Lighting Engineering & Power Engineering
2024, Vol. 63, No. 1, 7–15
https://doi.org/10.33042/2079-424X.2024.63.1.02

OPEN ACCESS

Actual Tasks in Creating Digital Twins for Precise Electrochemical Machining

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Article History
Received:
12 February 2024
Accepted:
15 March 2024
Published online:
26 April 2024

Keywords
Electrochemical Machining;
Multi-physics Simulation;
Digital Twin;
Industry 4.0

Abstract
The development and application of manufacturing processes digital twins is an established trend in the development of precision machining methods, which is inherent in Industry 4.0. Digital twins are most actively implemented in additive manufacturing and for non-deformation finishing processes: laser, electrical discharge, and electrochemical. The main advantage of this approach is the ability not only to understand and control the process but also to manage it in real time while simultaneously monitoring the condition of the equipment. Electrochemical machining (ECM) is stands out among non-deformation methods. ECM combines high material removal rates with the absence of tool wear and thermal effects on the processed material. The most promising process is pulsed electrochemical machining (PECM), in which the cathode carries oscillatory motion and high-density electrical pulses are applied when it is near the lower dead center. This ensures high productivity and processing accuracy, as well as improved conditions for electrolyte renewal in the machining zone during the cathode's return stroke. Due to the complexity and interrelated of the processes involved in PECM, multi-physical models are used to create digital twins. Based on the review of existing models for PECM, tasks have been formulated for creating DT of machining processes for complex-shaped details, where two-dimensional models, which most modern research is based on, cannot be applied. The most important tasks are the design of cathodes, optimization of electrolyte supply and integration of electrochemical machining process digital twins and equipment for its implementation. The possibilities of creating such integrated digital twins using available software on the market are determined.

INTRODUCTION

Industry 4.0 enables achieving a higher level of automation and productivity through interrelated digital technologies. One of them, recognized for its significant potential, are digital twins (DT), which involve creating, maintaining, and using virtual copies of manufacturing process components in real time [1]. Manufacturing DT provides a unique opportunity to model and optimize production systems while simultaneously providing equipment condition monitoring and comprehensive production automation capabilities [2, 3]. This applies particularly to for manufacturing technologies based on complex interrelated physical and chemical processes for which it is practically impossible to control parameters in the machining zone.

Among such technologies in modern manufacturing, various additive methods stand out primarily. By their nature, they the most embody the ideas of digitization, practically eliminating unnecessary links between digital design using CAD systems and the direct production of designed products on equipment with digital software control with nearly unlimited possibilities for their geometry. Despite the rapid development of additive technologies, they still have certain limitations in terms of accuracy and surface quality of the resulting details. For instance, tolerances on their dimensions are limited by the sizes of powder particles used in additive processes. In addition to this, the final dimensions and shape of individual parts are affected by temperature deformations inherent in such processes as Powder Bed Fusion and Directed Energy Deposition [4].

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Cite as: Plankovskyy, S., Tsegelnyk, Y., Voronov, R., Kalaitan, I., & Petrenko, V. (2024). Actual tasks in creating digital twins for precise electrochemical machining. *Lighting Engineering & Power Engineering*, *63*(1), 7–15. https://doi.org/10.33042/2079-424X.2024.63.1.02

Therefore, in the production of high-precision products, combined technologies are used in which, as the next step after additive processes, finishing operations of dimensional processing are used [5].

For this task, non-deformation machining methods are most suitable: laser, electro-erosion, and electrochemical, as their use does not lead to the formation of residual stresses in the surface layer of the workpiece, which during relaxation lead to its deformation with possible exceeding the tolerance limit. Among such methods, electrochemical machining is the most promising for executing finishing operations. Unlike other mentioned methods, it is not associated with thermal impact on the surface layer, which can also lead to the formation of residual stresses.

