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Investigating the energy consumption of the PECM process for consideration in the selection of manufacturing process chains

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Abstract

The initial planning of manufacturing process chains provides the opportunity to sustainably influence the energy requirement for the manufacturing of industrial products by selecting the process chain with the lowest energy consumption. However, the task is still challenging due to the need for energy consumption data of manufacturing equipment. In this paper, the analysis of the energy consumption of a manufacturing process is illustrated by the example of the Pulse Electrochemical Machining (PECM) process. A comparison of two machine tool generations of the same manufacturer shows the improvement in energy consumption. Based on the information gained from the analysis, an approach for the provision of energy consumption data is presented.

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Keywords: *Energy; Planning; Electrochemical Machining (ECM)*

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1. Introduction

In recent years, the environmental impact of products gains importance for the competitiveness of industrial companies [1]. Particularly in the high-volume production of industrial products, the efficient use of energy becomes a vital aspect for many companies due to economic and ecological reasons. In this context, the selection of manufacturing process chains offers the opportunity to sustainably influence the energy requirement by considering energy consumption as one criterion. However, the provision of appropriate energy planning data is still a challenging task for many companies.

This paper presents a methodological approach to analyze the energy consumption of manufacturing processes and to predict the energy demand of process chains. Parameters for the energy consumption will be gained from measurements of the manufacturing processes and will be used to set up a framework for a company-specific energy consumption data base. The methodology will be exemplified by analyzing the Pulse Electrochemical Machining (PECM) process.

2. Literature review

Previous research activities aim at considering the energy consumption during different phases of the product engineering process as one criterion. Schulz et al. [2] develop a method to adapt a life cycle assessment (LCA) in the design phase of the product. They determine power parameters for machine tools in two modes and the corresponding time parameters in order to estimate the energy consumption and other environmental impacts. Weinert et al. [3] present a concept for the energy-aware production planning and control. Based on measurements, they set up a mathematical model for the representation of manufacturing equipment in

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different operating states. Another approach to model the energy consumption in manufacturing systems is presented by Seow and Rahimifard [4]. In this approach also the auxiliary energy for supporting activities and even the indirect energy for lighting and heating are considered. The indirect energy is determined for zones of the manufacturing system which have similar indirect energy requirements.

The energy consumption has been investigated for a number of machining processes such as grinding [5], turning and milling [6, 7, 8]. Another study provides preliminary data on the environmental assessment of Electrical Discharge Machining (EDM), including the energy consumption as one main impact of the process on the environment [9]. For Electrochemical Machining (ECM) an investigation of the specific energy consumption was presented by Kozak et al. [10]. The investigation considers the theoretical energy consumption for dissolving the workpiece material. The additional energy consumed by the machine tool, the electrolyte supply, and for the cooling of the electrolyte is not included. Thus, the total energy consumed by the process is difficult to determine.

3. Methodology

3.1. Concept

The main criteria for choosing an appropriate approach for the data acquisition are the effort of data acquisition and the applicability of the data to predict the energy consumption of a process already during the planning phase of the product engineering process. The concept presented in this paper is shown in Fig. 1 and aims at the application of data gained by empirical analysis of processes already applied in the company. The equipment and knowledge for conducting such measurements are usually available in the maintenance or facility management department of industrial companies.

