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EDM electrode manufacture using rapid tooling: a review

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Abstract Electrical discharge machining (EDM) is a non-conventional process for the manufacture of complex or hard material parts that are difficult to machine by conventional machining processes. During EDM, the electrode shape is mirrored in the workpiece. As a result, problems are transferred on the electrode manufacturing process. Rapid tooling (RT) is a new technology which uses rapid prototyping (RP) models to reduce the time and cost of tool manufacture. The various methods of manufacturing RT electrodes, with respect to different materials and the incorporated supplementary processes, are classified in the present work. Recent international research work on RT electrodes is reviewed and the results on the performance of RT electrodes are tabulated.

Introduction

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes. It uses thermal energy to machine electrically conductive hard material parts regardless of their geometry. Many automotive and aerospace components, as well as moulds and dies are manufactured using ED machining. During EDM, there is no direct contact between the electrode and the workpiece. Thereupon, EDM eliminates the mechanical stresses arising during machining.

Electrical discharge machining is accomplished with a system comprising two major components: a machine tool and a power supply. The machine tool holds a shaped electrode, which advances into the workpiece and produces a shaped cavity. The power supply produces a high frequency series of electrical spark discharges between the electrode and the workpiece, which remove metal from the workpiece by thermal erosion or vaporization. A relatively soft graphite or metal electrode can easily machine hardened tool steels or tungsten carbide [1, 2].

There are several different types of machines and industrial applications that use the EDM process for high precision machining of metals with Die Sinking and Wire EDM being the two major EDM variants.

The most common performance measures for EDM (Fig. 1) are:

- material removal rate (MRR), measured in mm^3/min,
- tool wear ratio (TWR), measured as tool removal rate to workpiece removal rate (V_{elec}/V_{work}, %), and finally
- surface quality (SQ) of the eroded cavity, measured in μm, Ra.

Generally, depending on the MRR, EDM can be characterized as: roughing, semi-roughing, and finishing.

Because of the nature of the EDM process, optimization of the process parameters is required, in order to achieve the desirable performance specifications.

In addition, the surface finish, dimensional accuracy and geometry of the electrode, as well as the material properties, such as thermal conductivity, and wear resistance affect EDM performance measures, too.

The above factors often lead in the manufacturing of more than one separate electrode of a specific geometry,

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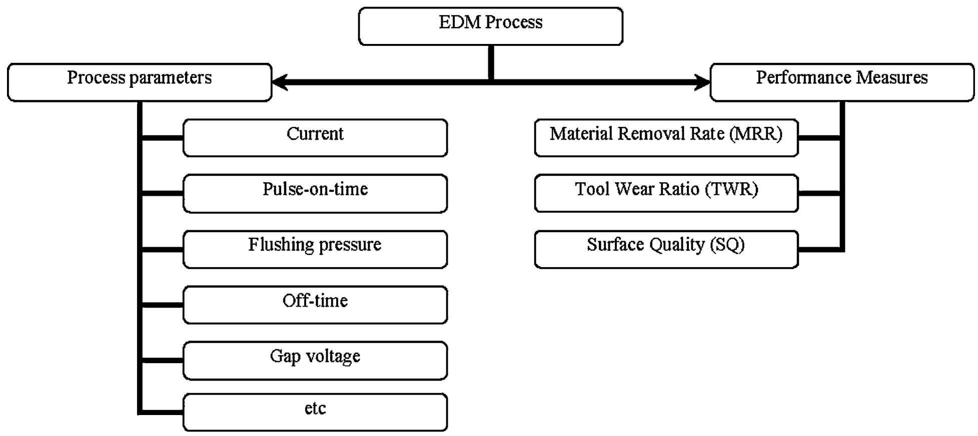

Fig. 1 Process parameters and performance measures of EDM process

which run sequentially, in order to manufacture dies and moulds. So, the cost of EDM tooling is increased by the complexity of the eroded cavity.

In order to reduce the product development time and the cost of tooling, layered manufacturing techniques were developed commonly known as rapid prototyping (RP) technology. This technology encompasses a group of manufacturing techniques, in which adding the material layer-by-layer generates the shape of the physical part. Many of these techniques are based on either the selective solidification of the liquid or the bonding of solid particles [3].

Rapid tooling (RT) is a progression from RP. It is the ability to build prototype tools directly, as opposed to prototype products directly from the CAD model, resulting in compressed time to market solutions.

The three broad classifications of the RT techniques are direct, indirect and patterns for casting [4]. The direct approaches use a RP-based process to manufacture tooling inserts directly, whereas the indirect methods use the RP process to generate a pattern from which the tooling inserts are made. Finally, rapid casting uses RP patterns to produce final metal parts.

In the present work, the various methods of producing RT electrodes are classified and a large number of the supplementary processes which integrate each route are reported. Classification is carried out according to the materials and the supplementary processes and a review of work reported on RT electrode manufacture is attempted. Emphasis is given on the RT electrode variations used, and the performance measures achieved. Finally, the results of recent research work are tabulated and the future prospects of RT electrodes are discussed.

Rapid prototyping constraints

Rapid prototyping techniques can be classified in three categories according to the initial state of the raw material used (liquid, powder, and solid). Regardless of the material state, all RP techniques use the following five main steps to produce prototypes, patterns or final parts: CAD model preparation, STL translation, slicing and production of technological program, additive manufacturing, and finally, post-processing of the prototype.

Performance measures of RP techniques such as dimensional accuracy, surface roughness, mechanical strength, build time, as well as material properties and post-processing, define the final use of the corresponding prototype (Fig. 2).