Electrochemical machining methods are widely used in the production of parts with complex geometric shapes, such as turbine blades and unicycle (monowheel) gas turbine engines [6]. Additionally, they are applied for machining details made of hardened steels, high-strength, and refractory alloys. Recently, pulsed electrochemical machining (PECM) has attracted the greatest interest among researchers [7]. In this process, the tool (cathode) carries oscillatory motion at a frequency of 50…80 Hz, and high-density electrical pulses are applied when it is near the lower dead center. This ensures high productivity and accuracy of machining, and improved conditions for electrolyte renewal in the machining zone during the cathode's return stroke [8].

The task of efficiently controlling the PECM process is complicated by the fact that several different physical and chemical processes occur simultaneously at significantly different speeds. The gaps between the cathode-tool and the machined detail are typically measure fractions of a millimeter, making it impossible to input sensors into the machining zone for process control. Therefore, to determine machining parameters, design tools and technological adaptations, and develop control algorithms for the PECM process, the main approach recognized is the use of numerical modeling. In recent years, a number of studies have been conducted in this direction, in which complex multi-physics models for PECM have been proposed [9, 10].

Comparison of PECM results with parameters determined based on such modeling with the results of actual experiments has shown satisfactory coincidences between the predicted and actual machining accuracy. Some progress has also been made in developing tool design methodologies for PECM [11] and principles for controlling equipment operating parameters [12].

At the same time, the results of known studies have a somewhat limited nature. Most of the developed models are two-dimensional, which limits possibilities of their use in the case of machining complex-shaped details. During the creating models, some processes are excluded without sufficient justification. There are no research's works that consider the problems of creating integrated digital twins of the electrochemical machining process and equipment for its implementation. Therefore, the aim of this paper is to critically analyze the state of developments in creating digital twins for PECM, formulate priority tasks for improving approaches to their creating, and identify ways to solve these tasks.

EXISTING MODELS OF ELECTROCHEMICAL MACHINING

Early researchers on modeling the electrochemical machining process focused on two-dimensional stationary tasks for direct current. In cases of constant electrolyte characteristics, this allowed for considering only the electric field. The result of this approach was the development of the $cos(\varphi)$-method, which relates the gap between the cathode-tool and the machined detail to the angle of inclination of the normal to the cathode surface [13]. This approach hasn't been providing sufficient accuracy in predicting the results of the ECM process and was later improved by due to the effects of gas release on the electrolyte conductivity [14], temperature and flow rate [11]. Such models were simplified and used experimental data to determine the anodic dissolution rate. Attempts to account for the chemical reactions occurring during modeling and multi-ion transfer [15, 16] were unsuccessful due to computational expense.

Interest in the use of electrochemical machining increased significantly with the advent of the pulsed version of the method – PECM [7], especially in combination with cathode oscillation [17]. Due to intermittent current supply and oscillatory motion of the cathode-tool the conditions for electrolyte renewal in the machining zone are improved. The principle and stages of pulsed electrochemical machining with cathode-tool oscillation are shown in Fig. 1. In the first stage, new electrolyte into the gap between the cathode and the anode of the machined detail are applied. In the second stage, the cathode moves towards the anode, and one or several electrical current pulses are applied near the lower dead center of the cathode oscillation. This leads to the dissolution of the material of the machined detail. The gas (hydrogen) released at the electrode and the heat generated by the process (Joule heating and heat in the double electrochemical layer acting on the electrodes surfaces in contact with the electrolyte) change the electrolyte conductivity in the gap. After the current supply is stopped, in the third stage, the cathode returns to the top dead center, after which the process repeats.

