However, it is also used in cases where it is unavoidable to machine materials with high hardness, which again cannot be machined with another alternative production technology. The main aspect that makes EDM disadvantageous compared to other production technologies is the economic efficiency of the production process associated with long production times [10]. These reasons led us to perform experimental measurements, the aim of which was to expand the theoretical basis concerning the economic efficiency of the application of electrical discharge machining technology in real conditions of technical practice. Another goal was to design a mathematical model with subsequent optimization of the energy intensity of individual processes performed on an EDM machine.

2. Theoretical analysis of energy consumption during electrical discharge machining

Material removal during electroerosion is a relatively demanding and complex process. Its principle lies in removing material particles through discharges that occur between two electrodes, one electrode representing the tool, and the other representing the workpiece in the presence of a dielectric [11]. In this process, the dielectric plays an important role as an insulator. Its selection is also relevant in terms of saving the consumed energy during the EDM process. Improper choice of the dielectric results in a significant reduction in the effect of electric discharges between the two electrodes, which also significantly contributes to the deterioration of the overall efficiency of the electro-erosive process. Although electrical discharge machining is one of the powerless machining methods, it is one of the more demanding production technologies in terms of energy [12]. As mentioned in the introduction, the EDM process itself does not form a primary element in the energy consumption of an electrical discharge machine. It’s much more energy-intensive part is the partial section, through which the circulation and adjustment of the dielectric are ensured. No less energy-intensive partial sections of the electrical discharge machine are also sections involved in the operation of individual portals, the transport of the wire electrode in the case of WEDM, and the computer control of the entire process. Although the instantaneous power consumption of the entire EDM machine is relatively small in comparison to other conventional or progressive production machines, its overall balance for machining a comparatively large area is significantly larger [13]. This is mainly due to the small amount of material removed during one discharge cycle. Even with the application of the highest frequency of cycles of individual electric discharges, it is not realistic to approach the quantity of material removal typical for other machining technologies [14]. For comparison, machining a surface with a size of 100×100 mm using milling or a laser, takes a fraction of the time compared to electrical discharge machining. Machining this dimension of the machined surface with electrical discharge technology takes several tens of minutes. However, it should be pointed out that, considering the objectivity, with the exception of grinding and other finishing technologies, electrical discharge machining achieves an incomparably higher quality of the machined surface compared to other standard machining technologies. One of the crucial aspects that disadvantage this progressive
mac \text{hining technology as opposed to other conventional or progressive machining technologies is its economic efficiency of operation. It is characterized in particular by a very low ratio of total cutting power to total electricity consumption [15]. One of the factors that strengthen this unfavorable aspect is that in the electro-erosive process, there is a significant loss of energy in the form of waste heat. Additionally, the electrical energy that is transformed into thermal energy during the electro-erosive process removes the material particles from the workpiece and thus heats the dielectric [16]. In order to maintain the dimensional accuracy of the workpiece and reduce the effects of evaporation, the dielectric must be continuously cooled, which is essentially counterproductive. On the one hand, the dielectric is heated through electric discharges, and on the other hand, it is cooled by a special unit to maintain the desired temperature. This unpropitious contraindication further aggravates the already unfavorable overall balance of the economic efficiency of the electro-erosive process. If remedial action could be taken in this area, it would be of great benefit in terms of saving the energy consumed during the EDM process. Another important factor that contributes to the deterioration of the overall economic efficiency of the electro-erosive process is the long machining times [17]. Regarding this area in practice, many times there are several errors made. These are especially the cases when the actually achieved quality is slightly higher than is required. Consequently, this adversely affects the prolongation of machining times [18]. And when it comes to the electro-erosive process, this is especially true. Therefore, a certain solution in increasing the overall economic efficiency of electrical discharge machining is also the optimization of the achieved quality of the machined surface with regard to the overall economic efficiency of the process.

3. Detailed analysis of electricity consumption of an EDM machine

In general, an EDM machine has a large number of elements that are among the less demanding in terms of electricity consumption. These elements are grouped into individual technological units, which represent the individual structural parts of the EDM machine. The structural unit consists of a cooling system, a drive system, a control system, and a system for generating electrical impulses. The following Fig. 1 shows the basic construction architecture of an EDM machine.