The most widespread of RP techniques is StereoLithography (SL), which produces accurate plastic prototypes

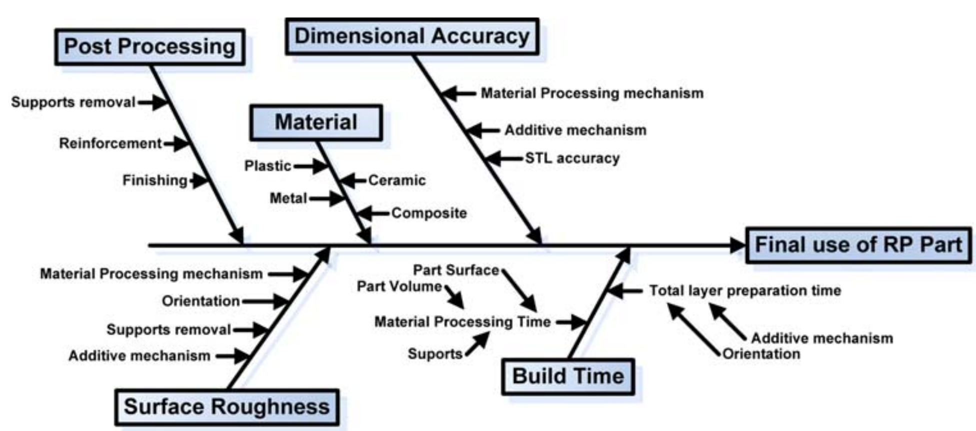

Fig. 2 Factors affect the final use of RP parts

from photocurable resins [5]. Laser Sintering (LS) is an alternative technique, which uses powders (metal, ceramic, plastic, or a combination) to produce parts. Both of them incorporate a laser beam to manufacture prototypes. In general, it is reported that SL gives better dimensional accuracy (±0.15 mm) [3, 5] and surface finish (between 1 and 5 μm, Ra on horizontal and vertical surfaces) while LS gives better mechanical strength of prototypes especially when it uses metal powders [6].

In addition to the above two techniques there are a number of RP techniques which can produce both prototypes and functional parts: Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), 3D Printing, Thermo Jet Printing (THJ), etc. Although these techniques are oriented on RP, many researchers attempted to manufacture electrodes, too [7–11].

EDM constraints

Electro discharge machining of metals makes use of electrical energy to remove material. Electrical energy is turned into thermal energy through a series of discrete electrical discharges occurring between the electrode and workpiece immersed in a dielectric fluid. The thermal energy generates a channel of plasma between the cathode and the anode at a temperature in the range of 8,000 to over 12,000 °C [12], initialising a substantial amount of heating and melting of material at the surface of each pole. When the pulsating direct current supply, occurring at the frequency rate of approximately 20–30 kHz is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the pole surfaces in the form of microscopic debris. The volume of material removed per discharge is typically in the range of 10^{-6} to 10^{-4} mm^3 and the MRR is usually between 2 and 400 mm^3/min depending on the specific application [1].

Due to the EDM mechanism, the part and the electrode are eroded at the same time. EDM performance is affected mostly by the process parameter values (on-time, current, off-time, etc.), and thus their values are set according to the desirable performance (see Fig. 1). Also, the material of the electrode must have suitable properties to decrease the electrode wear rate and increase the part MRR. Moreover, due to the high pressure and temperature present on the electrode during EDM machining, the electrode material must have acceptable mechanical strength and melting point to reduce tool wear and edge weakness. Furthermore, since the shaped electrode defines the area in which spark erosion will occur, the dimensional accuracy of the produced part depends on the dimensional accuracy and the surface texture of the electrode. Finally, shape details and recesses affect the electrode performance since they define the electric field in which machining takes place (Fig. 3).

Rapid tooling electrodes

Electrodes manufactured using RP techniques ought to be of high dimensional accuracy and appropriate surface roughness in order to fulfil EDM specifications. Thus, post-processing of RP parts for EDM applications (roughing, semi-roughing, and finishing) is necessary. It includes several stages according to the material electric properties (non-conductive, conductive, pattern for casting) and quality characteristics (dimensional accuracy, surface roughness).

Post-processing of non-conductive materials includes surface finishing, primary metallization to change the conductivity and secondary metallization to reinforce the final electrode properties. The above three sub-processes can be applied on a positive or a negative RP part (direct or indirect electrode). In a negative shape case, two more steps must be

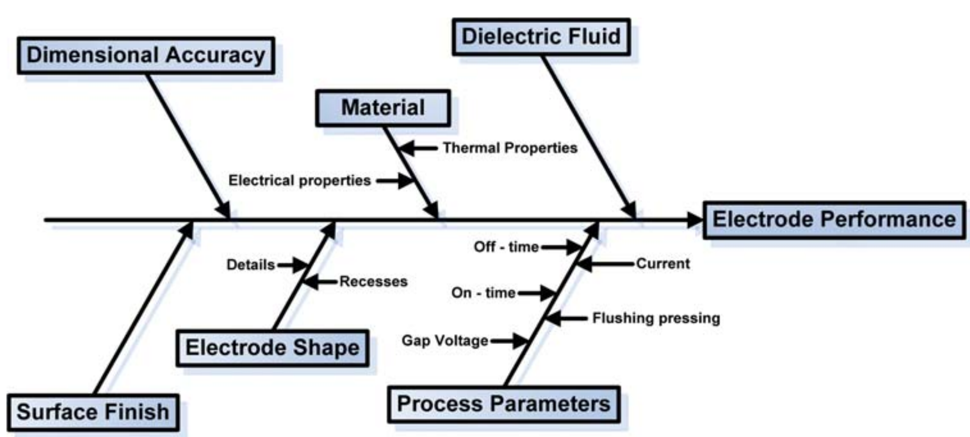

Fig. 3 Factors affect electrode performance

applied: Backfilling the metal shell cavity with an appropriate material, and RP pattern (mandrel) removal process.

Conductive materials such as metal powders, metal powder resins, and metal matrix ceramics (MMC) powders need special post-processing according to each RT process.

Metal parts made from RT cast patterns need finishing to improve SQ and eliminate the stair stepping phenomenon. Also, scaling of the STL file and modification on face small features is necessary [13]. Moreover, cast patterns need post-processing, too.

Figure 4 presents all the possible RT electrode manufacturing variations.

