

# Investigation of Kinematic–Geometric Characteristics of Electrochemical Machining



V. V. Lyubimov, V. M. Volgin and V. P. Krasilnikov

**Abstract** Electrochemical machining (ECM) is a non-traditional method of machining, based on the anodic dissolution of the workpiece, which allows to obtain surfaces of a complex shape (turbine blades, dies and molds, etc.); to produce through and blind holes of different or variable cross-sections, including the curved axis; to remove a defective surface layer from the workpiece after electrical discharge machining or cutting (ECM without shaping) in order to ensure a specified surface roughness; to remove burrs and round sharp edges. Distinguishing features of electrochemical shaping include a narrow interelectrode gap, an electrolyte flow in the space between electrodes, a high localization of dissolution in a specified area of the workpiece, and a high dissolution rate. The efficiency of ECM depends significantly on the shape and size of the electrode-tool, as well as the trajectory and speed of its movement. This article is devoted to the investigation of the combination of kinematic and geometric ECM characteristics. It is shown that the reduction of interelectrode gap under traditional modes leads to a significant increase in the total current and the difficulties of ECM process control. The possibilities of local machining with point and linear electrode-tools are analyzed.

**Keywords** Electrochemical machining · Productivity · Electrode-tool · Displacement velocity

## 1 Introduction

Electrochemical machining (ECM) and especially electrochemical micromachining have become more popular with recent advancements to fulfill the needs of the fabrication of macro- and microcomponents [1–12]. With rapid developments in the fields of automotive, aerospace, electronics, optics, medical devices, and much more, this process finds wide applications in the machining of titanium and titanium

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alloys, super alloys, and stainless steel structures which are difficult to machine by conventional machining processes. ECM provides advantages in the shaping of complex features with no thermal stress, burr formation, and tool wear and can be implemented on metals regardless of their hardness [13–22]. It is known from the theory of mechanical engineering technology that the following kinematic and geometric schemes of forming can be carried out:

- Surface treatment (one-time shaping) (Fig. 1a);
- Processing on the line (Fig. 1b);
- Processing at the point (Fig. 1c).

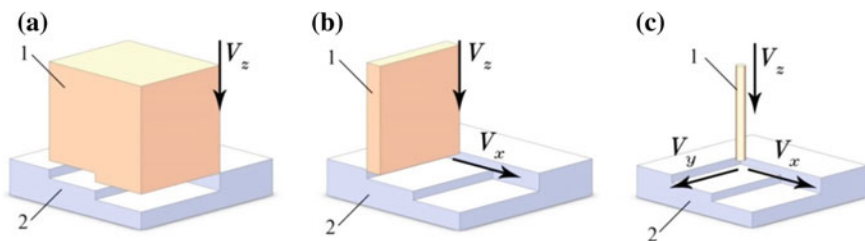
In most cases, ECM is used to perform copy-and-flash operations, that is, surface treatment (Fig. 1a). Thus, the most important advantage of the ECM is the possibility of forming over the entire surface to ensure high performance of the process. The required geometry of the resulting surface is provided by copying the geometric shape of the electrode-tool surface. In this case, there is a simple kinematics of the machine—rectilinear displacement of the electrode-tool along the  $z$ -axis as the anode dissolution of the workpiece material. However, in this case, there are difficulties in controlling the process of shaping and ensuring high accuracy. Increasing accuracy is provided in the transition to the minimum possible inter-electrode gaps (IEG). The accuracy of machining is associated with the magnitude of the IEG:

$$\Delta = ks \quad (1)$$

where  $\Delta$  is the local value of the machining error;  $k$  is the coefficient of proportionality;  $s$  is the local value of the interelectrode gap.

However, the decrease of the IEG is associated with a number of difficulties in the implementation of the ECM process:

- Increasing the probability of short circuits, that is, reducing the reliability of the processing process;



**Fig. 1** Kinematic–geometric schemes of ECM: **a** ECM on the surface; **b** ECM along the line; **c** ECM at the point; (1) electrode-tool; (2) workpiece;  $V_x$  is velocity in the direction of the axis  $O_x$ ;  $V_y$  is velocity in the direction of the axis  $O_y$ ;  $V_z$  is velocity in the direction of the axis  $O_z$

- Deterioration of electrolyte flow conditions in the IEG, which is associated with a significant increase of its hydraulic resistance;
- Increasing the current density and the total current requires the use of very high power supply (150–400 kW).