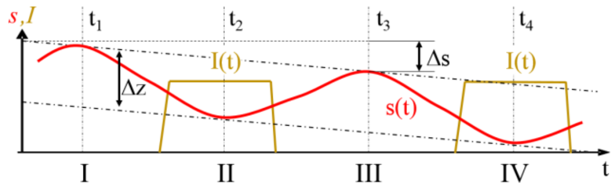

Figure 1. The principle of PECM with oscillating cathode: *s* is the cathode movement, *I* is the electrical current [17]

There are known attempts have been to apply models developed for the ECM process with direct current to the PECM process This was done in a one-dimensional model in [10]. However, the model used did not consider heat exchange during the current pulse. This could lead to overestimations of the temperature and electrolyte conductivity. In addition, direct transfer of approaches used for modeling ECM with direct current, which are characterized by modeling with a constant time step, is not possible for the case of pulsed machining. Considering the duration of the current pulse, this would require reducing the time step to values of approximately 10^{-4} seconds, leading to unjustified increases in modeling time. In principle, this problem can be solved by using a variable time step, but it is obviously impractical to simulate every electrical pulse or cathode oscillation in PECM. The fact is that both in direct current machining and in the pulsed variant, a quasi-stationary regime is established after some time, where before the start of the next machining cycle, the temperature distribution and electrolyte properties in the working gap coincide with the analogous characteristics of the previous cycle. This allows for the use of simplified models to reduce computational costs in modeling PECM.

In [18, 19], a quasi-stationary method for determining the temperature of the electrolyte during pulsed electrochemical machining with a reduced number of time steps was proposed. However, this method did not consider material removal, which made it impossible to predict the processing results. In [20], the next step was taken, and the approach to account for changes in the geometry of the machined detail was proposed. For this purpose, the average current was calculated for each machining cycle, allowing the modeling of PECM as a process with direct current. However, this approach did not account for the nonlinearity of the heating process. This drawback was eliminated in [21] by applying an algorithm consisting of two nested cycles. The internal cycle simulated the distribution of temperature and electrical current during several machining pulses, while the external one accounted for the dissolution of the machined material. This approach has allowed for the combine of processes with different time scales. The newest in the development of PECM models involved considering the oscillation of the cathode during machining.

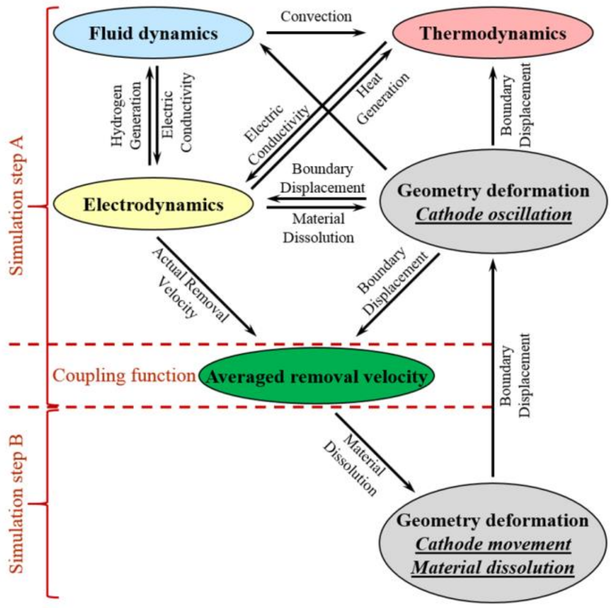

Figure 2. The principle and physical phenomena considered in the simulation model of the PECM process [22]

Such models have been described in [17, 22], and their schematic structure can be represented as shown in Fig. 2. The approach used to describe PECM with an oscillating cathode includes of electrodynamics, heat exchange, liquid dynamics, and cathode kinematics. To account for material removal, the computational grid for the machined surface is set as mobile. And its speed is determined by the material removal rate, which is determined experimentally depending on the current density using standard methods [23]. The acting voltage is defined as the difference between the voltage applied to the electrodes and the sum of overvoltage's, which are also experimentally determined [24]. The electrical impulse is synchronized according to the lower dead center of the cathode oscillation. Hydrogen generation during electrolysis and the influence of the hydrogen volume fraction on the electrolyte conductivity are considered. Joule heating is calculated for all current-carrying elements. Additionally, the heating in the electrochemical double layer is considered, which is accounted for as heat flow on the contact surfaces of the electrodes and electrolyte [25]. Considering these heating sources and convective heat exchange with the electrolyte flow, the temperature of the electrodes and electrolyte is determined. Moreover, the dependence of the electrolyte conductivity on temperature is also considered in the modeling. Thus, modeling the PECM process is considered as a coupled non-stationary nonlinear task, in which the fastest processes are excluded from consideration and replaced by empirical dependencies obtained during experimental studies. Recent modifications of this model take into account the features of current control implemented in modern PECM equipment [26].