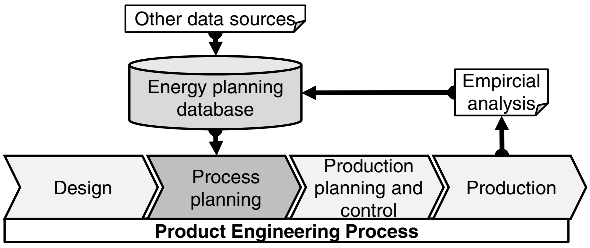


Fig. 1: Concept for the provision of energy planning data

However, a manufacturing process that needs to be considered for a new process chain might not yet be available in-house or the measurement of all relevant processes at a time might be too work-intensive. In case a process cannot be investigated in the production environment, other sources for energy planning data can be utilized. Based on Thiede et al. [11], methods for alternative acquisition of energy planning data can be structured as follows: (1) Cooperation and networks, (2) Publically available data and (3) Theoretic and empiric models. The cooperation with manufacturers of machine tools and other production equipment offers an opportunity to gain energy planning data that is not available in-house. In order to assess the energy- and media demand of equipment during the procurement phase, an intensified and standardized exchange of information between the equipment manufacturer and -user is advisable [12]. Likewise, the exchange of energy planning data can be arranged in a network of companies or could be part of an innovative business model [13]. If no data is obtainable by means of cooperation with equipment manufacturers and networks, publically available research and field studies can be a source for energy planning data [14, 15]. The challenge of this data is to correctly interpret and adapt the values to the considered case of process planning. If energy planning data can neither be obtained via data exchange in cooperation and networks nor through publically available sources, theoretical and empirical models can be applied to estimate the energy consumption of a process. For example, empirical models of cutting forces and specific cutting energy are available for processes with geometrically defined cutting edges. However, due to auxiliary equipment and the level of efficiency, machine tools and other equipment will consume more energy than the actual energy for the actual machining of the workpiece. Thus, the theoretical or empirical models only consider a fraction of the total energy consumption.

3.2. Process analysis

The energy consumption analysis of a manufacturing process requires a clear definition of the system boundaries. On the level of the process chain, the system boundaries are set to comprise all technological processes. Supporting processes like handling and transport are not considered [16]. These processes are only planned after the manufacturing process chain has been defined. The system boundary on the process level includes all electrical energy consumers that provide an essential and immediate contribution to perform the manufacturing process and to accomplish the desired result [17]. Following this definition, the cooling of media will be included in the investigation. In contrast, space heating or air conditioning will not be considered.

The energy consumption of the applied machine tool can be estimated by parameters for the power consumption and the duration of the operational states. In most cases it is sufficient to approximate the energy consumption by three operational states. With Equation (1), the energy consumption of a machine tool ($E_{machine\ tool}$) to manufacture one workpiece can be calculated. The state “productive” (P_p, t_p) represents the machine tool when the workpiece is being machined, whereas the state “non-productive” (P_{np}, t_{np}) describes the state of loading and unloading the machine tool, e.g. advancing and retracting axes to exchange workpieces. Additionally, the machine tool consumes energy in the “idle” state (P_{idle}, t_{idle}) when it is ready for operation but no machining is carried out.

$$E_{machine\ tool} = \left(P_p \cdot t_p + P_{np} \cdot t_{np}\right) + P_{idle} \cdot t_{idle} \qquad (1)$$

The power parameters can be gained from measuring established processes and will be provided by an energy planning data base. The parameters for the productive time (t_p) and non-productive time (t_{np}) for the machining of one workpiece can be gained from empirical values within the company or can be given as target values. Due to maintenance, technical and organizational downtimes, machines will be set to the "idle" state (t_{idle}), indicating that the machine is ready for operation but no machining is carried out. This may also apply to unoccupied and unscheduled time, i.e. in night shifts and on Sundays. The values for the downtime share in the occupied time can be determined according to guidelines. Possible data sources for the values can be manual operating protocols and machine data logging [18].

The energy consumption of peripheral equipment can be estimated according to the machine tool (Equation (1)). There are two ways to determine the power parameters, depending on whether centralized or decentralized peripheral equipment is concerned. For decentralized peripherals, the power consumption depending on the provided media flow will be determined. In case of centralized peripheral equipment, it is usually not possible to directly link the media consumption of one process to the power consumption of the peripherals. Therefore, the media flow rate consumed by the process (e.g. m^3/h) and an energy equivalent for the provision of the medium (e.g. kWh/m^3) will be determined separately. Eventually, the power parameter for the provision of the medium can be calculated by multiplication.

4. Setup for the investigation of the PECM process

Two machines from PEMTec SNC were applied for investigating the energy consumption of the PECM process. The PEMCenter 8000 provides a current of up to 8,000 A. The successor PEM 600 can provide a current of up to 9,600 A. The generator technique in the PEM 600 has been improved compared to the previous model and is expected to result in a significant decrease in conversion losses. Both machines comprise fans that provide convection for cooling. The fans are included in the power measurement of the machines. Due to the lower conversion losses, the number of fans in the new machine was reduced and the fans are now speed-controlled.

