Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2025 vol. 27 no. 4 pp. 148–179
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2025-27.4-148-179

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Modern methods of manufacturing of complex-profile electrode-tools for electrical discharge machining: a literature review

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ARTICLE INFO

Article history:
Received: 11 June 2025
Revised: 04 July 2025
Accepted: 09 September 2025
Available online: 15 December 2025

Keywords:
Experimental production
Electrical discharge machining
Tool electrode
Tool electrode configuration
Fabrication methods
Additive methods
Rapid prototyping technologies
Investment casting
Powder metallurgy

ABSTRACT

Introduction. Pilot production plays an important role in modern mechanical engineering. Copy-piercing electrical discharge machining (*CPEDM*) technology has become widespread in machining pilot parts manufactured in flexible production flows. Manufacturing tool-electrodes (*TE*) is one of the main stages of the CPEDM technological cycle. **Purpose of the work.** Review of existing studies of modern methods of manufacturing tool-electrodes for electrical discharge machining. **Research methods.** A literature review of studies in the field of electrical discharge machining devoted to tool-electrodes, carried out mainly over the past 20 years, is presented. Various configurations of structural elements machined using *CPEDM* technology, as well as *TE* configurations for their machining, are described. The dependences of the influence of the geometric parameters of the simplest *TE* configurations on the output parameters of *CPEDM* are shown. The main groups of *TE* manufacturing methods are identified. The limitations, advantages, and disadvantages of alternative methods to traditional ones are described. The main trends in the development of modern *TE* manufacturing methods are revealed. **Results and discussion.** Based on the literature review of modern research in the field of electrical discharge machining, current trends in the development of tool-electrode configurations are presented, and problems in the manufacture of complex-shaped tool-electrodes using traditional methods are identified. It has been established that among the alternative methods for manufacturing tool-electrodes, investment casting, powder metallurgy, and additive methods are of greatest interest to modern scientists. It has been shown that each method has its own advantages and disadvantages, confirmed by a number of studies. The following current areas of development of complex-shaped tool-electrodes and methods for their manufacture are highlighted: topological optimization of tool-electrodes, use of modern high-tech casting methods; expansion of the range of tool-electrodes materials with improved electrical discharge properties; optimization of powder metallurgy modes, *FDM* printing, and selective laser melting; increasing the thickness and quality of tool-electrodes coatings obtained using rapid prototyping technologies.

For citation: Ablyaz T.R., Osinnikov I.V., Shlykov E.S., Muratov K.R., Blokhin V.B. Modern methods of manufacturing of complex-profile electrode-tools for electrical discharge machining: a literature review. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2025, vol. 27, no. 4, pp. 148–179. DOI: 10.17212/1994-6309-2025-27.4-148-179. (In Russian).

Introduction

Currently, accelerated scientific and technological progress is affecting all sectors of production. Modern mechanical engineering enterprises are forced to operate in a highly competitive environment [1–2].

To maintain competitiveness, enterprises need to ensure flexible operations and a wide range of manufactured products, as well as the ability to respond quickly to changes in market requirements [3–5].

With intensifying competition and the rapid expansion of production portfolios, minimizing the time required to bring products to market is essential. At the same time, it is essential to maintain high quality

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standards for engineering products throughout their entire life cycle. In pilot production, companies design and develop new products and prepare for their mass production [6]. Customer requirements and product quality are key factors in the creation of a prototype.

During the technical and economic assessment stage of manufacturing technology optimization, considering the specific features and complexities of pilot production, prototype manufacturing methods are analyzed and selected [6]. As a rule, traditional manufacturing methods for mechanical engineering products are not optimally suited for prototype production. The high level of equipment utilization for traditional processing methods, the complexity of the part profile, and the high physical and mechanical properties of the product material all necessitate the use of alternative prototype manufacturing methods [7–9].

When machining complex structural elements (such as hard-to-reach surfaces, curved and narrow grooves, blind holes, and thin-walled structures), as well as complex-profile pilot parts manufactured in flexible production flows, electrical discharge machining (*EDM*) is widely used [10]. This machining method is based on copying the shape of the tool-electrode (*TE*) onto the workpiece-electrode (*WE*) through the action of electrical discharges between the *TE* and *WE* [11–12].

High machining accuracy and the non-contact nature of the process (absence of mechanical force on the *TE*) enable the *EDM* method to be used in machining complex structural elements. This method is often used in the production of various tools, such as casting molds, injection molds, and dies [13–17]. This method is widely used in the machining of blind curved grooves, deep, small-diameter holes, and internal splines and teeth [18].

A volumetric profile electrode tool serves as the tool in *EDM*. In copy-piercing machines, the volumetric profile electrode undergoes translational motion at speed V_z towards the *WE* (Fig. 1) [11].

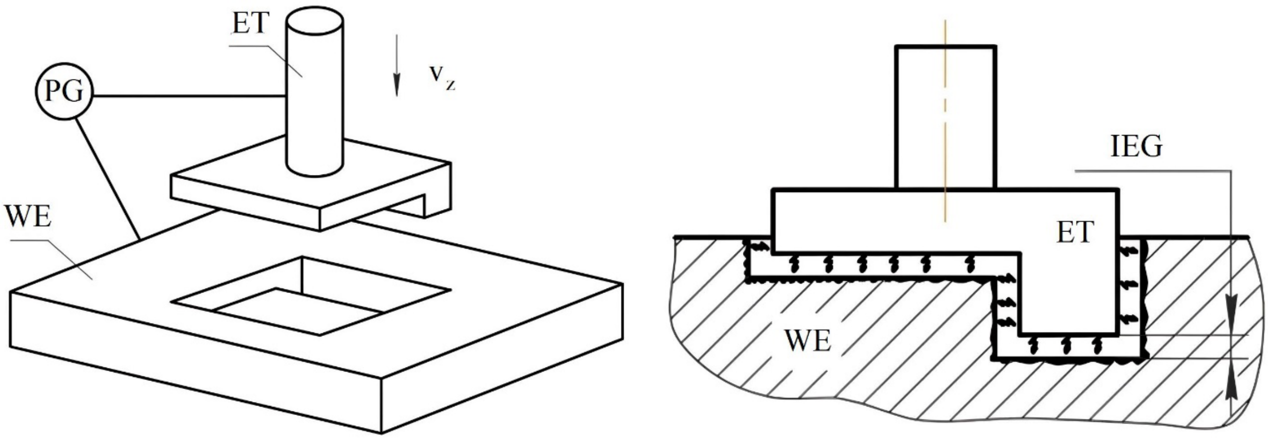


Fig. 1. Schematic of copy-piercing *EDM* process

Due to the ever-increasing complexity of structural components processed using the *EDM* method, the need arises for the use of *TE*s with complex geometries. One of the most time-consuming stages in this process is the manufacture of *TE*s. Machine-building companies are faced with the challenge of choosing a manufacturing method for *TE*s that maximizes economic efficiency by ensuring maximum productivity and minimizing time and material costs.

The problem of manufacturing tool electrodes for electrical discharge machining has been known practically since the advent of electrical discharge machining. Research into these methods remains relevant due to trends in modern mechanical engineering toward ever-more complex geometries, reduced mass and size characteristics, and other improvements to workpieces.

Currently, there are many studies in the field of electrical discharge machining (EDM) devoted to the methods of manufacturing *TE*.

The purpose of this paper is to review existing research on modern methods of manufacturing electrode tools for electrical discharge machining.

The following ***tasks*** were solved during the research:

– classification of methods for manufacturing *TE*, definition of methods alternative to traditional blade processing;

– determination of the advantages, disadvantages and limitations of modern methods of manufacturing *TE* in comparison with traditional methods;

– determination of development trends of the selected methods.

Research methodology

This paper presents a literature review of electrical discharge machining (*EDM*) research on electrode tools, primarily conducted over the past 20 years. Various configurations of structural components machined using *EDM* technology, as well as the configurations of *WE*s used for their machining, are described. The influence of the geometric parameters of simple *EDM* configurations on the output parameters of *EDM* is demonstrated. Key groups of *EDM* manufacturing methods are identified. The limitations, advantages, and disadvantages of alternative methods to traditional ones are described. Key trends in the development of modern *EDM* manufacturing methods are identified.

Results and Discussion

The configuration of the tool electrodes is determined by the geometric parameters of the structural elements being processed. A wide range of structural elements processed using the *EDM* method is extensively discussed in [19–23]. Fig. 2 shows examples of such structural elements.