Electrodes of non-conductive materials

According to the literature, EDM electrode fabrication attempts, using RP prototypes or patterns, were made very early, in parallel to RP development [14–17]. However, due to the SLA domination in the field of RP techniques, SLA acrylate and epoxy patterns were originally used to produce EDM electrodes and the other techniques followed. Recently, all the possible roots are investigated and new ways of producing RT electrodes are under consideration.

Rapid EDM electrode manufacture of non-conductive prototypes or patterns is divided in two subcategories: Positive metal-coated parts (direct tooling), and negative metal-coated parts (indirect tooling). RP part metallization uses a positive or a negative RP prototype to manufacture an electrode. Metallization of parts is divided in two stages, each one of which uses many alternatives such as electroless plating, spray metal, electroforming, electroplating, sheet metal forming, etc.

First stage metallization applies a thin metal coat (10–50 μm thickness) to change the non-conductive part to conductive. This can be achieved by electroless plating,

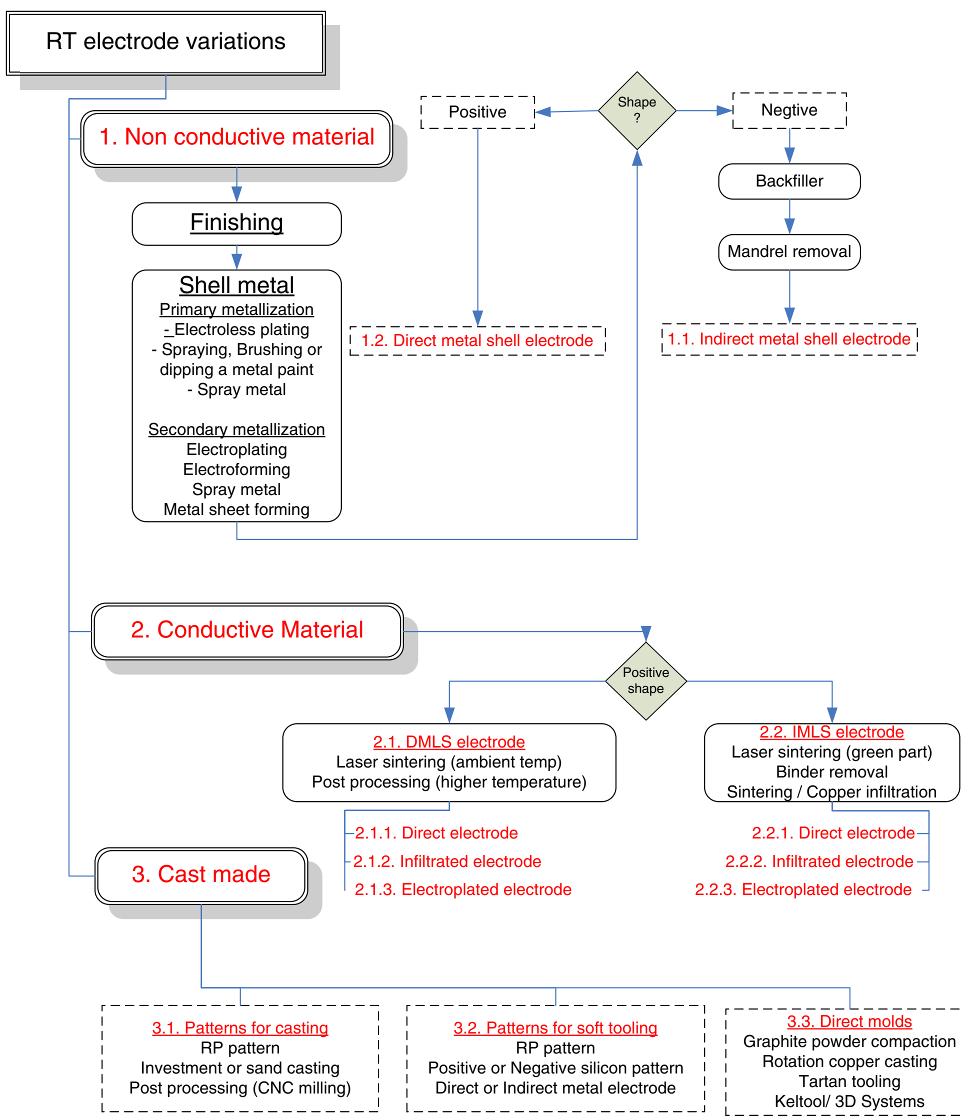

Fig. 4 Possible variations of EDM electrode manufacture using RT

brushing a metal paint, spraying a metal paint, dipping in metal paint, and direct metal spraying.

Electroless plating is used as a preliminary step in preparing plastic articles for conventional electroplating. After cleaning and etching, the plastic surface is immersed in solutions that react to precipitate a catalytic metal in situ. The plastic article, thus treated, can now be plated with nickel or copper by the electroless method to form a conductive surface, which can then be plated with other metals by the conventional electroplating method [18].

Applying a conductive paint is an alternative method for the manufacture of conductive plastic parts. The conductive metal coating is applied by spraying, dipping in metal paint, as well as by brushing or rolling a solution onto the substrate.

Second stage metallization applies a thicker substrate (more than 180 μm thick) to reinforce the electrode properties and performance. Electrode reinforcement can be achieved using electroplating, electroforming, metal spraying, or metal sheet forming.

Electroplating is the deposition of a metal coating onto an object by putting a negative charge onto the object and immersing it into a solution, which contains a salt of the metal to be deposited. The metal ions of the salt carry a positive charge and are attracted to the part. When they reach it, the negatively charged part provides the electrons to 'reduce' the positively charged ions to a metallic form [19].

Electroforming is a process for fabricating a metal part by electrodeposition in a plating bath over a base form or mandrel, which is subsequently removed. Build-up is achieved over all mandrel surfaces at an approximate deposition rate of 25 μm/h. Electroforming reproduces the form or mandrel exactly (about 1 μm), without the shrinkage and distortion associated with other metal forming techniques such as casting, stamping or drawing [20].