In addition to the machine, the PECM process comprises a module for the conditioning of the electrolyte which is separately supplied with electricity. The cooling of the electrolyte is provided by a separate cooling unit that can be part of the building service. Compressed air is also supplied by a central unit. In order to gain a complete picture of the energy consumption all electrical energy consumers providing an essential and immediate contribution to perform the PECM process are considered [17]. The measurement setup and the system boundaries for the investigation are shown in Fig. 2.

The volume flow rate of the electrolyte solution can be controlled via the machine control. Thus, the volume flow rate and the power consumption of the electrolyte supply unit can be related to each other. The volume flow rate of the compressed air is measured with a flow sensor.

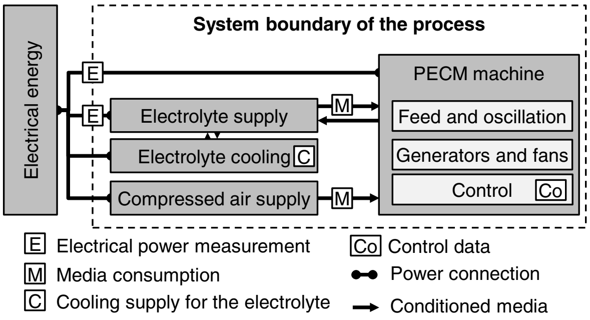


Fig. 2: System boundaries and measurement setup for the PEMCenter8000

5. Results

5.1. PECM machines

In Fig. 3 an exemplary power consumption profile for the investigated PECM machines is displayed. The profile shows different shares in the power consumption which can be attributed to the control and fans, the feed, the electrolysis of the material and conversion losses of the generators. The control and the fans run constantly and represent the power consumption in the idle mode (P_{idle}). The share of the power consumption for the feed occurs constantly during the productive time of the process (t_p). In the non-productive time of the process (t_{np}), the feed is only applied partly to retract and advance the z-axis for loading and unloading the workpieces. The power consumption of the control, the fans and the feed used in part-time sum up to the power consumption parameter (P_{np}) for the non-productive time. Further, the data captured from the machine control reveals the shares of power consumption related to the electrolytic dissolution of the workpiece material and the conversion losses of the machine. Both shares are included in the power consumption during the productive time of the process (P_p).

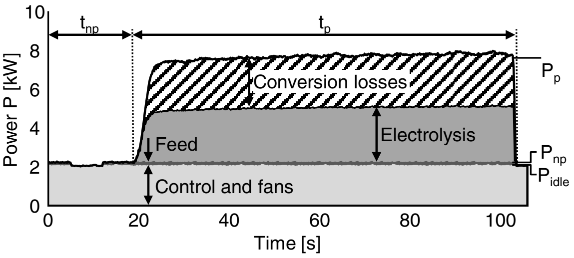
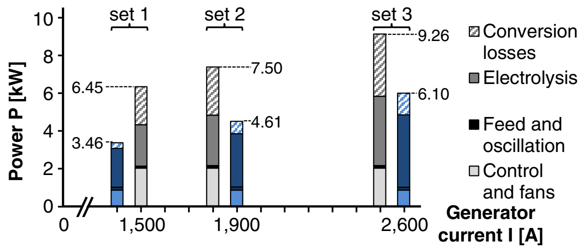


Fig. 3: Exemplary power profile of the investigated PECM process

In the experiments the feed rate is the varied parameter and set in the machine control. During the PECM process the dissolution rate of the workpiece material must be in balance with the set feed rate. For that, the generator current adjusts automatically to the set feed rate and potential and results in a balanced frontal gap. The value of the current level also indicates the process load of the machine. Therefore, the average generator current reached during the experiments will be used in the following evaluation to describe the three investigated parameter sets. Fig. 4 shows the shares in power consumption for the PEMCenter 8000 (grey bars) and the PEM 600 (blue bars). The power parameter P_p is indicated for both machines and the investigated parameter sets.