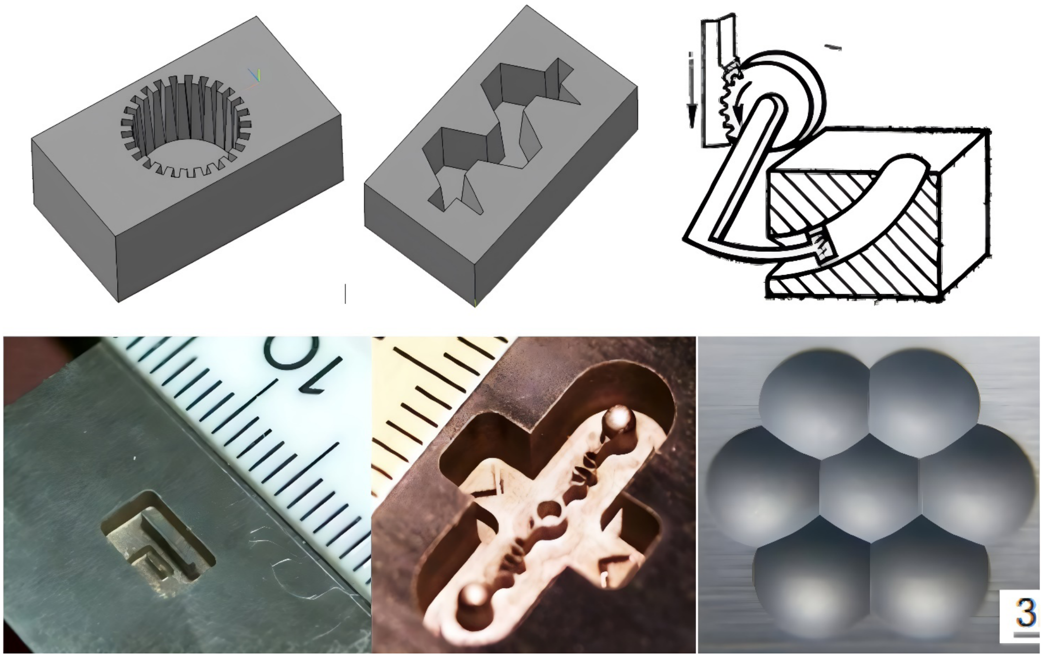


Fig. 2. Examples of structural elements processed by the *CPEDM* method

TE configurations

The design of complex-profile surfaces requires appropriate geometric parameters for the *TE*. Currently, numerous studies describe the design features of the *TE*.

Simple form TEs

In real-world production settings, the simplest *TE* configurations are rarely used, as the structural components processed with them can generally be machined using mechanical methods without any technological difficulties. However, there are a number of studies examining the influence of *TE* geometric parameters on the output parameters of *EDM*. In such cases, *TE*s with round, square, triangular, and other simple cross-sections are typically used. These *TE*s are manufactured using traditional blade-cutting methods without any difficulties.

The paper [24] presents a study of the performance of *EDM* depending on the configuration of the electrode shape. Simple configurations of TE with round, triangular, square and rhombic cross-sections were investigated. It was found that, with the same cross-sectional area, machining with a round *TE* is characterized by the highest material removal rate and the least wear of the *TE*. *EDM* with a rhombic *TE*, on the contrary, exhibits the greatest wear and the lowest material removal rate. This is due to the fact that rhombic electrodes have the largest peripheral area, which allows for faster heat dissipation into the environment. As a result, less thermal energy is available for material removal compared to other electrodes. However, in the sharp corners of these electrodes, a high heat concentration is observed, which leads to intense melting and evaporation processes of the electrode, which increases its wear. The graphs of the dependence of the material removal rate (*MRR*) and tool electrode wear rate (*EWR*) on its configuration are presented in Fig. 3.

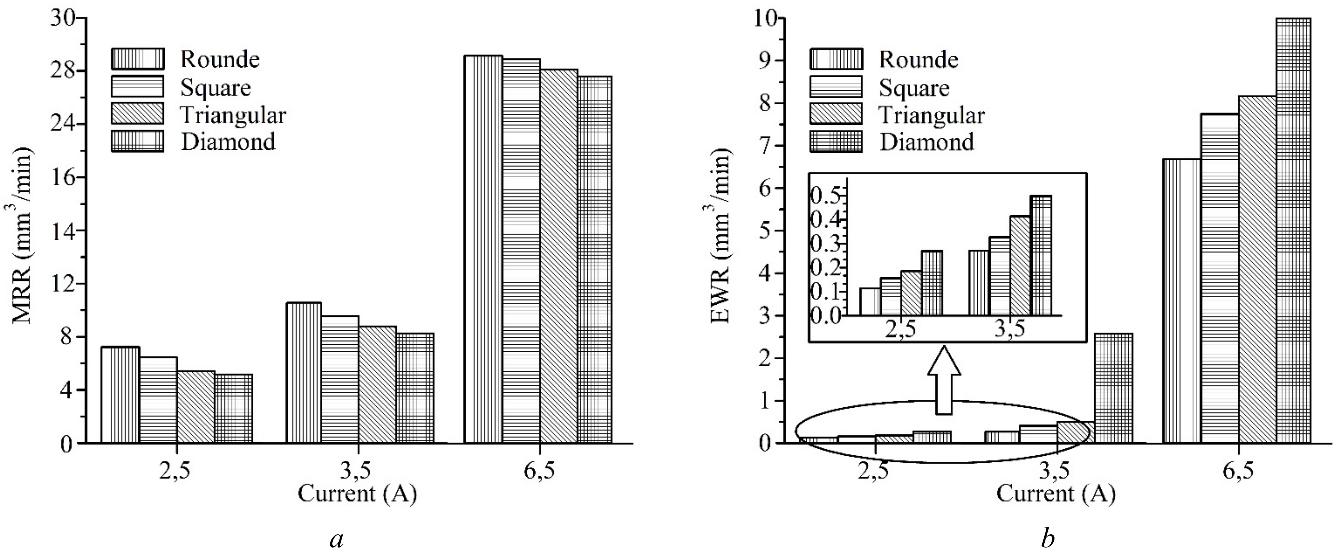


Fig. 3. Influence of *TE* configuration and current intensity on:
a) material removal rate (*MRR*); *b)* tool-electrode wear rate (*EWR*) [24]

The best performance of *TE* with a round cross-section among *TE* with a simple configuration was also confirmed by the authors of the study [25]. In this work, the performance of cylindrical *TE* was compared with electrodes of triangular and rectangular cross-section.

The work [107] also presents a study of the influence of the geometric parameters of rotating *TE* of the simplest configurations on the output parameters of the *EDM*. The study used *TE* of eight configurations, shown in Fig. 4.

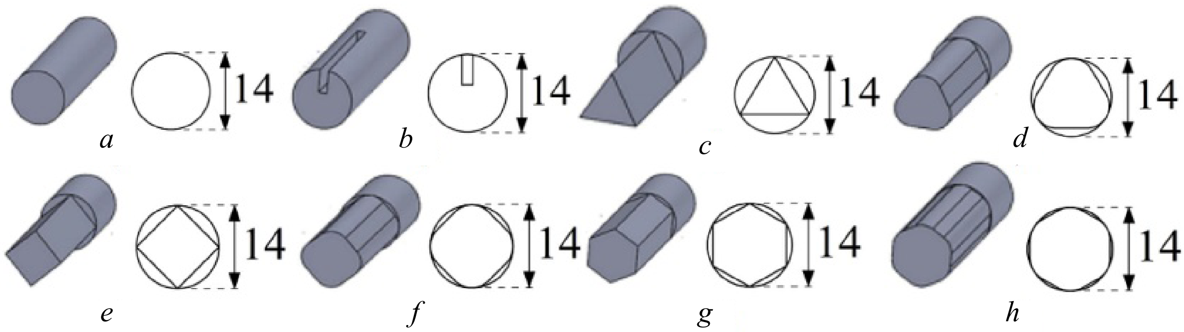


Fig. 4. Configurations of tool-electrodes:
a) cylindrical; *b)* cylindrical with a groove; *c)* triangular; *d)* triangular with rounded corners; *e)* square; *f)* square with rounded corners; *g)* hexagonal; *h)* hexagonal with rounded corners [107]

Of all the possible cross-sections, triangular, square, and hexagonal shapes were chosen because they were the easiest to design and manufacture for *EDM* testing. Electrode cross-sectional profiles were chosen based on the fact that non-cylindrical shapes — triangular, square, and hexagonal – are the easiest to machine. In these cases, cross-sections with sharp and rounded corners were tested. A cylindrical electrode with slots was also analyzed. A cylindrical electrode was also tested for comparison.

In all cases, the rotating outer diameter of the electrode cross-section was 14 mm. Therefore, all electrodes used in these tests had the same effective area. All radii used for electrodes with rounded corners were 4 mm, and for the slotted cylindrical electrode, the slot width was 2 mm and the depth was 5.5 mm. For electrodes with sharp corners, no radius was used. All these electrodes were manufactured on a machining center using a simple milling operation.

According to the results of this study, the use of profiled electrodes yields better results in terms of *MRR*, but not *EWR* and taper angle, compared to the characteristics of a simple cylindrical electrode. Moreover, the more intricate the electrode geometry, the lower the *TWR* and taper angle values can be. *EWR* will increase due to the difference in electrode volume, which depends on the shape of the electrode used. The discrepancy between the obtained data and the results of studies [24] and [25] is due to the rotation of the *ET* during machining.