This article is devoted to the investigation of the combination of kinematic and geometric ECM characteristics.

## 2 The Comparative Investigation of the Electrochemical Machining Schemes

The necessity of preserving a time of the properties of the interelectrode environment with a decrease of the IEG led to the need to move from a continuous process to a discrete or pulse-loop process [5]. In this regard, were developed:

- scheme of treatment with vibrating electrode-tool (Fig. 2c);
- loop processing (loop duration is 15–35 s) (Fig. 2a);
- pulse-loop processing (Fig. 2b).

Despite the transition to processing at small IEG, loop and pulse-loop schemes are characterized by a decrease in performance:

$$V_{ap} = 0.02k_1k_2k_3j, \text{ [mm/min]}, \quad (2)$$

where  $k_1$  is the duty ratio of the voltage pulses;  $k_2$  is the duty ratio of the voltage packages;  $k_3$  is the current pulse shape coefficient;  $j$  is the current density.

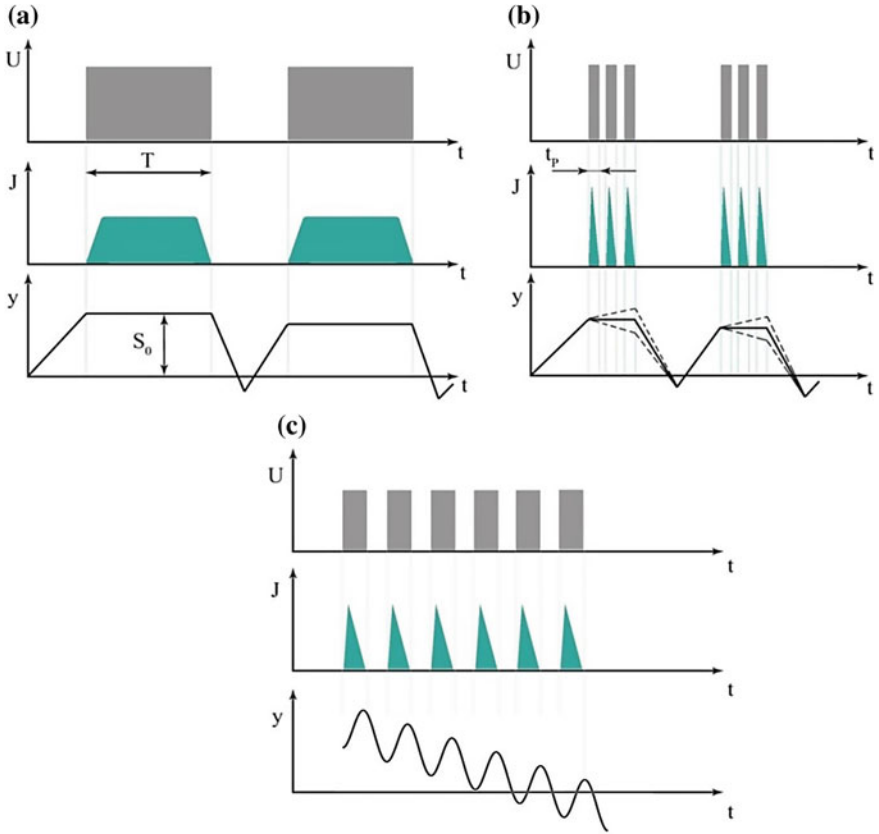
Practical application of pulse-loop processing modes showed that  $k_1$  and  $k_2$  vary in the ranges:  $k_1 = 0.2\text{--}0.5$ ;  $k_2 = 0.3\text{--}0.6$ ;  $k_3 = 0.7$ . Thus, there is a decrease in productivity by 6–22 times in comparison with the continuous process of ECM. Then the rate of anodic dissolution at  $s_0 = 50 \text{ }\mu\text{m}$ ,  $j = 200 \text{ A/cm}^2$ ,  $V_{ap} = 0.3\text{--}0.4 \text{ mm/min}$ .