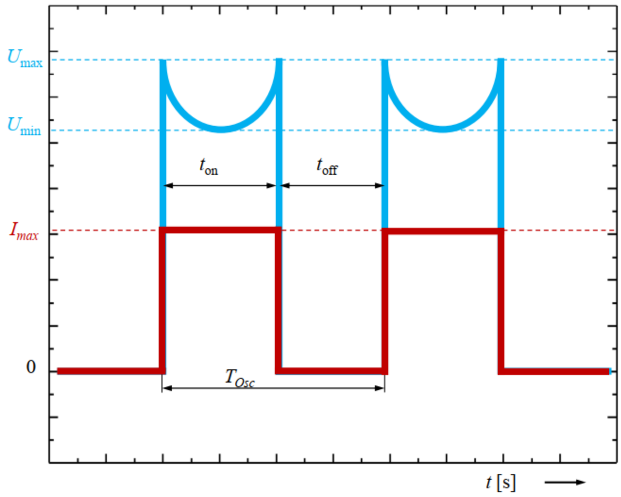

Figure 3. The principle and physical phenomena considered in the simulation model of the PECM process [26]

In this case, a voltage pulse is set at the electrode in a form that ensures a constant current value during the change in the gap between the electrodes when the cathode moves (Fig. 3). In the same paper, to reduce computational costs, it is proposed to calculate the velocity of the electrolyte in the gap by interpolating data from stationary modeling for the upper and lower positions of the cathode. However, it should be noted that such simplification does not seem sufficiently justified in general, as it excludes consideration of inertial loads caused by the oscillation of the cathode.

Using the described models, modeling of PECM have been conducted for a series of test problems in the two-dimensional case. Despite the qualitative coincidence of the processing results predicted by the modelling and the data of full-scale experiments, such studies are still quite limited. Therefore, the conclusion made in [9] that none of the PECM models has been sufficiently verified by comparing the geometry obtained in simulation and experiment is still valid today.

DIRECTIONS OF IMPROVING PECM SIMULATION MODELS

Based on the models, which are discussed in the previous section, we will consider the possibilities of improving PECM modelling with the final goal of developing a methodology for creating digital twins of such processes. The first, we will consider the possibilities for more detailed modeling of the physical processes occurring during PECM.

The next, we will consider the perspective tasks for which the use of such models is appropriate. Finally, the ways for creating integrated digital twins of the pulsed electrochemical machining processes and the equipment required for their implementation will be discussed.

PHYSICS

It should be noted that the idea of using experimental results to determine the metal dissolution rate and the overvoltage at the electrodes according to experimental results appears justified. Numerical calculation of these characteristics for industrial alloys requires prior accurate determination of several coefficients and is unlikely to yield more precise results. Additionally, using predetermined characteristics significantly simplifies the computational model and reduces computational costs.

Regarding the formulation of the known models described above, several remarks can be made. The task of determining the electrical conductivity of the electrolyte, considering Joule heating, heating in the electrochemical double layer, convective heat exchange, and hydrogen release during electrolysis are considered practically in all models.

At the same time, the penetration of anode dissolution products into the electrolyte are not considered, which not only affect the thermal condition of the electrodes and the boundary thermal layer but also change the electrolyte characteristics, which are included in almost all components of the model – density, thermal conductivity, heat capacity, and viscosity. The neglect of these phenomena in known scientific papers was not justified and their influence was not assessed. In a simplified form, these processes can be considered by adding a mass source to the model on the moving surface of the anode grid, which moves at the experimentally determined dissolution rate of the machined material.