*TE*s of the simplest configurations are rarely used in production settings, but they have high practical applicability in research and development. Data on the influence of the geometric parameters of ETs of the simplest configurations on the output parameters of the EDM can be used in the design of complex and modular EIs.

TE for deephole machining

Electrical discharge drilling is a technique for hole machining, also known as *EDM* drilling (*EDD*) [26–28]. *EDD* is used with cylindrical electrodes to create holes, especially those with small diameters and large aspect ratios, in difficult-to-machine materials without the expense of expensive cutting tools. However, problems with deephole machining or deep drilling often lead to undesirable surface quality and geometry issues.

The main problem with deephole *EDD* is its low productivity compared to blade machining. This is largely due to the low efficiency of fine material removal from the machining zone. When machining deep holes, fine material removal is difficult. Furthermore, secondary fine material is created, which returns to the *TE* and is re-thrown onto the hole wall, resulting in a rough inner wall [103–104] and a loss of hole shape.

Electrode configuration has a significant impact on the performance of the *EDD*. Insufficient flushing is a major problem, causing clogging of the machining zone with fine material and leading to short circuits [29–30, 62]. Flushing efficiency can be improved by using electrodes with different shapes. Changing the external and internal shape of the electrode can alter the behavior of the dielectric flow in the machining zone, thereby increasing flushing efficiency.

Researchers from the University of Melbourne conducted a major review study [31] in the field of electrical discharge machining. They described the *TE* configurations for *EDD* and their effects on the machining process. The spiral electrode, side-cut electrode, notch electrode, and step electrode can be combined with electrode rotation and vibration to significantly alter the dielectric flow behavior and provide a channel for fine material removal. The hollow electrode is one type of electrode commonly used in the *EDD* process. The dielectric can be delivered to the machining zone through the internal hole of the electrode, which helps in removing fine material [32–34]. The use of a slot electrode provides additional removal of gases and fine material from the machining zone, reduces side sparking and conicity [35–37]. In addition to the step electrode, spiral electrodes can also be used to improve the productivity of the *EDD* process. The spiral grooves provide channels for fine material removal and can reduce the amount of fine material in the machining zone and, as a result, reduce the relative wear rate of the tool [38].

Thus, the use of electrodes of various shapes improves the efficiency of the electrical discharge machining system. Electrodes of a certain shape provide additional channels for the evacuation of electrical erosion products and also help prevent short circuits and arcing.

Modular (composite TEs)

Modular electrodes are also widely discussed in numerous studies. For example, studies [39–41] present modular *TE*s consisting of a set of rods secured to a rotary table. Several small cylindrical copper electrodes are placed on the rotary table, rotating around a vertical axis. A large rotary table with multiple electrodes increases material removal. *EDM* products are easily removed from the gap due to the space between the electrodes. Similar *TE* designs can also be used to machine multiple holes in a single process step [42].

Another area of application for modular *TE*s is the machining of curved holes. Modular *TE*s have now been developed consisting of conductive segments mounted on elastic guides. This design allows for the machining of curved holes that are virtually impossible to process using traditional blade methods and the *EDM* method with electrodes of simple configurations [32, 43–46].

Complex-profile TEs

The diversity of *TE* configurations is dominated by electrodes with unique profiles designed to machine complex structural elements in a single process step [20]. These *TE*s are designed based on the geometric parameters of the elements being machined and are typically dedicated to a single product type. A wide range of products processed by *EDM* and the *TE*s used to machine them are presented in [47–48]. A distinctive feature of this group of *TE*s is the complex profiles of their active surfaces [49].

Topologically optimized TEs

Topologically optimized *TEs* deserve special mention. *TE*s used for machining dies, casting molds, and other complex structural components are often large in size and, therefore, heavy. Machining with such *TE*s places high loads on the machine's guides and drives, and also requires high material consumption during manufacture. Currently, topological optimization is widely used in mechanical engineering to reduce the mass and size characteristics of critical components while maintaining strength [50–53].

Incorporating topology optimization into the initial stage of the *TE* design process can speed it up several times over the traditional approach. This speedup is due to the minimal initial data required for optimization.

In works [54–61], the possibility of using topological optimization methods in the design of *TE*s is noted, and modern methods of their manufacture allow them to be manufactured without structural defects that reduce the strength and rigidity of their design.

Table 1 presents a summary of the characteristics of *TE*s, based on the analysis of studies devoted to *TE* configurations.

Table 1

Tool electrode configurations for *CPEDM*

TEs configuration	References	Application	Image
Simple-Form *TE*s	[24], [25]	Processing of structural elements with a simple cross-section (circle, square, etc.)	Fig. 5, *a*
*TE*s for deep hole machining	[26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38]	Deep hole machining, where the machining depth significantly exceeds the hole diameter	Fig. 5, *b*
Modular (composite) *TE*s	[32], [39], [40], [41], [42], [43], [44], [45], [46]	Processing of an array of holes. Processing of curved holes	Fig. 5, *c–d*
Complex-profile *TE*s	[20], [47], [48], [49]	Processing of complex profile shaped surfaces in one step	Fig. 5, *e–f*
Topologically optimized *TE*s	[54], [55], [56], [57], [58], [59], [60], [61]	Processing of large-sized products	Fig. 5, *g*

Based on an analysis of Table 1 and fig. 5, it can be concluded that the vast majority of *TE*s for *EDM* feature complex-shaped working surfaces. These surfaces make it possible to machine the corresponding structural elements, but the issue of *TE* manufacturing becomes pressing.

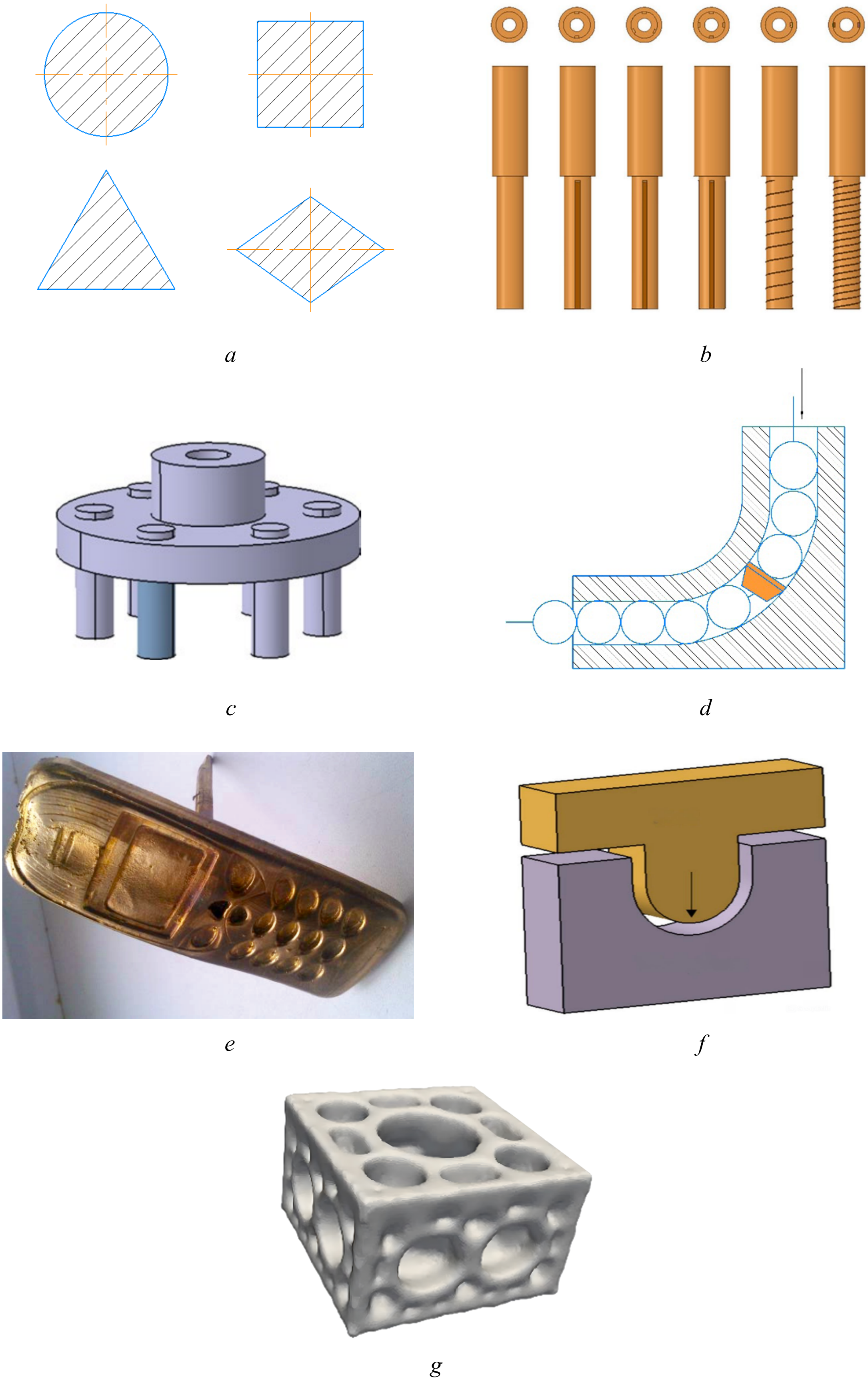


Fig. 5. Tool-electrode configurations for *CPEDM*

Electrode manufacturing is one of the key stages in the technological cycle of *EDM*. In pilot production, electrode manufacturing accounts for more than 50% of the financial and time costs [17]. This is due to the ever-increasing complexity of the profile of the structural elements being processed and the configuration of the electrodes.