![Figure 1. Structural units of an EDM machine](image)

The individual structural elements of the EDM machine are characterized by relatively low electricity consumption. However, after their inclusion in the relevant structural unit, this does not apply. In addition to the different power consumption, these components also differ in the function performed [20]. Of these components, the most energy-intensive are the cooling and dielectric supply systems, and the electrical pulse generation system. In the case of WEDM, the drive and transport
system of the wire electrode is only moderately demanding in terms of electricity consumption [21]. One of the least energy-intensive structural units of an electrical discharge machine is its control system.

The graph in Fig. 2 shows the electricity consumption of the individual components of the electrical discharge machine over time $t$ during steady-state operation, during which there is no change in its power parameters or the resulting quality of the machined surface.

![Graph of electricity consumption](image)

**Figure 2.** Consumption of electrical energy by individual structural units of an electrical discharge machine depending on the time $t$ of its operation

From the graph shown in Fig. 2 it can be observed that the consumption of individual components of the electrical discharge machine increases with the increasing time of steady-state operation, in other words, operation in which there is no change in its performance parameters or the resulting quality of the machined surface, but the other does not change nor decreases. It is generally known that the consumption of electricity also varies depending on the way the work is performed on the EDM machine. In addition, finishing operations are less energy-intensive. On the contrary, the increased consumption of the EDM machine is recorded in power roughing operations. From the graphic shown in Fig. 3, it can be seen how the power consumption changes with the change of operation mode of the EDM machine.
The graph in Fig. 3 shows that a change in the operating mode of the electrical discharge machine has a significant impact on the change in the power consumption of its individual components as well as the overall consumption. It can be observed that when changing the operating mode from stand-by power through average power to maximum power, there is an increase in electricity consumption for all components. It is a structural unit that serves to generate electrical impulses, circulate and cool the dielectric fluid. This is due to the application of higher discharge energy, which has a relatively negative impact on increasing the cooling demand of the dielectric fluid. The power consumption of the control part of the electrical discharge machine does not usually change when the operating mode is changed from average power to maximum power. On the contrary, a slight decrease in electricity consumption occurs in the structural unit, that ensures the drive of individual portals and, in the case of WEDM, also the transport of wire. This is because, at full power, a full cut is usually made, which requires the application of lower feed rates of individual portals. Nevertheless, it is important to point out one indisputable fact. The electricity consumption of an EDM machine cannot be understood solely on the basis of immediate consumption \[22\]. Considering the conditions of electrical discharge machining, this is a relatively misleading indication. Even though the immediate consumption of an EDM machine is low, in terms of its overall balance, it may not be such a beneficial value. When it comes to an extension of the machining times, the overall balance of the consumed electrical energy for machining a specific shape of the workpiece thus deteriorates significantly \[23\]. For example, machining a specific surface with higher surface quality, and by surface quality we mean its geometric accuracy and roughness, is much more time-consuming than machining a surface with a lower quality \[24\]. Thus, despite the low instantaneous power consumption in finishing operations, its overall balance may be much higher than in roughing operations where the instantaneous power consumption is increased \[25\]. In order to be able to detect and describe the relationships between instantaneous and total consumption in the context of the achieved quality of the machined surface after electrical discharge machining, it is necessary to design a mathematical model.
4. Design of a mathematical model of electricity consumption of an electrical discharge machine

As already mentioned above, an important tool for the exact determination of the mutual relations between the actual and the total consumption with respect to achieving an adequate quality of the machined surface after electrical discharge machining is the design of a mathematical model. The total electricity consumption of an EDM machine over time \( t \) can be determined by equation (1):

\[
E_{ED} = E_{CNC} + E_{CC} + E_{SP} + E_{SG}
\]  

Where \( E_{ED} \) - is the total electricity consumption of the EDM over a certain time \( t \) (kWh)
\( E_{CNC} \) - electricity consumed by the machine control system (kWh)
\( E_{CC} \) - electricity consumed by the cooling and dielectric supply system (kWh)
\( E_{SP} \) - electricity consumed by servo drives and wire electrode feed (kWh)
\( E_{SG} \) - electricity consumed by electric pulse generator (kWh)

Subsequently, it is necessary to quantify the size of the partial electricity consumption for a certain time \( t \) of individual structural units of the electrical discharge machine. The power consumption of the \( E_{CNC} \) through the construction part - the control system of the EDM machine, can be relatively easily mathematically described using equation (2), because it is a system in which power consumption is relatively stable even during the change of operating mode.