Metal spraying is the process of spraying molten metal onto a surface to form a coating. This is achieved by melting either pure or alloyed metals in a flame. The molten metal is then subjected to a blast of compressed air, which has the joint effect of creating tiny droplets of metal and projecting them toward the surface to be coated. The end result is a solid metal coating on the surface to be treated. The number of layers applied dictates the thickness of the coating [21].

If second metallization stage is applied on a negative pattern (mandrel), then two more stages are necessary to complete the electrode manufacturing process: mandrel removal, and back filling of the metal shell. Which one of the above two would be applied first is under consideration.

It is noted that the mandrel removal process affects the metal shell rigidity, while the back filling process distorts the metal shell due to the different thermal properties of the backfiller and metal shell materials. These problems become greater if a complex mandrel shape is used.

Very early [22–27] direct tooling of SL epoxy prototypes was used to produce metallized electrodes with a plastic (epoxy) core. A simple electrode shape (15 × 15 mm flat face) without details or recesses upon its face was used. The eroded material was a tool steel and the cut depth was 4 mm. Silver paint (10 μm) was used as primary metallization and a shell of electrodeposited copper (180 μm) as secondary metallization. The total processing time for electrodeposited coating was less than a working day. Parametric optimization, using the Taguchi method, of EDM for electroplated electrodes, was applied because of the unknown electric and thermal properties of metallized electrodes. After optimization, an MRR of about 3.7 mm^3/min and a surface roughness of about 1.6 μm (Ra) were achieved without damaging the electrode. These results could be considered as acceptable only for semi-roughing or finishing cutting. They inferred that, a shell of copper thicker than 180 μm is needed in order to use these electrodes for general applications. In this case, scaling of the STL model as well as a uniform shell thickness is required. They proposed as future work to investigate the electrodeposition of metal coatings; especially if it is applied on a complex geometry.

The heat distribution and the associated failure modes of the above electrodes were investigated by the same researchers [28, 29]. They concluded that the different leaner expansion between the epoxy core and the copper shell cause shear stresses between their interface and finally lead to electrode failure. Moreover, due to the substantial drop in the electrical conductivity of copper between ambient room temperature and the operating temperature range of EDM, they suggested further investigation with respect to its effect on heat generation and process efficiency. Also, they stressed the need to investigate the thermal behavior of complex SL electrodes too.

Moreover, attempts to improve electroplated electrode efficiency were made using copper pyrophosphate electrolyte instead of acid copper in the stage of secondary metallization of the electrode [30]. Although good pore closure properties were achieved in this way, the shear stresses between the epoxy core and the copper increased due to the operating temperature (55 °C) resulting in distortions of the electrode shell.

Dover et al. [26] attempted to use electrodeposition techniques to directly produce metal tools. They used a copper sulphate electrolyte system to produce EDM electrodes and a nickel sulphate electrolyte system to produce press tools. In order to limit the deposition to the required area they used high-speed selective jet electrodeposition. This forces the electrolyte through a small nozzle. With the anode upstream from the nozzle, the electrodeposit is limited to a small area on the cathode at the end of the nozzle. The nozzle is then moved in a vector path in a similar way to an SLA laser.

The assessment of RT copper shell electrode tolerance was investigated extensively using a SL7540 epoxy resin by Bournemouth University [31]. The shape of the part was complex with sloped surfaces, deep slots and details; a model which is difficult to be manufactured by CNC milling. They sprayed a silver paint and measured its average thickness using an eddy current sensor. The average thickness was about 3 μm. Then they electroplated the part for 37 h using a low current (1 A/100 cm^2). After that the part was drilled in several positions and the shell thickness was measured. They found big differences in the copper shell thickness depending on the position of measurement. The least deposition tended to occur in the inner cavities (about 20 μm), while the upper and outer faces had substantial copper deposition (about 180 μm). It was concluded that electroplated electrodes are unsuitable for industrial use due to the uneven copper shell thickness.

Dimensional accuracy issues of copper shell of electroplated electrodes were also investigated [32]. First it was noted that the accuracy of an electroplated electrode is a function of three factors: the accuracy of the RP model, the accuracy of the primary metallization, and the accuracy of the copper shell thickness. They focused on the accuracy of copper shell thickness and designed experiments to investigate its variation. They used as patterns CNC machined copper parts in order to avoid primary metallization. The shape of the model was a pad (80 mm × 100 mm) which had two half cylinders (12.5 mm in diameter with a perpendicular axis), and some other recesses and details on its face. Then, copper shell metallization was performed with an alkaline copper electrolyte at 45 °C during 25 h, at 1 A/dm^2 current. They did not use any method to improve the deposit homogeneity. The critical dimensions of the patterns were measured before and after electroforming using a 3-axis CNC machine. The average thickness of the copper deposit was found to be 0.25 mm but they observed large variations in the average thickness and its standard deviation depending on part characteristics. Finally, it was concluded that because of their lack of dimensional performances, electroplated electrodes were not satisfactory for industrial use.

Back filled EDM electrodes coming from electroforming of a negative RP model were produced by the previous researchers too [24, 30]. In this case, a SL model of the reverse form of the electrode was used. The electrode shape was a large convex dome ($R = 80$ mm, chord length $= 4$ mm) without any details or recesses upon its face. The eroded material was a tool steel and the cut depth was 8.7 mm. Silver paint (10 μm) was used as primary metallization and copper from an acid bath was used to produce a shell 2–3 mm thick. A copper shaft was set into the back of the shell using epoxy adhesive. Using the most efficient machine set-up determined by the Taguchi analysis with thin walled electroplated electrodes, they eroded an 8.7 mm deep cavity in 24 h. Considering that this time is unacceptable for ED machining, they changed the machine set up to typical roughing. Then having used the same electroformed electrode they managed to erode the same cavity in 39 min. The total processing time for the electroformed electrodes was about a working day depending on the electrode geometry. Although the back-filled electrodes gave better MRRs (about 50 mm^3/min) the difficulties on separating the shell from the epoxy negative body, as well as the stair stepping phenomenon of the SL models need to be overcome, especially for electrodes having curved geometry, recesses and details.