Underlying parameters

Feed rate [mm/min]			Mechanical pulse	50	[Hz]
set 1	set 2	set 3	Voltage	12	[V]
0.080	0.113	0.160	Pulse on-time	2.5	[ms]

Workpiece material (working area=2,557 mm^2) 1.4301
Electrolyte (pH=6.5, T=22°C, σ=71 mS/cm) $NaNO_3$

Fig. 4: Power consumption of the PECM machines
(PEM 600 in blue bars, PEMCenter 8000 in grey bars)

The results show that the share of power consumption for the electrolysis is equal for both machines when the results for each parameter set are compared. In contrast, the additional power consumption, i.e. the share of the conversion losses and the share of the control and fans, is significantly reduced for the PEM 600 (P_{idle}=0.93 kW) compared to the PEMCenter 8000 (P_{idle}=2.10 kW).

5.2. Electrolyte conditioning and supply

The investigated process is supplied with conditioned electrolyte by a peripheral module. The module comprises a number of filters and pumps which feed the electrolyte solution to the machining process and back to the supply module where the electrolyte is cleaned and refreshed. The pumps have different operating characteristics, e.g. the feed pump runs constantly to provide the process with the needed electrolyte flow rate. Other pumps show a cyclic operating behavior depending on certain time schemes or the filling level of certain tanks. Therefore, a long-term measurement is carried out to determine the average power consumption of the module depending on the electrolyte volume flow rate. Fig. 5 displays the power consumption of the electrolyte supply module for the volume flow rates (Q) between 0 and 40 l/min at a pressure of 5 bar. It should be noted that higher feed rates result in higher generator current and thus lead to a decrease in the frontal gap. This results in a decrease in the volume flow rate of the electrolyte. The volume flow rate for the three parameter sets amount to 16.9 l/min (P_p=3.57 kW), 15.2 l/min (P_p=3.30 kW) and 12.5 l/min (P_p=2.86 kW). The corresponding power consumption parameters can be interpolated from the measurement results. The volume flow rate of 0 l/min is tantamount to the idle state when the electrolyte supply module is ready for operation but no electrolyte is pumped to the process (P_{idle}=P_{np}=0.63 kW).

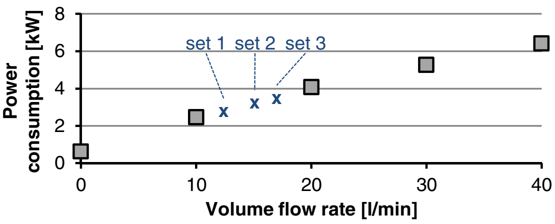


Fig. 5: Power consumption of the electrolyte supply at 5 bar pressure

5.3. Compressed air supply

The provision of compressed air requires electrical energy for the operation of the compressors. According to an empirical and a simulation study [14, 15], an energy equivalent of 0.12 kWh/m^3 can be assumed. Due to losses and leakages, an additional factor of 36 % can be assumed to add up upon the energy equivalent [15]. In the investigated PECM process the machine tool and the electrolyte supply unit require compressed air. In the electrolyte supply unit pneumatic valves are operated. The compressed air consumption per switching operation of a valve is very low and the number of switching operations is also low. Hence, the volume flow rate of compressed air to the electrolyte supply unit is very low and does not exceed 1 l/min, corresponding to 5 Watt of electrical power. Compressed air is also used by the machine tool to operate the cover of the working chamber. A compressed air consumption of 4 l is determined for one operation cycle of opening and closing the cover. The demand of compressed air for operating the cover will not reach a significant amount, as a PECM process can take several minutes. Hence, the compressed air demand of the investigated PECM process will not be further considered for the total energy consumption of the process.

5.4. Cooling supply for the electrolyte solution

The electrolyte solution serves as conductor medium in the PECM process and absorbs the heat loss originating from the electrical resistance. In order to provide stable process conditions, the temperature of the electrolyte is typically kept below 30 °C [19]. The cooling of the electrolyte is provided by a central refrigerating machine. In order to approximate the electrical energy needed to cool the electrolyte solution, it can be assumed that the heat flow absorbed by the electrolyte solution is equal to the heat flow needed to be taken from the electrolyte by the refrigerator machine.