An analysis of studies [11, 19] showed that, under conditions of serial production at modern mechanical engineering enterprises, when using electrophysical complex-profile machining technologies, traditional blade machining technologies and the use of press molds are employed for the manufacture of *TE*s. Thus, high-precision *TE*s obtained by high-precision blade machining methods are used for finishing *EDM* [70]. The use of these *TE*s is characterized by the removal of minimal allowances from the machined surfaces of the product during the *EDM* process, while the wear of the *TE*s is insignificant, which makes the use of high-precision blade machining technology in the manufacture of finishing *TE*s cost-effective.

The use of blade technologies in the production of roughing and semi-finishing electrode sets does not provide the required economic benefits. Excessive wear of the electrodes during the *EDM* process, as well as the low material utilization rate during electrode production, significantly impacts the cost-effectiveness of the final component manufacturing process.

Implementing approaches for rapidly adaptable pilot production of components requires new approaches to developing and refining process modes using cost-effective technologies for creating tool electrodes. Difficult-to-machine surfaces and complex geometries of modern components lead to complex tool electrode shapes and a significant increase in their manufacturing costs. This raises the challenge of finding alternative, cost-effective methods for manufacturing tool electrodes for *EDM* of prototypes.

Currently, the most common methods for producing *TE*s are additive manufacturing, casting, electroforming/electrodeposition, and powder metallurgy.

Powder metallurgy

Powder metallurgy (*PM*) technology for electrode fabrication is a simple and controllable method offering advantages over other methods, according to a study [69].

A study by *Garba*, *Abdul-Rani*, *Yunus* et. al. [70] provided a comprehensive review of the research on *TE* manufactured using powder metallurgy. *TE* can influence both macro- and microvariables in electrical discharge machining, and their properties can be significantly controlled by varying the sintering and compaction conditions. Powder metallurgy offers many advantages over traditional manufacturing methods, including better control of electrode properties, improved productivity, and lower costs.

This paper describes numerous studies devoted to the influence of *TE* material on the *EDM* process and the output parameters of the workpiece. A wide range of materials suitable for *TE* manufacturing using the *PM* method is presented. A schematic of *TE* manufacturing using the *PM* method is shown in fig. 6.

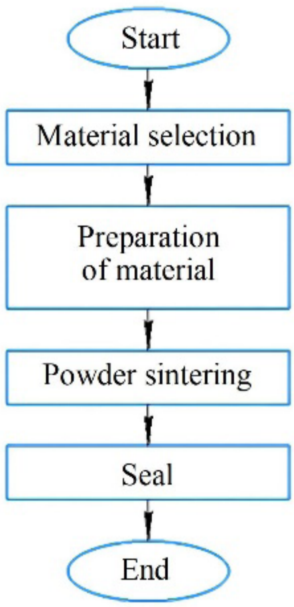


Fig. 6. Schematic of tool-electrode manufacturing by powder metallurgy (*PM*) method [71]

Despite its advantages, the *PM* method has a number of limitations. The most significant among these are the difficulty of manufacturing large-sized parts and the limitations of profile curvature. Furthermore, this method is prone to structural defects and inhomogeneity in the properties of the resulting product, which is unacceptable for critical parts or for *EDM* using large-sized *TEs*.

Investment casting/burnt-out casting

Numerous studies show that investment casting (*IC*) offers significant advantages for electrode manufacturing, allowing for the production of complex shapes, shorter production times, and lower production costs [64].

The *IC* method involves producing shell molds using wax or polymer 3D models of the product and a sprue system, removing the models from the mold, and then pouring the melt of the product material into the mold [49].

IC allows the production of *TE* with high surface cleanliness, thin-walled structures and complex geometry [63].

The manufacturing scheme of the finished product using the *TE* obtained by the *IC* method is shown in Fig. 7.

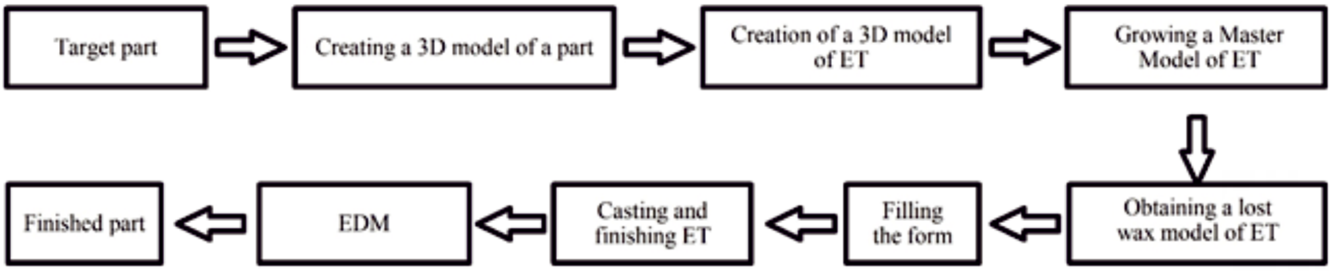


Fig. 7. Schematic of finished product manufacturing using an investment cast tool electrode

The authors of [64] conducted a study of the influence of the *TE* material obtained by the *IC* method on the roughness of the treated surface. Models for obtaining shell molds, as in many other studies [49, 65–67], were made by the stereolithography (*SLA*) method from liquid photopolymers (Fig. 8).

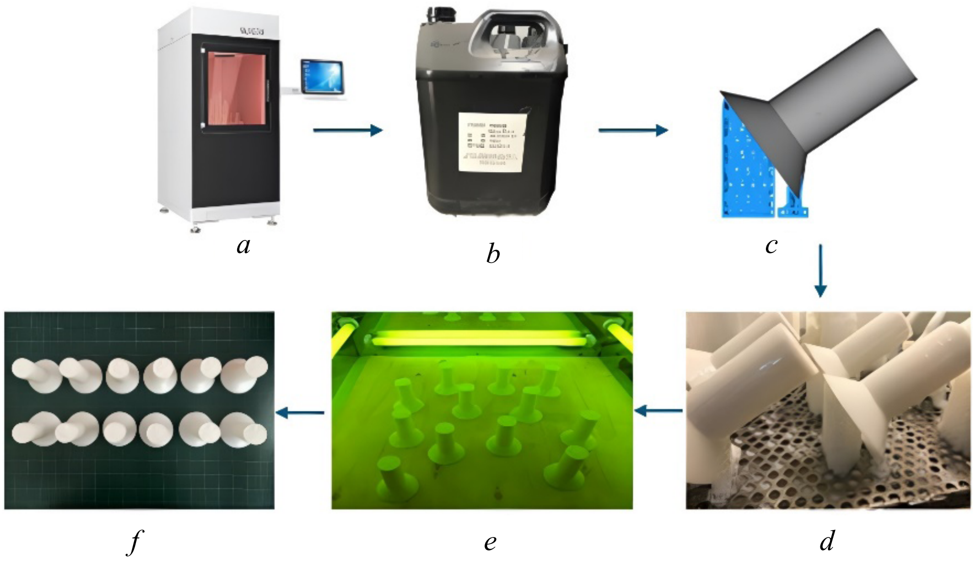


Fig. 8. Prototyping process using *SLA* method [64]:

a) Zongheng SLA-600 3D printer; *b) HONY-01* epoxy resin; *c)* model support design; *d)* model in 3D printing process; *e) UV* curing, *f)* finished models

The resulting *TE*s were found to have a shrinkage of 0.8–1.9% and a surface roughness of ***Ra*** 3.20–6.35 µm, depending on the material. These *TE*s allow for a roughness ***Ra*** of 10 µm on the machined surface.

A significant disadvantage of the *IC* method is the defects characteristic of casting processes and described in [68], such as pores, shrinkage cavities, and cracks. To minimize these defects, it is rational to use modern casting methods, such as injection molding or centrifugal casting [64].

Additive manufacturing methods for electronic components

Currently, there is active development of additive technologies in the creation of complex *TE* for pilot production [72].

In the manufacture of *TE*, traditional manufacturing methods are limited by complex geometry and local integration of channels [106]. A comparison of the process chains of tool manufacturing using additive and traditional manufacturing methods is presented in Fig. 9.