Further reduction of the IEG becomes impossible due to the decrease in the reliability of the ECM process (a significant increase in the probability of short circuits, deterioration of the conditions for washing the interelectrode gap).

Therefore, further improvement of the ECM is associated with the justification of the process conditions of processing with non-profiled electrode-tools in the local areas of the treated surface (line processing (Fig. 1b) or at a point (Fig. 1c).

It is possible to significantly reduce the interelectrode gap to  $s = 1.0\text{--}20 \text{ }\mu\text{m}$  by the significant improvement in the conditions of the evacuation of the anode dissolution products from the interelectrode gap. In this case, the current density up to  $100 \text{ A/mm}^2$  will be reached.

Thus, even with the preservation of interelectrode gaps similar to the pulse-loop processing without loss of productivity, the ratio of the treated area to the end area of the electrode-tool is possible as:



**Fig. 2** Timeline of various ECM schemes: **a** loop processing; **b** pulse-loop processing (a scheme with inlet/outlet of the electrode-tool during the supply voltage pulses); **c** scheme of ECM with vibrating electrode-tool;  $T$  is the duration of the voltage pulse during loop ECM (15–35 s);  $t_p$  is the duration in pulse-loop;  $s_0$  is the interelectrode gap;  $U$  is the voltage technology;  $J$  is the current in the electrode gap;  $y$  is the displacement of the electrode-tool

$$\frac{S_w}{S_{ET}} = 6-22, \tag{3}$$

where  $S_w$  is the area of the treated surface;  $S_{ET}$  is the working area of the electrode-tool.

This ratio can be achieved without loss of performance values 15–55 by reducing of the interelectrode gap to the minimum values (1.0–20  $\mu\text{m}$ ).

A high-frequency pulse voltage with a voltage pulse frequency of up to 20 MHz is recommended for local shaping.

The most important task of designing the operations of the ECM by unprofiled tool is to select the type and size of the local electrode-tool and the conditions of its displacement. This takes into account:

- dimensions and geometric parameters of the treated surface (processing area, radii, minimum dimensions of the geometric elements of the treated surface, the angles of inclination of the processed elements)
- the expected path of the electrode-tool;
- requirements for accuracy and surface quality.

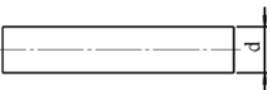
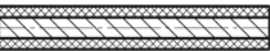

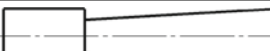
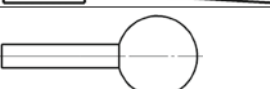
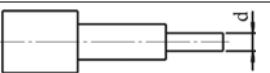

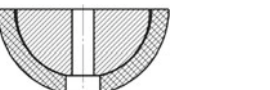
The most used and proposed electrode-tool types by the authors are given in Table 1.

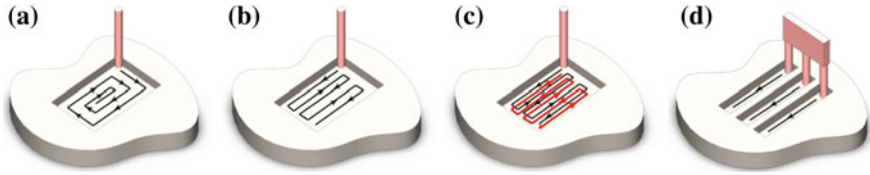
The displacements of the local electrode-tool are selected depending on the shape of the treated surface:

- path by surface (Fig. 3a);
- surface scanning (Fig. 3b);
- layer-by-layer removal of allowance (Fig. 3c);
- matrix removal of allowance (Fig. 3d).