Copper shell electroformed electrodes were also fabricated to investigate their performance and viability [33]. The part, used as a pattern, was a square cavity (80 × 80 mm) with many delicate features on its face. These features included rectangular, triangular, hemispherical and conical protrusions and recesses. First, they fabricated a stereolithographic pattern and then used silicon RTV and vacuum casting (soft tooling) to produce flexible silicon cavities. Then they performed copper electroforming on the above cavities to produce a copper shell. Details of the first metallization stage of the silicon cavity, as well as the second metallization stage, and the separation method between the silicon cavity and the copper shell were not reported. The above shells were then preheated and back-filled with zinc to give the electrode the necessary mechanical strength. Then, experiments were conducted using pre-set machining conditions in order to study the electrode performance. Electric pulse duration ‘on’ and ‘off’ as well as peak current ‘IP’ were used as process variables. Hardened steel (H13 grade steel) was selected as the eroded material. A 5 mm deep cavity was eroded in each EDM experiment. As the main purpose of research was to study the wear properties of the electroformed electrodes they used each one of the two electroforms until it failed during the experimentation process. A CMM machine was used to measure electrode features before and after each EDM experiment. Distortion of the electrode features and unequal shell thickness according to depth of the cavity were inspected after EDM. The above researchers, having studied the experimental results, concluded that feature distortions were created due to incomplete filling of the backing material as well as unequal shell thickness created during copper shell electroforming and not during ED machining. Also, they concluded that rough machining conditions could deform the tool. Semi-roughing to finishing machining may be undertaken using these tools. In this case, it may be imperative to use more than one tool to perform a single operation.

Stereolithography and ThermoJet (THJ) mandrels were used to manufacture thin walled electroformed electrodes [11, 34]. The research goal was to manufacture RT electrodes quickly as well as to investigate electroforms and electroformed electrode performance. They concluded that not only SLA patterns but also THJ can be used as THJ gives much better build times than SLA. They designed experiments using both SLA epoxy and THJ wax models.

Firstly, they used eight SLA mandrels in order to measure the performance of electroforms as well as the performance of electroformed electrodes. These mandrels were manufactured on a SLA250/50 machine with a SL5170 material system. All mandrels had a tolerance between ±0.15 mm. The shape of mandrels was a cavity with a detail and a recess on its face. An airbrush was used to spray even amounts of silver paint on each model especially on recesses. The coating thickness was between 5 and 40 μm. Then they applied electroforming on mandrels. A different plating time was used for each mandrel in order to produce different shell thickness electroforms. The average shell thickness of the electroforms was between 0.4 and 3.0 mm. Copper sulphate electrolyte containing organic additives was used to minimise stress and allow a smooth deposition of copper. The operational current density was between 10 and 60 mA/cm^2. They used either polyurethane (PU368) mixed with fillite sand (4:1) or tin bismuth alloy as backfiller in order to manufacture electroformed electrodes. A suitable preheat of metal shell was used in order to eliminate the distortions. Finally, the mandrels were removed using boiling water. The performance of the electroforms was established by measuring the dimensional changes of eight electroforms after extraction from their respective SL master mandrel. They found that all dimensional changes were between ±0.15 mm. Then the performance was investigated using a ROBOFORM 31 EDM machine and five electroformed electrodes as tools. Erosion currents of between 12 and 6 A were used. The MRRs were between 5 and 50 mm^3/min and the surface roughness was set at a value of 1.62 μm. Two of the above electrodes failed at an early stage showing edge split on details. After EDM the electrodes were sectioned and the normalized percentage wear rate was measured. It was found to be between 0.02 and 0.18%. The normalized percentage wear rate is defined as the original electroform dimension divided by the post-sparking dimension and then multiplied by the dimensional difference between the two. Finally, the remaining three electroformed electrodes were sectioned and the actual shell thickness in recesses and details was measured. A different shell thickness was found, as it was expected, at recesses and details. A smaller thickness of plating was measured on details, which is one of the most important factors of premature wear of electrodes (edge split phenomenon).

Secondly, having realized that a considerable time is spent to produce SL mandrels the above researchers tried to manufacture electroformed electrodes using THJ mandrels. They designed the same project and found similar results. The dimensional changes of eight electroforms in comparison to their respective THJ mandrels were between −0.15 and 0.25 mm, and the normalized percentage wear rate of four sparked electroforms were between 0.01 and 0.07%.

Finally, the above researchers designed experiments to investigate the relationship between shell thickness and depth of erosion. The shape of the mandrels was a cavity with three scaled recesses inside. They used wax mandrels divided in two categories. The shape was the same for each category on the X and Y dimensions and different on the Z dimension. The cavity depths were 15 mm and 7 mm for each category. The plating time of the mandrels was between 24 and 86 h. The average shell thickness of the electroforms was between 0.5 and 1.67 mm. The electroformed electrodes used to erode hard steel cavities and examined in situ every 15 min until all three blocks failed or until the pre-set level of erosion had been reached. After that, electrodes were metallurgically micro-sectioned in order to examine both the copper distribution and the deposit structure. It was concluded that an electroplating time between 40 and 80 h was needed to produce electroforms of an average shell thickness of 0.6 mm, which was critical to erode a 6 mm tool steel cavity. Even then small, deep cavities would not erode to a significant depth. They proposed sequential machining using automatically loaded electroformed electrodes as a solution to erode cavities with more than 6 mm in depth. Also, a current density of up to or over 60 mA/cm^2 could be used in the electroplating procedure to produce appropriate electroforms in a period of about 25 h, but this would result in the reduction of the metal distribution.