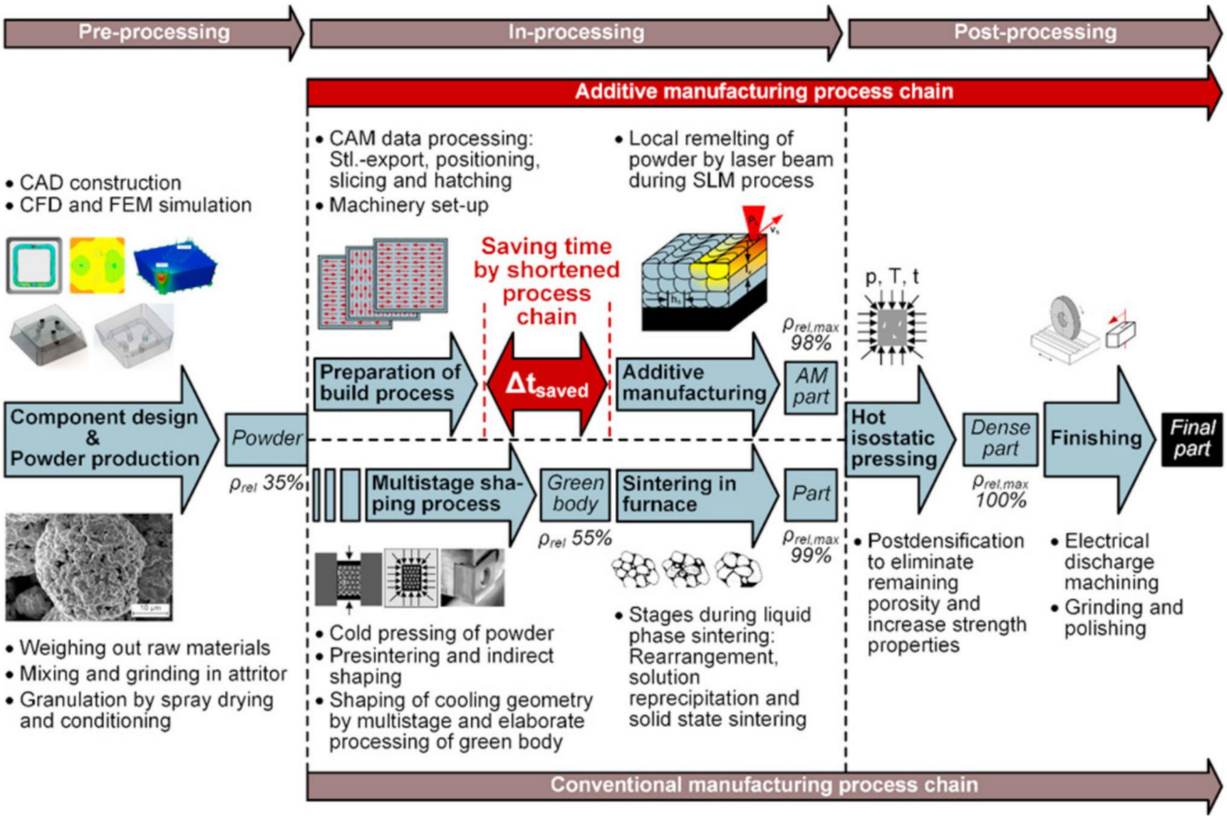


Fig. 9. Comparison of technological chains of additive manufacturing and traditional production of tool electrodes [106]

Modern additive manufacturing methods are characterized as promising production technologies, enabling the production of complex electronic components with high precision, including those with complex geometric shapes and spatial configurations. Additive technologies enable the production of components with complex geometries and spatial configurations in the shortest possible time. This eliminates the need to develop specialized tooling and fixtures or a separate process plan for each component [73–74].

Additive manufacturing methods for *EDM* tools offer a number of advantages:

1) the possibility of using the equipment in both pilot and serial production without retooling;

2) energy efficiency of production;

3) flexible reconfiguration of equipment for the production of *TE* of various configurations for the *EDM* of various products;

4) high level of automation of the technological process;

5) reduction of time costs for technological preparation of production and manufacturing of *TE*;

6) high level of repeatability of the characteristics of the technological process and manufacturing of *TE* and equipment;

7) a wide range of materials used, as well as the possibility of combining them and using them on one piece of equipment;

8) high level of predictability of time and material costs at all stages of production;

9) reduction in the number of personnel for equipment maintenance, low required qualifications of operators;

10) the possibility of varying the physical and mechanical properties of the *TE* material depending on the required output parameters of the *EDM*.

Currently, from the wide range of additive manufacturing methods, the following technologies are most widely used in the production of electronic components:

• *FDM* (fused deposition modeling) is the production of products from thermoplastic materials (for example, ABS or PLA plastic) by layer-by-layer application of material heated to a highly elastic state in the form of a thread;

• *SLS*/*SLM* (selective laser sintering/selective laser melting, respectively — selective laser sintering/melting) is production of products from metal powder materials by sintering/melting them with a laser beam;

• *SLA* (stereolithography apparatus) is the layer-by-layer growth of a product through the crystallization of liquid photopolymer materials by a laser beam.

Fused deposition modeling (*FDM*) is a widely used 3D printing method that can be used to produce electrodes for *EDM*. *FDM* involves melting a thermoplastic material (*TPM*) and extruding it through a nozzle to create a 3D object layer by layer. To produce electrodes using *FDM*, the thermoplastic material is mixed with an electrically conductive material (*ECM*) to enhance the electrical conductivity of the finished *TE* [75–80].

The stages of creating *TE* using the *FDM* method are shown in Fig. 10.

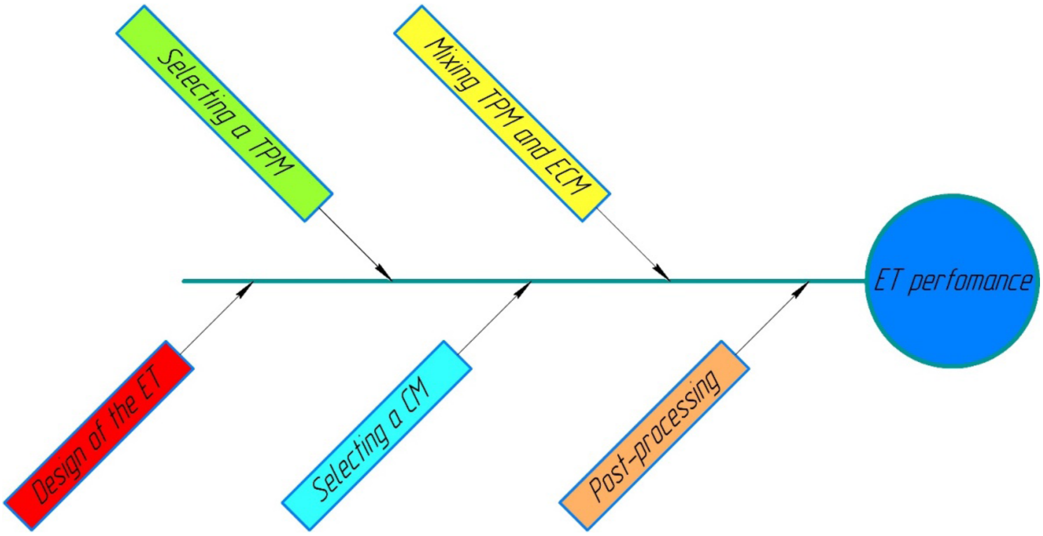


Fig. 10. Schematic of manufacturing tool electrodes by *FDM* method

Research in the field of additive manufacturing methods for *TE*s has shown that the *FDM* method allows for the efficient production of electrodes that meet the technological requirements of *EDM* [75, 76]. However, the question remains regarding the relationship between the electrical discharge properties of *TE*s obtained by this method and those of ETs made from solid material, manufactured using a blade cutting tool or by casting.

The authors of [77] investigated the conductivity of *TE*s based on *PLA* and *ABS* produced by *FDM*. It was found that the conductivity of the materials increased with increasing deposition time, reaching maximum conductivity after 48 hours. However, the results were not confirmed using real-time processing and therefore require further verification.

Fefar and *Karacagikar* [78] compared the electrical discharge properties of metallized *FDM* electrodes with solid copper electrodes in the *EDM* of *EN-19* alloy steel workpieces. The study showed that under identical machining conditions, the performance of the metallized *FDM* electrode was not different from that of the solid copper electrode.

A study [79] confirmed these findings. The experiment showed that the electrode produced using *FDM* performed better than the solid copper electrode.

Danad et al. [80] investigated the feasibility of machining an *ABS* part manufactured using *FDM* that was subsequently coated with copper to provide electrical conductivity. These *TE*s were found to have a lower mass than metal ones with comparable performance values.

The disadvantages of the *FDM* method for manufacturing *TE*s are described in detail in a review study [70]. The most significant ones are the multi-stage production, low processing accuracy, and technological difficulties of metallization.