Local electrode-tools have limited dimensions which imply restrictions on the limit value of the total current flow through the electrode. Since the total current is

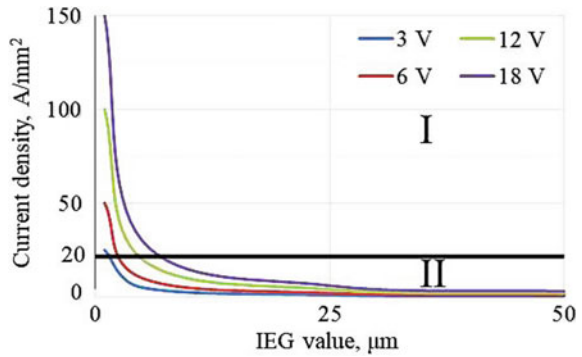
**Table 1** Types of local electrode-tools

No.	Type of local electrode-tool	Parameters	Notes
1		The cylindrical tool without insulation	$d \approx 10\text{--}100 \mu\text{m}$
2		The cylindrical tool with insulation of side surface	–
3		The conical tool with straight cone	–
4		The conical tool with reverse cone	–
5		The tool with the spherical working part	–
6		The stage tool	$d \approx 10\text{--}20 \mu\text{m}$
7		The tube tool	
8		The tool with the linear treatment area	–



**Fig. 3** Displacement path of the local electrode-tool: **a** path scheme; **b** scanning scheme; **c** one-time or layer-by-layer removal of the allowance; **d** matrix removal of the allowance

**Fig. 4** Dependence of current density on the IEG value: I is unacceptable area of the current densities; II is area of acceptable current densities



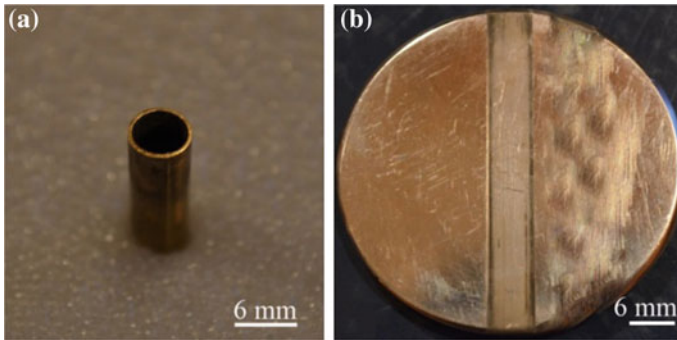
determined depending on the area of the working part of the local electrode, depending on the processing conditions, the choice of the interelectrode gap and the permissible current densities can be made (Fig. 4).

The choice of the velocity of the electrode-tool displacement is poorly justified at present. It is known [13, 14, 17, 18, 21] that velocity of the electrode-tool displacement ranges from 0.05 to 8  $\mu\text{m}/\text{min}$  in the micromachining. The velocity of the local electrode ranges from 50 to 700  $\text{mm}/\text{min}$  in the machining of cavities with large dimensions (of order of a few millimeters).

### 3 Experimental Study and Discussion

The experimental study of the processing of the annular electrode-tool was made (Fig. 5a). The resulting surface is shown in Fig. 5b.

The electrode-tool was made of brass brand LA77-2 GOST 17711-80 with a diameter of 6 mm with a wall thickness of 0.5 mm, in a sample of steel grade X12N10T. ECM modes: The amplitude of the pulse voltage was 12 V; pulse duration was 1  $\mu\text{s}$ ; pulse repetition rate was 250 kHz; working fluid was 10% aqueous solution of  $\text{NaNO}_3$ ; the displacement velocity of the tool was 700  $\text{mm}/\text{min}$ .



**Fig. 5** Electrode-tool and the resulting surface: **a** photograph of the end part of the electrode-tool; **b** photograph of the resulting cavity

## 4 Conclusion

The investigation of the kinematic and geometric characteristics technological ECM schemes is carried out. It is established that with the development of the method of ECM, there is a tendency of developing processing schemes by unprofiled (local) electrode-tool. The rational path of the non-profiled electrode-tool displacement is offered depending on geometrical parameters of the processed surface. The possible technological equipment and modes of machining by point or linear electrode-tool are analyzed.

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