\[
P_{CNC} \cdot t = E_{CNC}
\]  

Where \( P_{CNC} \) - is the power input of the control system of the EDM machine (kW)
\( t \) - operating time of the control system (hours)

However, determining a mathematical notation to define the total \( E_{CC} \) power consumption through a cooling and dielectric supply system is a bit more challenging. This is because its total power consumption varies depending on the operating parameters of the EDM machine and its current operating mode [26]. The rule is that when applying finishing operations with less discharge energy, the total electricity consumption through the cooling and dielectric supply system decreases. Conversely, in roughing operations, its total consumption increases. This power consumption of the \( E_{CC} \) by means of the electrical discharge machine assembly used for cooling and dielectric fluid supply can be described by equation (3).

\[
E_{CC} = (P_{CP} \cdot t_{CP}) + (P_{c} \cdot t_{c})
\]  

Where \( P_{CP} \) - is the power input of the control system of the EDM machine (kW)
\( t_{CP} \) - is the operating time of the circulation pump (h)
\( P_{c} \) - heatsink input (kW)
\( t_{c} \) - cooler operating time (hours)

Another structural unit of the electrical discharge machine, in which the total electricity consumption \( E_{SP} \) varies slightly depending on the operating mode of the EDM machine, are the servo drives and the wire electrode feeding system. Therefore, determining the mathematical notation to determine the total power consumption of the \( E_{SP} \) is a little more complicated in this case as well. In general, the consumption of electrical energy of this component of the electrical discharge machine is primarily dependent on the speed and direction of movement of the work table. During roughing operations, the speed of the work table is somewhat lower compared to the cases where finishing operations are applied. Together with the currently achieved quality of the machined surface, or with the change of the size of the wire tool electrode, the speed of its rewinding also changes, which also has an impact on a small change in the total electricity consumption of this EDM machine unit. Its size
can be empirically described using mathematical formula (4).

\[ E_{SP} = \sum_{i=1}^{n} \left( P_{SPi} \cdot t_{SPi} \right) + \sum_{i=1}^{n} \left( P_{WMi} \cdot t_{WMi} \right) \]

(4)

Where \( P_{SPi} \) is the power input of the i-th servo drive of the EDM machine (kW) 
\( P_{WMi} \) - power input of the i-th wire electrode drive mechanism (kW) 
\( t_{SPi} \) - operating time of the i-th servo drive (hours) 
\( t_{WMi} \) - operating time of the i-th wire electrode drive mechanism (hours) 
\( n \) - number of power units

One of the most important components of an EDM machine is an electrical pulse generator. To construct an empirical notation, however, it is one of the most demanding tasks due to the large number of input factors that primarily or secondarily affect the total electricity consumption of this component. The vast majority of the total electricity consumption of the \( E_{SG} \) generator is consumed directly in the discharge process. The magnitude of this consumption is a function of the input technological parameters, of which the decisive position takes peak current \( I \) (A), pulse on-time duration \( t_{on} \) (\( \mu \)s), pulse off-time duration \( t_{off} \) (\( \mu \)s) and voltage of discharge \( U \) (V). Other technological and process parameters only indirectly participate in the total electricity consumption of the electric pulse generator. Its magnitude can then be empirically described using a mathematical relation (5), as a function of the main technological parameters and the total duration of electric discharges.

\[ E_{SG} = \sum_{i=1}^{n} \left( P_{Dh} \cdot t_{Dh} \right) = f(I, t_{on}, t_{off}, U) \]

(5)

Where \( P_{Dh} \) is the current value of the power of the i-th discharge (W) 
\( t_{Dh} \) - the duration of the i-th discharge (\( \mu \)s) 
\( n \) - is the total number of discharges

Following the determination of partial empirical relationships describing the total power consumption of individual components of the electrical discharge machine, it is possible to proceed to the determination of a complex mathematical model (6), which empirically describes the total consumption of the \( E_{ED} \) machine over a certain period of time \( t \).

\[ E_{ED} = \left( P_{CNC} \cdot t \right) + \left[ \left( P_{CP} \cdot t_{CP} \right) + \left( P_{C} \cdot t_{C} \right) \right] + \left[ \sum_{i=1}^{n} \left( P_{SPi} \cdot t_{SPi} \right) + \sum_{i=1}^{n} \left( P_{WMi} \cdot t_{WMi} \right) \right] + \left( \sum_{i=1}^{n} \left( P_{Dh} \cdot t_{Dh} \right) \right) \]