Selective laser sintering (*SLS*) is an additive manufacturing method that enables the production of three-dimensional, complex-shaped parts directly from their *CAD* models. *SLS* creates parts layer by layer by consolidating successive layers of powder material. Consolidation is achieved by selectively fusing or sintering each layer using thermal energy delivered by a focused laser beam, which, using a mirror deflection system, scans the layers according to the cross-section of a mathematically sliced *CAD* model of the object. The main characteristic of *SLS* is the ability to produce complex-shaped parts without the need for tooling. It helps eliminate labor-intensive pre- and post-processing compared to traditional manufacturing processes [81–83].

The *SLS* method is one of the most widely used alternative methods for manufacturing complex-shaped *TE*s, as it helps reduce the time to final product and processing costs. This is confirmed by numerous studies [84].

An important factor in the *SLS* production of *TE*s is the deposited material. A study [85] described the production of electrodes for electrical discharge tools using the *SLS* method with four materials: copper, a bronze-nickel alloy, a steel alloy, and a combination of copper and a bronze-nickel alloy. Cross-sectional micrographs were used to analyze the porosity and compaction behavior of the electrodes. The steel alloy and the bronze-nickel alloy demonstrated improved compaction behavior and the lowest porosity compared to *Cu* and mixtures of *Cu* and these alloys. It was concluded that the addition of the bronze-nickel alloy to pure copper improved the compaction process.

The authors of [86] conducted an experiment to study *SLS* electrodes made from powdered bronze-nickel alloys, copper-bronze-nickel alloys, pure copper, and steel alloys. The materials were selected based on their electrical discharge properties and the feasibility of fabrication by the *SLS* method. It was concluded that the productivity of *TE*s manufactured by the *SLS* method is significantly lower compared to mechanically processed copper *TE*s. Among *TE*s obtained by the *SLS* method, bronze-nickel *TE*s demonstrated the best performance indicators for *EDM*. It was also found that the use of copper as a material for laser sintering is irrational.

In addition to traditional materials used in *EDM* (copper, graphite, brass), a number of fundamentally new composite materials are currently being used that rival standard materials in terms of *EDM* process output parameters. However, products made from these materials are virtually impossible to produce using subtractive processing methods.

L. Amorim et al. compared copper powder and a new TiB_2–*CuNi* metal matrix composite electrode fabricated by *SLS*. In the *EDM* experiments, it was found that the TiB_2–*CuNi* electrode significantly outperformed the copper powder electrode [87].

In the study [88], three new metal matrix materials were presented: *Mo–CuNi*, TiB_2–*CuNi*, and ZrB_2–*CuNi*. Electrodes were fabricated using the *SLS* method. Experiments were conducted at different discharge energy levels, and the output characteristics of the *EDM* were represented by the material removal rate and tool wear. The results showed that the new composite materials are rational for use as *EDM* electrode materials. Electrodes made from these materials demonstrated excellent stability of the *EDM* process over a range of variable process parameters.

There are a number of studies reflecting the shortcomings of *TE*s obtained by the *SLS* method, among which one can highlight the porosity and discontinuity of the obtained *TE*s, as well as their increased wear.

Dürr et al. [81] investigated *TE*s produced by selective laser sintering (*SLS*) from a powder mixture of bronze and nickel. The porosity of the resulting *TE*s reached 20%. The authors found that the wear of such electrodes was comparable to that of massive copper electrodes; however, the wear was unstable, which negatively affected the shape of the *TE*s and the workpiece. A repeat experiment was conducted in which the *TE*s were impregnated to reduce porosity. The use of such *TE*s resulted in a significant reduction in relative wear.

The authors of [82] also encountered difficulties in the *EDM* of *TE*s produced by the *SLM* method. *TE*s made from powders of pure copper, bronze-nickel alloy, copper-bronze-nickel alloy, and steel alloy were studied. The steel alloy electrode produced by the *SLS* method removed virtually no material from the workpiece, while the performance of the remaining *TE*s produced by the *SLS* method was lower compared to solid copper electrodes.

As noted earlier, the possibility of using topological optimization methods in the design of electrical discharge components (*TE*s) (Fig. 11) is noted in [54–61]. *SLM* technology is one of the few methods that allows the production of topologically optimized electrical discharge components. During electrical discharge machining, electrical discharge components are subjected to the complex action of thermodynamic, electrophysical, hydromechanical, and other forces. Therefore, it is necessary to ensure the absence of defects in the internal structure of the electrical discharge components, which is achieved by using appropriate growth modes.

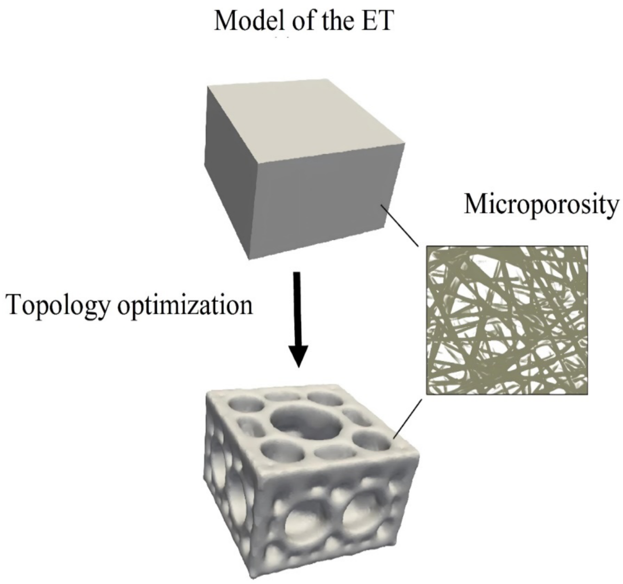


Fig. 11. Optimization of tool electrode geometry

It has been established that during the production of *TE*s using *SLS* and *SLM* methods, the appearance of structural defects is observed, which directly depend on the parameters of the growth process. The most significant manufacturing parameters influencing the quality of the final product are laser power, scanning speed, hatching distance, layer thickness, chemical composition of the powder material, and the atmosphere in the growth chamber [82]. The most common and difficult to eliminate defect arising in products manufactured using *SLS* and *SLM* methods is porosity. The formation of pores is determined by many parameters: the physicochemical properties of the powder material, the parameters of the *SLM*/*SLS* equipment, and the sintering/melting process parameters [83].

The deposition modes also directly affect the quantity and size of pores. Due to insufficient power density, the powder layer is not fully melted, spherodization is observed, and interlayer lack of fusion and particle fusion occur [84]. The appearance of lack of fusion and increased porosity can also be caused by insufficient overlap of individual tracks. During the cladding process, areas of lack of fusion form between individual tracks, where the powder particles are not fully exposed to the laser beam [85].

In the opposite case, when the current power density value is too high, voids are also formed due to the evaporation of the material or alloy components with a lower melting point.

The presence of pores and lack of fusion negatively impacts the performance of the *TE*, significantly increasing its wear during the *EDM* process. Furthermore, structural defects that arise during manufacturing reduce the stability of the spark generation process during *EDM* and, consequently, the performance parameters and quality of the finished surface.

Based on the analysis of the research, it can be stated that the *SLS* method is rational to use in the production of complex-shaped *TE*s, however, the use of this method requires additional research to optimize the surfacing modes and minimize structural defects, as well as the selection of materials that simultaneously satisfy the processes of *EDM* and *SLS*.

Another group of current methods for producing complex-profile *TE*s involves the use of rapid prototyping technologies, such as electroforming or *SLA* (layer-by-layer growth of a product by curing a photopolymer with a laser beam) followed by the application of a conductive coating. This combination of methods can be used to simultaneously produce multiple electrodes, offering a cost advantage.

In die and mold manufacturing, the *EDM* cycle can account for 25 to 40% of the tool shop's development time. In today's manufacturing environment, cost reduction is a primary goal, with significant emphasis placed on reducing task completion times. Advances in rapid prototyping have enabled significant time savings in ongoing research.

The use of these non-traditional manufacturing methods is explored in [10], where these methods are compared with traditional methods of producing electroformed electrodes in terms of processing time, material removal rate, tool wear, and surface roughness under several standard machining settings. It was found that traditionally manufactured electrodes perform similarly to non-traditional (electroformed) electrodes. If the electrodes could be manufactured with a much more uniform shell thickness, this could reduce the randomness of defects. Electroformed electrodes perform, on average, comparable to solid electrodes.

Research groups are conducting research in many areas of rapid prototyping of electronic components. This research shows that significant opportunities still exist for potential research to improve manufacturing technologies for complex electronic components.

Harris et al. [89, 90] found that low volume part production could be accomplished in much less time and at a lower cost using additive manufacturing technologies such as additive manufacturing of *TE*s and rapid tooling.

Noguchi and *Nakagawa*, and *Chan* [91–92] showed that the combination of *SLA* and rapid forming metallization processes is a rational method for producing *TE*s.

The studies [93] and [94] showed comparisons between non-traditional electrodes produced by electroforming and conventional machined electrodes. *Jensen* et al. [94] showed a general comparison of non-traditional electrodes with machined electrodes, but did not provide a detailed insight into the performance of the electrodes. The studies of *Leu* et al. [93] show a more detailed comparison of different electrodes in terms of material removal rate as well as the roughness parameter ***Ra***, but this work is based on the *EDM* process of *TE*s produced by conventional methods.