Most of the listed studies have certain some disadvantages in the formulation of models for calculating electrolyte flow parameters. Firstly, it concerns the modelling of the turbulent component of the flow. Almost all papers without any justification use the $k - e$ turbulence model, while for flow conditions near walls, more accurate results should be expected when using models of the $k - \omega$ or SST [27].

In addition, none of the listed models considers the effect of Lorentz forces on the flow of the electrolyte, which is an electrically conductive moving environment. This may be due to the short duration of the electric pulse in the PEMC cycle, but such a simplification of the model was also carried out without any assessment of the possible errors, especially considering the relatively high frequency of current pulses (50…10 Hz).

Finally, despite the rather high calculated electrolyte flow rates, the reviewed papers the possibility of cavitation are not considered. This is certainly a case in which the stability of the electrochemical machining process can hardly be ensured, but this case should be considered in terms of limiting the electrolyte supply regime.

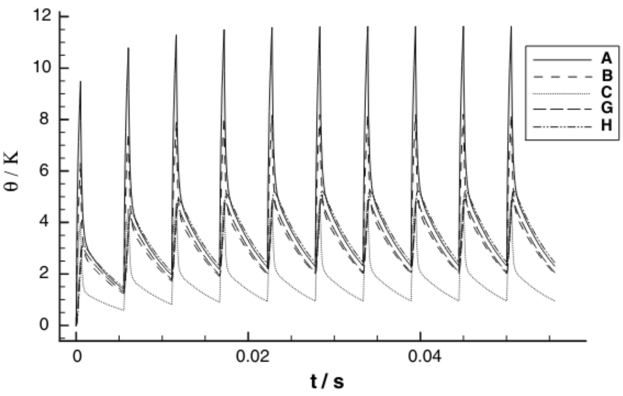

Figure 4. Establishment of quasi-stationary temperature regime during PECM [25]

It should be noted that for ECM with a fixed cathode-tool profile, the transient and steady-state machining regime can be distinguished quite clearly. For the steady-state machining regime, material removal occurs consistently across the entire tool surface, and after some time, a quasi-stationary machining regime is established, characterized by uniform initial temperature and electrolyte composition (Fig. 4). This regime is the main one for determining the shape of the tool's working surface. The transient regimes from the start of machining to the quasi-stationary regime is not critical for the result – setting the tool shape and PEMC parameters that ensure the specified machining accuracy and productivity. The main task of modelling this stage should be to establish the limits at which the ECM process becomes unstable up to the possibility of electrical discharges. In view of this, the modelling time of pulsed electrochemical machining can be limited it takes to reach the quasi-stationary regime, which significantly reduces computational costs.

Finally, besides thermal processes, in some cases, the calculation model should include equations for determining the stress state of the cathode. This is particularly relevant in cases where the cathode is a plastic printed base coated with a thin metal layer [28]. This method of tool creating is perspective for machining details of large size and complex shape. However, such a tool may have problems related to metal delamination under the influence of uneven heating.

PERSPECTIVE TASKS OF MODELLING ELECTROCHEMICAL MACHINING

The main purpose of computer modelling in the listed previously studies is to calculate the distribution of temperature, volumetric hydrogen concentration, electrolyte velocity, and electric current density in the interelectrode gap and determine the dissolution rate of the material being processed based on these data.