Investigations of copper electroformed electrodes were also performed by NJIT [35]. They used an SL epoxy as a sacrificial pattern. Electroless plating was used as primary metallization. The mandrel was a cavity 60 × 60 mm (11.4 mm deep) with an 'H' shape inside. The SL cavities were polished to a surface finish of 1.22 μm. After polishing the dimensions of the 'H' shaped mandrel were measured. Then two electrodes were made with a shell thickness of 1 mm and 2 mm copper each. Both mandrels were electroformed at room temperature to avoid thermal expansion. Then, the mandrels were removed applying heat (incineration). Finally, the copper shell was backed with a tin–lead alloy and the dimensions of the electrode were measured and compared with the dimensions of polished mandrels. A deviation between 0.013 and 0.091 mm for the 0.1 mm electroformed electrode and a deviation between 0.01 and 0.074 mm for the 0.2 mm electroformed electrode were found, respectively. They noted that this route of making electrodes does not require a uniform thickness of the plated copper compared to the electroplating process. Thermal deformations caused by burning out the SL masters and backfilling the electroformed metal shell with molten metal are identified as the major sources of inaccuracy. The thickness of the electroformed copper shell must be optimized in order to minimize the manufacturing cost. Also, the same researchers produced electrodes by electrodeposition of RP masters [36, 37]. They suggested non-uniform thickness of the plated copper as one of the most important disadvantages of this process.

Spraying metal on a positive or a negative SL pattern has also been investigated [15, 27]. It was found to have inferior characteristics to electroplated and electroformed electrodes. Bocking et al. [30] concluded that the advantage of using electroplating compared with metal spraying is that the coating has a greater density and tends to be much stronger. In addition, when providing adequate control of the process, the coating is not subject to the same magnitudes of internal stress as metal-sprayed coatings. Furthermore, problems may appear, such as a variable thickness of the metal particularly within deep cavities, recesses, bores, and blind holes.

Table 1 summarizes the results of RT electrode performance, which were produced using non-conductive materials.

Electrodes of conductive materials

Current research and development activities of rapid EDM electrode manufacture using conductive materials, is mainly concentrated on increasing the performance of RP techniques as well as expanding the materials available and the performance of RT electrodes.

Selective laser sintering (SLS) is the most efficient RP technique for producing metal parts. SLS uses compound metal and binder powders for direct manufacturing of metal parts. It is divided in two categories: Indirect metal laser sintering (IMLS), and direct metal laser sintering (DMLS). IMLS uses a plastic binder material, while DMLS uses a metal binder. Furthermore, DMLS can be divided in solid state sintering (SSS) and liquid phase sintering (LPS). A classification of the binding mechanisms in SLS and SL melting as well as all the commercial SLS metal powder systems was presented in Ref. [6].

The IMLS process uses a polymer-coated stainless steel powder infiltrated with bronze. A Laser beam fuses, or sinters the powder to form the prototype, called the 'green' part. This is characterized by increased porosity, which is the main reason for post-processing in a furnace. The binder material is decomposed and the steel powder sinters to form small necks between particles. The part will now be 60% dense and is called 'brown'. At this stage it is possible to conduct some finishing work on the part because it is easier to be done now than after the next stage of bronze infiltration. In this stage the 'brown' part is placed in a crucible with a measured amount of bronze placed next to it. This crucible is then placed in the furnace for the second cycle. During this second cycle, the bronze melts and by capillary action wicks into the insert to form an infiltrated, now fully dense, part [38].

On the other hand, DMLS allows manufacturers to produce prototype and production tools directly from powder metals without the use of a polymer binder. The material used is a special alloy mixture comprised mainly of bronze and nickel. The material can be sintered without pre-heating and exhibits negligible net shrinkage during the sintering process. An expansion of the powder volume is caused by a built up of pores and mixed crystal formations. This expansion leads to the partial compensation of the sinter loss that has occurred. A sturdy but porous sintered compact is formed.

The present research is mainly concentrated on extending the range of the materials available and the performance of the electrodes.

Direct metal laser sintering to fabricate metal sintered electrodes was first investigated by the University of Chemnitz [39]. The DLMS electrode shape was simple (cylindrical) and the metal powder system consisted of Ni, bronze and a few percent of copper phoshite. Copper phoshite interacted with bronze as low melting material. Then a second thermal sintering followed. Optimization of the process showed that the laser power, laser speed, sintering strategy and hatch distance had the biggest impact on the porosity of the sintered electrodes. Then, the electrodes were infiltrated by a silver-containing brazing metal as well as of a tin-containing plumb bob in order to improve rapid electrode performance. The MRR achieved with these electrodes was up to 12.5 mm^3/min and exhibited higher TWRs (see Table 2) than conventional electrodes and unacceptable surface roughness of the eroded material. Finally, it was suggested that the performance of the electrodes as well as the dimensional accuracy and surface roughness might be further improved for manufacturing use.

Direct metal laser sintering was also used by the National University of Singapore (NUS) [40] to fabricate metal electrodes. The metal powder system consisted of copper, tin, nickel and phosphorus. Four electrodes were fabricated and tested in EDM experiments. These were a solid copper electrode; a copper electroplated DMLS electrode; an electroless copper plated DMLS electrode; and an untreated DMLS electrode. All the electrodes had a simple prism geometry. Then the electrodes were tested on roughing, semi-roughing and finishing EDM. It was concluded that untreated DMLS electrodes can be considered for both roughing and semi-roughing when minimal material