The absorbed heat flow ($\dot{Q}$) can be estimated based on Eq. (2). Therein, the voltage applied in the gap (U_{gap}), the current (I_{gap}), the pulse time (t_{pulse}) and the pulse frequency (f) yield the electrical power applied in the process. The efficiency of the process (η_E) allows for estimating the fraction of electrical power which is converted to heat losses and absorbed by the electrolyte solution.

$$\dot{Q} \approx U_{gap} \cdot I_{gap} \cdot \left(t_{pulse} \cdot f\right) \cdot (1 - n_E) \qquad (2)$$

The efficiency of the dissolution process depends inter alia on the material and the current density applied in the process. Based on the experience of the machine tool supplier, the efficiency can be assumed to be 50 % (η_E = 50 %) for the estimation of the heat flow. The resulting values for the absorbed heat flow ($\dot{Q}$) in the three experiments are given in Table 1. In order to calculate the consumption of electrical power for the cooling, an energy equivalent (EE) of 3.0 $kWh_{cooling}/kWh_{electrical}$ is assumed. This expresses that the cooling system consumes 1 kWh of electrical energy to provide 3 kWh of cooling. The energy equivalent is supposed to be an average value that also incorporates the energy consumption of the cooling system in possible idle times of the process. This allows for calculating the electrical power consumption connected with the cooling of the electrolyte.

Table 1: Thermal transfer to the electrolyte and required electrical power for cooling – exemplarily calculated for current levels reached at the PEM 600

		Parameter set 1	**Parameter set 2**	**Parameter set 3**
Current level [I_{gap}]	**[A]**	**1380**	**1910**	**2590**
Heat flow $\dot{Q}$	[kW]	1.04	1.43	1.94
$EE_{cooling\ system}$	[kWh/kWh]		3.0	
$P_{p,\ electrolyte\ cooling}$	[kW]	0.35	0.48	0.65

6. Provision of energy planning data

In order to apply the data gained from the process analysis to estimate the energy consumption of the PECM process a concept for the provision of energy planning data is needed. The planning data to estimate the energy consumption can be subdivided into the time- and power parameters. The time parameters can be applied to all energy consumers considered for the energy consumption of the process. Based on the feed rate and a rough definition of the workpiece dimensions and material, the productive time of the process (t_p) can be estimated. For example, the productive time for processing the investigated workpiece with parameter set 2 was 87 s. The non-productive time (t_{np}) for loading and unloading the workpieces can be calculated using the correlation between distance and time. Additionally, the manual or automated handling of the workpieces needs to be considered. For the investigated application the machine tool manufacturer assumes a non-productive time of 17 s per cycle. The additional time when the machine is operated in the idle mode (t_{idle}) can be determined with data from time studies as well as manual operating protocols and machine data logging systems. For the investigated process, the idle time could not be determined in a series production environment. Therefore, it is assumed to be 20 % of the utilization time, i.e. 21 s.

The power parameters were analyzed separately for the energy consumers within the process and depend on different influencing variables. In order to provide appropriate energy planning data for a new energy planning case, the influencing variables will be structured. A generic structure can include the manufacturing equipment, the manufacturing task and the set of process parameters as main criteria for the classification of the power consumption parameters. The framework for the classification of the power parameters is displayed in Fig. 6. It should be noted that the cube in Fig. 6 shows the data sets available from the present investigation. In a company-specific data base far more data sets can be expected to be available once the framework has been implemented.