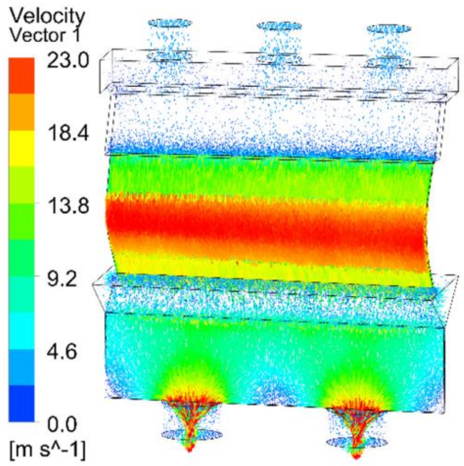

Figure 5. Simulation results of the tangential flow field model [29]

From a practical standpoint, one of the main tasks of modelling should be tool design. This should include not only determining the shape of the working surface, as discussed in the previous section, but also optimizing the input method of electrolyte into the interelectrode gap. This is especially important when machining large parts to ensure identical conditions on the entire machined surface. The velocity distribution for the input tangential electrolyte proposed in [29] through several feed channels are shown in Fig. 5. As a result, a more uniform electrolyte velocity field and machining process stability were ensured. But obviously, such problems should be solved by an optimization procedure.

This applies, for example, to cases where the electrolyte is supplied through the cathode. Such a suppling method can be easily arranged for cathodes made by 3D printing [28]. The shape and location of the electrolyte supply channels in this method of cathode production can be arbitrary. In addition to the functions related to ensuring the machining process, the electrolyte can also perform the task of cooling the cathode to prevent the detachment of the metal layer for the already mentioned case of metallized plastic cathodes.

Another task to be solved by the simulation modelling of the PEMC process is to determine the shape, magnitude and frequency of the voltage pulse supplied to the cathode. The problem in the fact that the current characteristic change, which is depicted in Fig. 3 for PEMC are idealized. The symmetrical shape of the voltage pulse cannot practically ensure the same current density due to the time-varying electrical conductivity of the electrolyte. Precise control the current parameters in the machining zone is particularly important during the final machining cycles, where dimensional accuracy of the details is precisely maintained. The characteristics and frequency of the stress pulses are also important in multi-axis electrochemical machining processes, such as jet electrochemical machining [30]. In such processes, to ensure machining accuracy, these parameters must be coordinated with the contour speed of the tool [31].

Finally, the development of effective numerical models of PEMC processes is necessary for creating integrated digital twins of electrochemical machining processes and their equipment. Digital twins are one of the key technology of Industry 4.0 and, in addition to optimizing machining parameters, they should be as the basis for developing CNC algorithms and monitoring both the stability of the machining process and the condition of the equipment [32, 33].

APPROACHES TO CREATING INTEGRATED DIGITAL TWINS OF PECM

Almost all researchers papers devoted to the simulation of electrochemical machining use two-dimensional models. The reasons for this are clear: even in two-dimensional cases, the time required to obtain solutions for such problems can take several hours, and in the three-dimensional case, it can increase to tens of hours. This significantly complicates the execution of optimization calculations and practically excludes the use of such models for creating digital twins of machining processes with the aim of developing effective CNC algorithms. Therefore, the obvious direction for creating such digital twins is the use of Reduced Order Models (ROM). The most effective way to create these models is to process numerical experiment data with further calibration based on real-scale experiments data.

Numerical ROMs are simplified versions of Multiphysics models that retain the main characteristics of the original systems but with significantly reduced computational complexity, allowing them to operate in real-time. ROM models allow for efficient modeling and analysis of complex processes, making them ideal for use in digital twins. ROM models easily integrate with data collection systems and IoT platforms. This allows to use of real-time data from sensors and devices to update models and improve the accuracy of predictions to configure them. Integration with big data also allows to use of machine learning techniques to automatically improve models over time.

The main obstacle to using sensor data for calibrating numerical models is the difficulty of inputting them into the machining zone. The gap between the electrodes during PECM is the tenths of a millimeter. Therefore, even if sensors that can be input into the interelectrode space are found, it is hard to imagine that their presence would not affect the measured parameters. However, there is another way to measure the PECM parameters. And it can be based on the use of the previously mentioned metallized plastic cathodes. Connecting thermocouples to the metal layer on the surface in contact with the plastic, given the small thickness of this layer (~10^2 μm) will allow for the measurement of the temperature distribution on the surface where the cathode contacts the electrolyte. More opportunities can be provided by using fiber optic sensors, which are immune to obstacle from electrical and electromagnetic fields. These sensors have high measurement accuracy, and one sensor can profile temperature along the fiber at ones. Fiber optic sensors can also be used to measure pressure and voltage. Thus, the use of metallized electrodes allows for the calibration of numerical models of electrochemical machining. Obviously, the numerical models must also be created for such a cathode design.