Table 1 Summarized results of RT electrodes using non-conductive materials

	Arthur et al. [24]	Booking et al. [30]	Yarlagadda et al. [33]	Yang and Leu [35]	Rennie et al. [11]	Dilma et al. [31]	Gillot et al. [32]
RP process	SLA/Epoxy	SLA/Epoxy	SLA/Epoxy	SLA/Epoxy	SLA/Epoxy, THJ/Wax	SLA/epoxy SL7540	CNC/copper
Conductivity	No	No	No	No	No	No	Yes
STL post-processing	Scale STL	No	No	No	No	No	–
Prototype post-processing	Finishing	Finishing	Finishing	Finishing	Finishing	Finishing	–
Rapid electrode variation	Metal shell electrode	Back filled electrode	Soft tooling Back filled electrode	Back filled electrode	Back filled electrode	Metal shell electrode	Metal shell electrode
Shape complexity	Simple (15 mm × 15 mm flat face)	Large convex dome (R = 80 mm, Chord length = 4 mm)	Square cavity (inner dimensions 80 mm × 80 mm) with small features	60 mm × 60 mm cavity with an 'H' shape inside	Pocket shape with recesses cavities and protrusion	Complex part with sloped surfaces, deep slots and details (base: 200 mm × 200 mm)	80 mm × 100 mm complicate part
Metallization (first stage)	Conductive paint (10 μm)	Conductive paint (10 μm)	It is not reported	Electroless plating	Sprayed conductive paint (5–40 μm)	Spraying conductive silver paint (electrodag 1415M)	No
Final metallization (shell)	Copper electroplating (180 μm)	Copper electroforming (2–3 mm)	Copper electroforming	Copper electroforming (1–2 mm)	Copper electroforming (0.4–3 mm)	Copper electroplating	Copper electroplating (0.25 mm)
Electrolyte solution	Copper sulphate	Copper sulphate, copper pyrophosphate	It is not reported	Copper sulphate with additives	Copper sulphate containing organic additives	$CuSO_4$ Low current electrodeposition time: 37 h	Alcaline copper (45 °C)
Core/backfill material	Epoxy	Epoxy, copper shaft	Zink	Tin–lead alloy	(i) Alchemix PU368 polyurethane with fillite sand (4:1), (ii) tin bismuth alloy	Epoxy	Copper
Separation method	–	Thermal	It is not reported	Burned	Boiling water	–	–
EDM optimization	Taguchi design	Yes	Yes	No	No	–	–
Eroded material	Tool steel (4 mm cut depth)	Tool steel (8.7 mm cut depth)	H13 grade tool steel (5 mm cut depth)	Hard steel (10 mm cut depth)	Hard steel	–	–
Material removal rate (mm^3/min)	Low (up to 3.7, copper ∼4.4)	Similar of solid copper (∼50)	Prefixed EDM parameters	Similar of solid copper	Similar of solid copper (5–50)	Copper shell thickness is investigated. Uneven copper deposition in inner cavities (20–180 μm)	Copper shell thickness is investigated. Uneven copper deposition in inner cavities
Tool wear ratio (%) (V_{elec}/V_{work})	Up to 100%, 0% after optimization	Up to 100%, 0% after optimization, Higher wear of solid copper		It is not reported	0.002–0.18% (normalized percentage wear rate)		
Eroded cavity surface roughness (μm, Ra)	Up to 1.6, depends on prototype roughness	Up to 1.6, depends on prototype roughness		It is not reported (electrode = 1.27 μm)	Up to 1.6, Depends on prototype roughness		
Total time	Model (1/2), Coating (1/2)	Model (1), Coating (1)	Several days	It is not reported	24 h		About 1 day

Table 2 Summarized results of RT electrodes using conductive materials

	Durr et al. [39]			Tay and Haider [40]			Dilma et al. [31]	Meena and Nagahanumaiah [41]	Stucker et al. [42–45]	Zaw et al. [46]	Li et al. [47]	Zhao et al. [48]
Metal powder system	Ni-bronze and Cu phosphate			Copper, tin, nickel, and phosphorus			Cu, Ni, Sn, P Direct metal 50	Cu, Ni, Sn, P Direct metal 50	ZrB_2–Cu 1700 & ZrB_2–Cu ART	ZrB_2–Cu TiSi-Cu	TiC–CuW with Ni TiC–Cu	Steel, polyester and phosphate
Binding material	Bronze			Bronze			Bronze	Bronze	Coating polymer	Copper	CuW, CuW with Ni	Polyester
Sintering process	DMLS (EOSINT-M160)			DMLS (EOSINT-M)			DMLS (EOSINT-M)	DMLS (EOSINT-M250)	SLS or cold-pressing	Cold compaction in 350bar	Cold compaction	SLS/RAP-I
Prototype post-processing	Thermal second phase sintering			Thermal second phase sintering. Remove foreign contaminants, sand blasted			Thermal second phase sintering	Thermal second phase sintering	Polymer debind (1,700 °C)	Furnace (i) 350 °C (40 min), (ii) 1,000°C (1 h), (iii) 1,070–1,300 °C (1 h)	Furnace (i) 350 °C (60 min), (ii) 1,250 °C (1 h)	(i) 260–300 °C, polyester decomposed, (ii) high temperature sintering (760–1,040 °C)
Infiltration	No	Solder molten (tin) from a plumb bob infiltration	Silver-containing brazing metal infiltration	No	Copper electroplated	Electrolessly copper	Copper electroplated	No	Copper (1,700°C)	No	No	(iii) Copper infiltration (1,120 °C)
EDM variation	Die sinking (hydrocarbon dielectric)			Die sinking			Electroplated copper shell thickness is investigated	Die sinking	Die sinking	Die sinking	Die sinking	Die sinking
Eroded material	Steel C45, steel X210Cr12			Hardened tool steel XW 5				EN 24 steel	Steel 2.5 mm cut depth	Tool steel	Tool steel	Steel 45
Electrode shape complexity	Simple (cylindrical)			Simple rectangular prism geometry			Complex part with sloped surfaces, deep slots and details (base: 200 × 200 mm)	Rectangular (face area: 60 mm^2)	Brick (9.5 × 9.5 × 6.35 mm^3) post-processed by grinding and polishing	Disks (Diam: 25 mm)	Disks (Diam: 10 mm Height: 10 mm)	Simple (Diam: 20 mm Height: 10 mm)
Material removal rate (mm^3/min)	0.5–2.2	6–12.5	6–12.5	0.23–3.98	2.09–60.3	0.39–9.3	Uneven copper deposition in inner cavities (10–180 µm). Unsuitable for EDM	Optimized according to process parameters. Further investigation is needed.	Up to 21	ZrB_2–Cu had lower performance measures than conventional electrodes	Good performance close to that of commercial electrodes for finishing conditions	Finish machining parameters
Tool wear ratio (%) V_{elec}/V_{work}	45–100	60–320	25–70	75–103	1.82–10.36	19.05–103.98			0.2–10			5–15%
Eroded cavity surface roughness (µm, Ra)	Unacceptable			8.8–11.2	2.2–12.8	6.8–10.7			5–25 Depending to on-time parameter			Up to 3 µm

removal is required and that electroless copper plated electrodes were appropriate when dimensional accuracy and moderate material removal are essential. Performances of these electrodes can be seen on Table 2.