(6)

Based on the established mathematical model (6), it is possible to empirically determine the total electricity consumption of an EDM machine. The individual input parameters of the mathematical model can be filled since the information about the input of partial elements of a given structural unit is usually provided by their manufacturer. However, the situation is more complicated when implementing the input parameters related to the component for generating electrical pulses. For this partial mathematical model, it is necessary to perform further studies and experiments in the future, based on which we would be able to determine the actual power consumption of the electric pulse generator using empirical calculation when filling the values of technological parameters. To simplify the task, simple monitoring is enough to identify the power input of this structural unit of the EDM machine, at least in our case.

Based on the monitoring, we can relatively accurately obtain the current values regarding the power input of the pulse generator in various operating modes of the EDM machine. In addition, we can easily record this data using a monitoring device depending on the time of its operation \( t \).
5. Optimization of energy intensity of an EDM machine

Optimization of electricity consumption of an EDM machine using the established mathematical models is an important element in increasing the overall economic efficiency of the EDM process. Thanks to the optimization, we could also achieve significant savings in machining time. We can also predict the size of the costs associated with electricity consumption and thus more effectively adjust its size to the customer's desired final quality of the machined surface. The performed optimization can be therefore focused on minimizing the total costs associated with the consumption of electricity by the electrical discharge machine while still achieving the upper limits of the required quality of the machined surface. However, it can also be oriented towards achieving adequate quality of the machined surface in a narrow tolerance band, which is required by the customer with regard to achieving favorable total electricity consumption and thus the overall economic efficiency of the process. The graph in Fig. 4 shows the optimization of the total power consumption of the electrical discharge machine with respect to achieving the desired quality of the machined surface.

![Graph](image)

**Figure 4.** Optimization of the total electricity consumption of the EDM machine with regard to achieving the required quality of the machined surface

Based on the performed optimization of the total electricity consumption of the $E_{ED}$, which is shown in Fig. 4, it can be observed that as the quality of the machined surface increases after electrical discharge machining, the total power consumption increases as well. Thus, the balance of the overall economic efficiency of the EDM process is considered unfavorable. However, it is possible to achieve significant savings in electricity consumption of an EDM machine, but with a lower quality of the machined surface. After all, the aim of the performed optimization was to find the optimum between the achieved quality of the machined surface and the total consumption of electric energy during the process of electrical discharge machining. It was found out that the optimal electricity consumption can be achieved in the area of qualitative values representing the finishing operations.
6. Conclusions

The nature of the total electricity consumption of EDM is completely different compared to other conventional or progressive technologies. In general, with conventional machining methods, most of the electrical energy is used to drive the spindle or the individual portals. However, this does not apply to electrical discharge machining. In this method of machining, the electrical energy is not only consumed by the servo drives to drive the portals but mainly by ensuring the treatment and circulation of the dielectric fluid. Additionally, electrical energy is also consumed during the electro-erosive process to provide discharge energy, which is primarily involved in removing metal particles from the material being machined. Since electrical energy is consumed during EDM in the electro-erosive process itself and also in the treatment and supply of dielectric fluid, it is evident that with a change in the machining mode, the total electricity consumption of the electrical discharge machine will also change. Hence, in order to be able to minimize this electricity consumption, it is necessary to know its partial mechanisms in detail. The proposed mathematical model should be therefore used for this purpose. If anything, it makes it possible to model various machining modes, and at the same time monitor their impact on the total electricity consumption. Taking into consideration the pursuit of achieving favorable economic efficiency of the electrical discharge machining process, it is necessary to pay attention to its optimization as well. Accordingly, this paper aimed to describe an empirical approach to mathematical modeling of processes associated with electricity consumption through its partial structural units with subsequent optimization of the whole process. The achieved results revealed the mutual relations between the total electricity consumption and the achieved quality of the eroded surface after electrical discharge machining. It was found out that with the increase in the required quality of the machined surface, there is also an increase in the total electricity consumption of an electrical discharge machine. The performed optimization has shown that a favorable economic efficiency in terms of total electricity consumption and the achieved results regarding the quality of the machined surface can be achieved during the machining modes that are typical for finishing operations.

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