The manufacturing equipment can be structured into classes of comparable machines. In the case of the PEMCenter 8000 and PEM 600, the investigation showed that the power consumption of the two machine tools differs significantly. Hence, a distinction of the energy planning data for both machines is advisable. The manufacturing task comprises all operations carried out by the manufacturing equipment during one cycle. As differing manufacturing tasks will affect the power consumption parameters, a classification according to the performed operations is necessary. For PECM the manufacturing task can be classified by the processed material, the size and the contour of the working surface. For the investigated manufacturing task of a planar tool and workpiece, the working surface of 2,557 mm^2 is

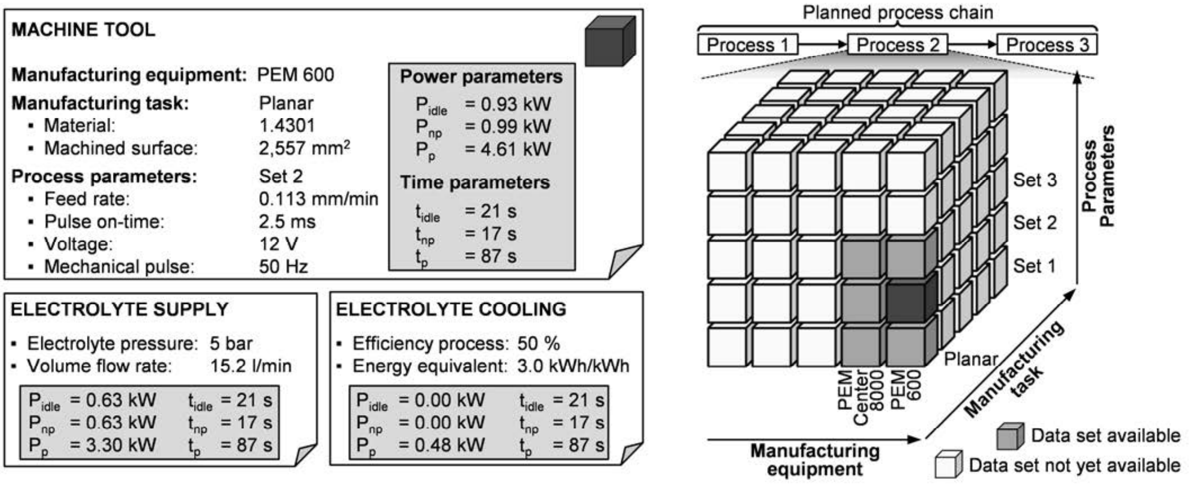


Fig. 6: Framework for the provision of energy planning data – exemplary data for the machine tool (PEM 600, planar tool and workpiece, parameter set 2)

constant during the entire process. The energy planning data also depends on the applied process parameters. The investigated process parameters result in different product quality, e.g. surface roughness. Based on an estimation of the process parameters, the process planner can chose the energy planning data set, e.g. parameter set 2 with a feed rate of 0.113 mm/min.

Concerning the energy consumption of the electrolyte supply unit, the power consumption parameter for the productive time depends on the volume flow rate consumed in the process. For parameter set 2 the volume flow rate amounts to 15.2 l/min. The heat flow to the electrolyte is determined by the process parameter and the estimated efficiency of the process. Based on the estimated heat flow, the power needed to cool the electrolyte solution is calculated by an energy equivalent for the central cooling system.

The applicability of the described concept is based on the availability of structured energy planning data. Also the knowledge of the process planner to select proper parameter sets is required for estimating the energy consumption.

7. Conclusion and outlook

In this paper a method considering the energy consumption of manufacturing process chains was presented which is based on the empirical analysis of manufacturing processes. The system boundary for the process analysis was set to include all consumers of electrical energy which provide an essential and immediate contribution to the process. The analysis was exemplarily performed for the Pulse Electrochemical Machining (PECM) process with two comparable machine tools and also taking into account the consumption of compressed air, electrolyte solution and cooling of the electrolyte solution. The results show a significant improvement in the generator technology of the new machine tool. This was also considered in the concept for the provision of energy planning data. A generic structure for an energy planning data base was proposed, including the manufacturing equipment, the manufacturing task and the applied process parameters as main criteria for the classification of energy planning data. In future work, the influence of other process parameters like pulse frequency, voltage and pulse on-time can be investigated using the presented methodology. The energy planning data gained from the analysis will be applied to estimate the energy consumption for the processing of other parts. The predicted energy consumption will be compared to measurements in order to validate the prediction method. Further, the presented method for analyzing the energy consumption of manufacturing processes will be used to analyze other finishing processes.

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