A key step in manufacturing *TE*s using rapid prototyping technologies is the metallization of their non-conductive housings. The applied coatings must meet the requirements of conductivity, uniformity, electrical erosion resistance, and adhesion strength. Several coating methods are currently used on components made from non-conductive materials.

Non-conductive materials, partially or completely coated with metal deposited on their surface, possess unique characteristics due to the combination of beneficial properties of conductive and non-conductive materials. These materials are widely used in many branches of mechanical engineering [95–96].

Currently, metallization methods are classified into three main groups: mechanical, physical, and chemical. Each group includes several methods, used individually or in combination. More detailed classifications of metallization methods also exist, based on the type of combined materials and the technological specifics of the metallization process.

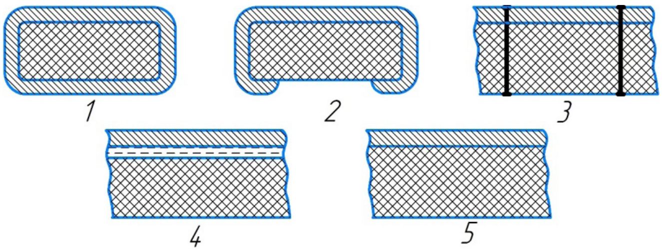


Fig. 12. Mechanical methods of metallization:
1 – wrapping; 2 – bending; 3 – riveting; 4 – gluing; 5 – hot stamping or pouring [97–98]

Traditional and most basic mechanical methods of metallization, when the metal coating is formed in advance and in finished form is attached to the surface of the product, are shown in Fig. 12 [97–98].

Despite the high labor intensity of these mechanical metallization methods, they are widely used in the manufacture of small-sized parts. The main limitation of these methods is the high metal consumption required for the target coating and the large amount of waste generated. Furthermore, coatings obtained by mechanical methods require post-processing, which is typical for metal parts.

Physical methods, which involve melting or evaporating the metal followed by deposition on the target surface (Fig. 13), are characterized by the use of more complex specialized equipment, but are also widely used in modern mechanical engineering enterprises [99].

One of the physical methods widely used for metallization of plastic and fabric products is liquid metal spray metallization. This method allows for the production of coatings from a wide range of metals, such as aluminum, zinc, lead, copper, nickel, tin, and various alloys. The method involves melting the deposited material in a gas torch flame, an electric arc, or a plasma stream, followed by spraying it onto the surface to be metallized using streams of compressed air or gas.

Electrolytic metallization methods (galvanotechnics) are generally used to create a wide range of coatings with various mechanisms of action (e.g., anti-corrosion, protective and decorative, wear-resistant, anti-friction, reflective), as well as for the production of metal copies of products (electroplating).

These metallization methods require preliminary surface preparation, depending on the coating's intended purpose. Before cadmium or zinc plating, the target surface must be degreased and etched. In the case of chromium or nickel plating, in addition to removing grease and oxides, mechanical surface preparation by grinding and polishing is also necessary. This is because surface defects are revealed during the coating process due to the correlation between current density and surface microrelief.

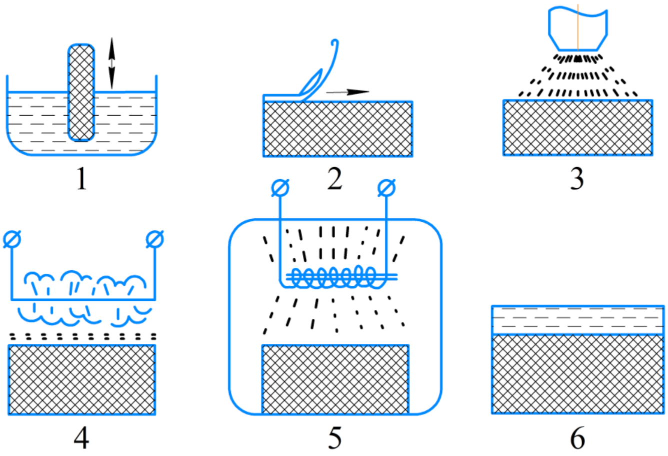


Fig. 13. Physical methods of metallization:

1 – dipping; 2 – smearing; 3 – spraying; 4 – blasting; 5 – spraying (steaming); 6 – painting [99]

In the electroplating process, the workpiece serves as the cathode, and plates made of the coating material serve as the anode. When applying an alloy coating, separate anodes are used (e.g., copper and zinc for brass plating).

In the work [100] two types of technological schemes for applying galvanic coating are presented:

1) the scheme with full immersion of samples (Fig. 14, *a*) is used to apply a coating to all surfaces of the metallized product and is characterized by a high metallization rate;

2) the gradual immersion process (Fig. 14, *b*) is designed for metallization of complex-shaped parts. It allows for maximum metallization of individual structural elements (grooves, cavities, etc.).

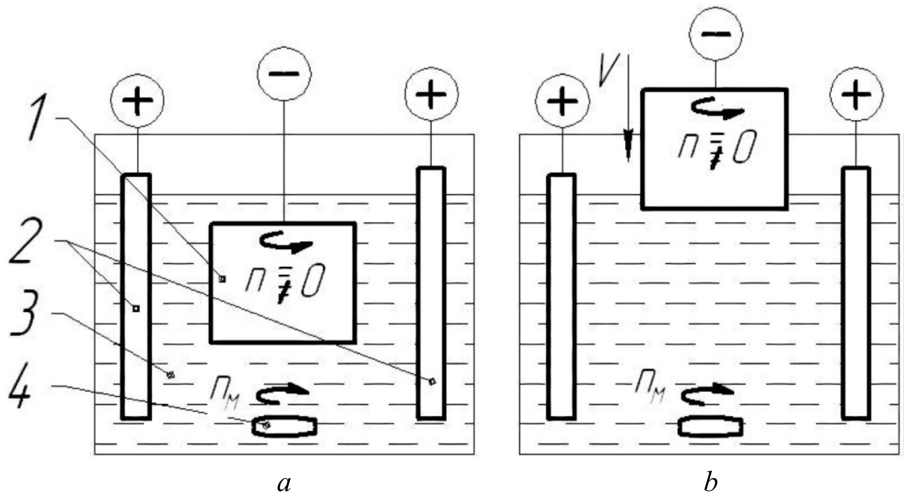


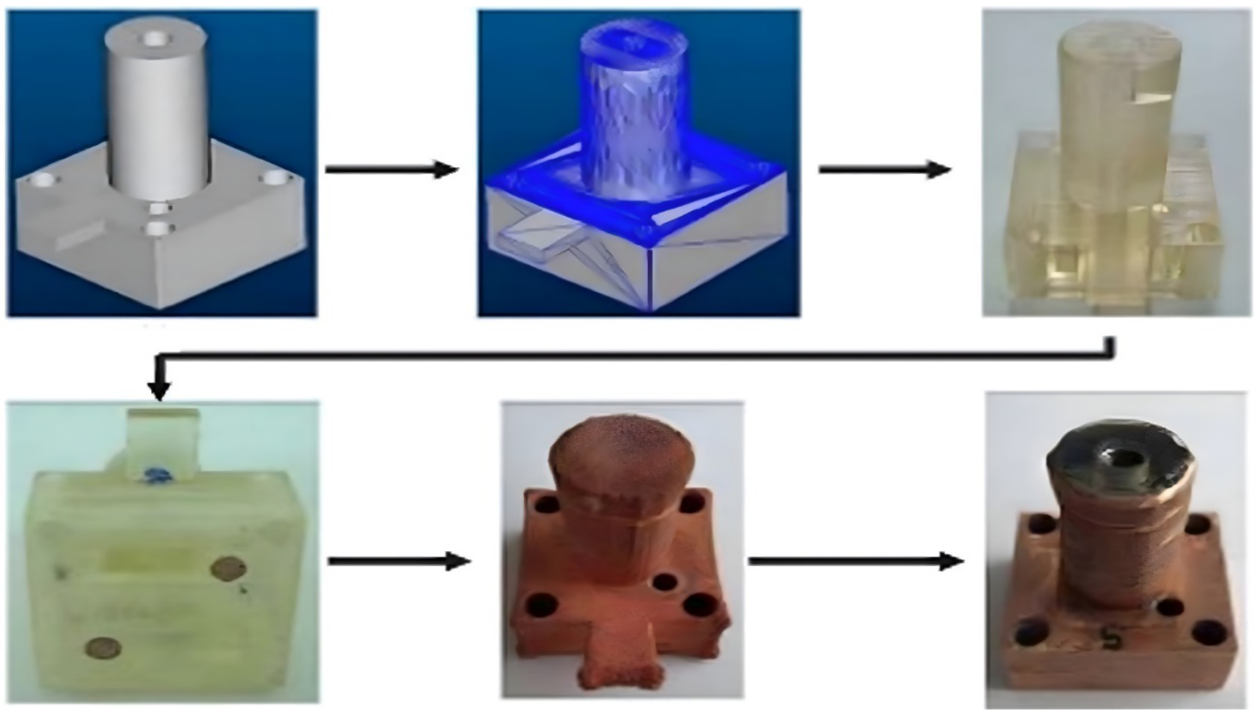
Fig. 14. Schematics of galvanic metallization for non-conductive substrates with pre-applied conductive coatings:

a) complete immersion; *b)* gradual immersion. 1 – sample; 2 – electrodes; 3 – electrolyte bath; 4 – magnetic stirrer [100]

To increase the productivity of the copper metallization process, it is recommended to perform additional rotation of the metallized product during the processing.