The ultimate goal of developing numerical models of PECM should be to create integrated digital twins of both the machining process itself and the equipment used to implement it. This task can be solved by using software packages in which has implemented the capabilities of combining ROM models, multi-domain modelling and sensor data integration. Such opportunities are provided by the following platforms: ANSYS Twin Builder, SIMULIA by Dassault Systèmes, Siemens Digital Twin and others. It should be noted, however, that although creating of a digital twins library equipment for EMC seems possible, developing of some universal digital twins for machining processes appears to be an unreal task, at least at the current level of modelling. However, creating basic versions of modelling models for the main processes of precision EMC and developing a methodology to calibrate them using experimental data can be an achievable goal for researchers.

CONCLUSIONS

Precision electrochemical machining methods are perspective for manufacturing high-precision parts, including finishing dimensional machining of additively created parts. The widespread using of these technologies is hindered by the absence of reliable tool design methodologies and machining parameters determination. Such methodologies can be developed based on Multiphysics models of electrochemical machining processes. The analysis of contemporary researchers in this area are executed in the paper, the disadvantages of the used models are noted and the ways to improve them are identified. The development of tool design methodologies, optimization of electrolyte supply, integration of digital twins of electrochemical machining processes and the equipment used to implement them are identified the most important tasks for further research. An approach to the calibration of numerical models of electrochemical machining based on sensor data using metallized plastic tools is proposed. The possibilities of creating such integrated digital twins using the software available on the market are determined.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Актуальні завдання створення цифрових двійників для прецизійного електрохімічного оброблення

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Анотація. Розробка і застосування цифрових двійників виробничих процесів є сформованим трендом у розвитку методів прецизійного оброблення притаманних Індустрії 4.0. Найбільш активно цифрові двійники впроваджуються у адитивному виробництві та для бездеформаційних процесів фінішного оброблення: лазерних, електроерозійних та електрохімічних. Основною перевагою такого підходу є можливість не тільки розуміти та контролювати процес, але й керувати ним в режимі реального часу одночасно здійснюючи моніторинг стану устаткування. Серед бездеформаційних методів виділяється електрохімічне оброблення (ECM). ECM поєднує високу швидкість зняття матеріалу з відсутністю зношування інструменту та термічного впливу на оброблюваний матеріал. Найбільш перспективним виглядає процес імпульсного електрохімічного оброблення (PECM) в якому катод здійснює коливальний рух, а електричні імпульси високої щільності подаються коли він знаходиться біля нижньої мертвої точки. За рахунок цього забезпечується висока продуктивність та точність оброблення та покращені умови для оновлення електроліту в зоні оброблення при зворотному русі катоду. Зважаючи на складність та взаємопов'язаність процесів, що протікають під час PECM для побудови цифрових двійників використовуються мультифізичні моделі. На основі огляду існуючих моделей для PECM сформульовані задачі для побудови цифрових близнюків процесів оброблення деталей складної форми, для яких не можуть бути застосовані двовимірні моделі, на яких базується більшість сучасних досліджень. Як найбільш важливі виділено задачі дизайну катодів, оптимізації подачі електроліту та інтеграції цифрових близнюків процесу електрохімічного оброблення та обладнання для його реалізації. Визначено можливості побудови таких інтегрованих цифрових близнюків з використанням наявного на ринку програмного забезпечення.

Ключові слова: електрохімічне оброблення, мультифізичне моделювання, цифровий двійник, Індустрія 4.0.

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