The use of methods for applying conductive coatings in the production of *TE* using rapid prototyping methods is presented in the work [70]. It is shown that electrolytic and galvanic methods are mainly used in the production of *TE*.

The technology for fabricating *TE*s using the *SLA* method from non-conductive polymeric materials with subsequent application of a conductive coating is presented in detail in the study [101]. A comparison was made of the output parameters of *EDM* using *TE*s made of photopolymer resin with an applied copper coating and solid copper *TE*s processed mechanically. The stages of *TE* fabrication using the *SLA* method are shown in Fig. 15. Based on the experiments conducted, the authors identified the possibility of using *a* *b* *c*



d *e* *f*

Fig. 15. Stages of tool-electrode creation by *SLA* method and subsequent coating [101]:

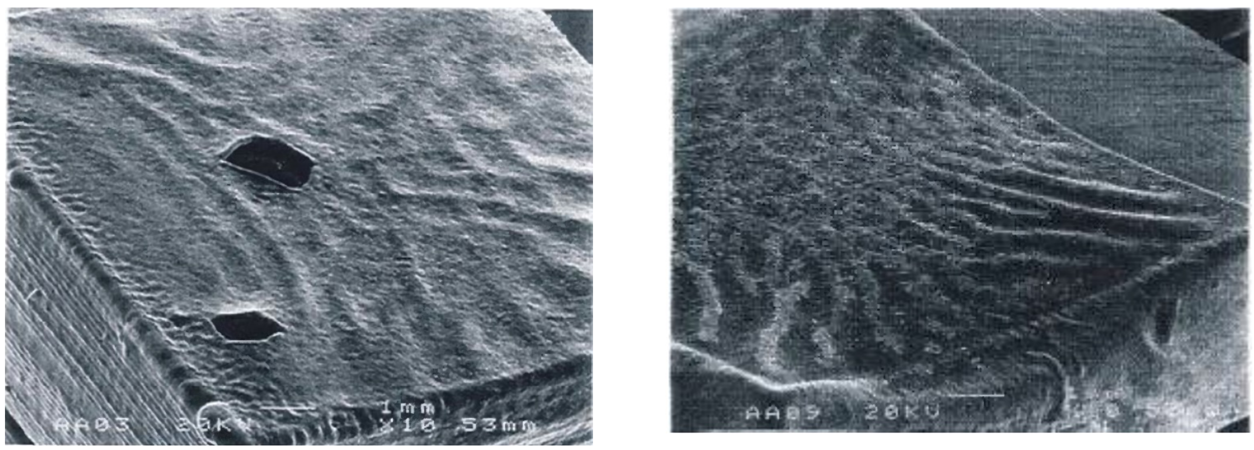
a–b) creation and preparation of 3D model; *c–d)* obtaining and preparing tool-electrode for metallization; *e)* coating; *f)* post-processing

polymer *TE*s with an applied copper coating. However, these *TE*s were characterized by low durability. This is due to the thinning of the conductive coating.

The widespread use of *TE*s produced by rapid prototyping methods is hampered by a number of shortcomings associated with the applied conductive coatings. The authors of a critical review study [102] clearly presented (Fig. 16) and described the defects of metallic *TE* coatings. It was shown that the majority of *TE* defects arise from uneven heat dissipation and insufficient coating thickness.

Electroforming and *SLA* technologies with subsequent application of a conductive coating are applicable for the production of *TE*s for *EDM*, but further research is needed to improve the thickness and quality of these coatings.

Based on the analysis of research into methods for manufacturing tool electrodes for *EDM*, a summary Table 2 has been compiled.



a *b*

Fig. 16. Defects of conductive coating: *a)* delaminations and ruptures; *b)* deformations [102]

Table 2

Methods for manufacturing tool electrodes

Method	Research	Advantages	Flaws
Traditional blade cutting methods (turning, milling, abrasive machining)	[11], [19], [62]	Wide processing capabilities. A wide range of equipment in mechanical engineering enterprises. Possibility of obtaining *TE*s with high roughness and accuracy indicators for finishing *EDM*	Difficulties in processing complex *TE*s. High costs for cutting tools and equipment. High level of equipment utilization. High wear of cutting tools during the production of TEs from materials with improved physical and mechanical properties
Powder metallurgy	[69], [70]	Wide range of *TE* materials. The ability to control the properties of the electrode by changing the composition of the material and sintering conditions. High performance	Difficulties in manufacturing complex-profile *TE*s. The complexity of manufacturing large-sized parts. Structural defects and inhomogeneity in the properties of the resulting product. High cost of equipment
Investment casting (*IC*)	[49], [63], [64], [65], [66], [67]	Possibility of obtaining complex-profile and thin-walled *TE*s. High level of adaptability of the method in pilot production conditions. Possibility of obtaining *TE*s with high roughness indices. High performance	Limited range of *TE* materials. High cost of equipment. Casting defects (pores, shrinkage cavities, cracks). High cost of equipment
Fused deposition method (*FDM*)	[70], [75], [76], [77], [78], [79], [80]	Possibility of obtaining complex-profile and thin-walled *TE*s. High level of adaptability of the method in pilot production conditions. Reduced mass and dimensional characteristics of the *TE*s. Low cost of equipment	Difficulty in manufacturing large-sized products. Low accuracy and roughness of *TE*s. Technological difficulties in metallization
Selective laser sintering (*SLS*)	[81], [82], [83], [84], [85], [86], [87], [88]	Possibility of obtaining complex-profile and thin-walled *TE*s. High level of adaptability of the method in pilot production conditions. Wide range of *TE* materials	Structural defects and heterogeneity of properties of the resulting product. High cost of equipment. Low accuracy and roughness of *TE*s
Stereolithography (*SLA*), electroforming	[10], [89], [90], [91], [92], [93], [94], [101], [102]	Possibility of obtaining complex-profile and thin-walled *TE*s. High level of adaptability of the method in pilot production conditions. Reduced mass and dimensional characteristics of the *TE*s. Low cost of equipment	Difficulty in manufacturing large-sized products. Technological difficulties in metallization. Low resource of *TE*s. Coating defects

Based on an analysis of research into tool electrode manufacturing methods for *EDM*, it can be concluded that the use of additive and other methods, as alternatives to traditional subtractive machining, will improve the competitiveness of modern mechanical engineering companies utilizing *EDM* technology in their production, by reducing the cost of manufactured products, decreasing *EDM* manufacturing time, and expanding the range of products that can be processed. However, there is a need for more thorough development of technological processes using alternative manufacturing methods and their implementation in a pilot production environment for *EDM*, taking into account the shortcomings and limitations of these methods.

Conclusions

This paper provides a review of research on methods for manufacturing tool electrodes for wire-cutting electrical discharge machining (*EDM*). Current trends in the development of tool electrode configurations are presented. Challenges in manufacturing complex-shaped tool electrodes using traditional methods are identified. It is established that among alternative methods for manufacturing tool electrodes, investment casting, powder metallurgy, and additive manufacturing are of greatest interest to modern scientists. Each method is shown to have advantages and disadvantages, confirmed by a number of studies. The analysis revealed several relevant areas for research.

Directions for future research

1. Topological optimization of tool electrodes to reduce their mass and dimensional characteristics, while maintaining strength and electrical discharge properties.
2. Investigating modern high-tech casting methods (die casting, centrifugal casting) for the manufacture of tool electrodes.
3. Expansion of the range of new powder materials with improved electrical discharge properties; optimization of processing parameters; and development of specialized equipment for obtaining complex-profile products in the manufacture of tool electrodes using powder metallurgy.
4. Optimization of *FDM* printing parameters for tool electrodes to improve the accuracy and roughness of the resulting tool electrodes.
5. Expansion of the range of *TPM* and *ECM* for *FDM* printing of tool electrodes.
6. Expansion of the range of new powder materials with improved electrical discharge properties to ensure the performance of tool electrodes obtained by the SLS method comparable to tool electrodes obtained by traditional methods.
7. Optimization of *SLS* printing parameters to reduce porosity and, consequently, wear of the tool electrode, as well as to improve the manufacturing accuracy.
8. Increasing the thickness and quality of coatings on tool electrodes obtained using rapid prototyping technologies to increase their service life by stabilizing heat dissipation and increasing strength and electrical discharge characteristics.

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Conflicts of Interest

The authors declare no conflict of interest.