The University of Bournemouth investigated the shell thickness of copper shell electroplated DLMS electrodes [31]. The shape of the part was complex with sloped surfaces, deep slots and details; a model which is difficult to be manufactured by CNC milling. A current density of about 1 A/100 cm^2 during electroplating was used. Big differences in the copper shell thickness were found depending on the position of measurement. The least deposition tended to occur in the inner cavities (about 10 μm), while the upper and outer faces had a copper deposition between 40 and 180 μm. It was concluded that electroplated DLMS electrodes were unsuitable for industrial use due to the uneven copper shell thickness.

Finally, Taguchi fractional factorial design experiments were applied in order to investigate the effects of EDM parameters on the DMLS electrode performance [41]. These researchers used an EOSINT M 250 machine and an EOS DirectMetal 50 metal powder system. It was found that, as with conventional electrodes, the current is the main parameter. They also noticed that the electrode wear at the front edge was higher than the side wear due to the porosity of the DMLS electrodes.

Indirect metal laser sintering was also used to manufacture simple shaped electrodes [42]. Due to the problematic expansion of the metal powders during SLS the research concentrated on the development of new materials with advanced electrical and mechanical strength properties. Thus, MMC is the field in which research has been conducted until now.

The feasibility of manufacturing sintered EDM electrodes using MMC was investigated first by the University of Texas [42–45, 49, 50]. They first created a powder mixture that contains ZrB_2 and a polymer and then used cold-pressing for simple (cubed) electrodes as well as SLS for more complex electrodes to sinter the mixture into the desired shape. The part was then placed into a high-temperature (1,973 K), controlled-atmosphere furnace to debind the polymer binder and sinter the ZrB_2 particles. Parallel, they infiltrated the porous ZrB_2 part with copper. After sintering, the furnace cooled to ambient temperature to give a ZrB_2–Cu electrode with continues phases of ZrB_2 and Cu matrices.

These researchers designed and performed experiments to investigate ZrB_2–Cu electrode performance measures according to EDM process parameters (on-time, current, off-time). In their research they used cubed electrodes made by cold-pressing. The electrodes were finished before EDM. Eroded material was a tool steel. They achieved workpiece material removal rates (WRR) of about 21 mm^3/min and TWRs between 0.2 and 10% (Table 2). They pointed that the WRR was increased according to current. Also, after a critical on-time value (180 μs), the WRR stayed constant or it was slightly decreased. After changing the off-time value from 100 to 240 μs, and keeping constant the on-tine to 560 μs, they found that the WRR was increased. Also, they showed that at low on-times the tool material removal rate (TRR) and WRR are increased with increasing on-time, but TRR is much lower than WRR. At high on-times WRR reaches a maximum value while TRR decreases with increasing on-time. Finally, the surface roughness of workpieces was between 5 and 25 μm (Rq, root-mean-square value).

Research has been also conducted by NUS [46]. They investigated the performances of electrodes fabricated from compounds of ZrB_2 and TiSi with Cu at various compositions. They used cold compaction at 350 bar instead of the SLS/RP technique to sinter the above powders to 25 mm diameter disks. Then, they sintered the green parts in a furnace. The temperature was first ramped to 350 °C for degassing and then raised to about 1,000 °C and finally to a higher, sintering, temperature. This temperature varied between 1,070 and 1,300 °C depending on the material system composition. They concluded that the performance of Cu–TiSi electrodes was poorer than that of Cu–ZrB_2 electrodes. It was also found that Cu–ZrB_2 electrodes had a wear rate between that of Cu and graphite but the MRR was low and the relative electrode wear rate was higher than that of conventional electrodes. This was due to the poor bonding between Cu and ZrB_2 which occurred due to the low sintering temperature (1,300 °C).

Li et al. [47], also present a study on the effect of titanium carbide TiC on the performance of sintered copper-based materials, as EDM electrodes. They showed that electrodes with 15% TiC show the highest relative density, lowest electrical resistivity, and good EDM performance (Table 2).

Zhao et al. [48] used a SLS/RAP-I system, developed by NUAA, China, to fabricate direct RT electrodes. A multicomponent powder system which consisted of steel, polyester and phosphate was used. Laser sintering was used to fabricate the green part. Then post-treatment was applied in three steps. Firstly, low temperature sintering was applied (260–300 °C) to decompose the polyester. Secondly, high temperature sintering was applied (760–1,040 °C) and a rigid inorganic compound was produced from the phosphate-steel reaction. Finally, copper infiltration was applied at 1,120 °C to improve quality. After fabrication of three electrodes with different component proportions of sintered material, they conducted experiments to study the influence of the process parameters on electrode performance and to optimize the process. They concluded that these electrodes were suitable for finishing cuts in EDM.

Results of direct tooling EDM electrode manufacture are summarized in Table 2.

Electrodes made using cast methods

Cast made electrodes originating from RP patterns (positive or negative) can be divided in tree subcategories:

- Cast metal electrodes come from RP Patterns. Investment casting and sand casting are the two most popular processes for producing metal parts [51]. In order to use these processes for electrode production, STL file modifications and CNC finish machining of metal cast parts is needed to produce dimensionally accurate electrodes with an acceptable SQ. Finish-machining techniques for rapidly manufactured parts were developed [13, 52], which will be incorporated on cast metal parts.
- Patterns for metallized electrodes come from soft or hard tooling. This will be necessary if more than one pattern is needed [33].
- Direct electrodes come from hard tooling. Many methods have been tested, such as graphite powder compaction [14–16, 53], rotational copper casting and tartan tooling [24], and the 3D Keltool method. The most promising method of these is the latter, which produces compact metal parts replicating the RP pattern.

Conclusions and future prospects

Since EDM is one of the most extensively used non-conventional material removal processes and RP technology has become well documented, many attempts have been made to manufacture RT electrodes for roughing, semi-roughing and finishing EDM applications.

The unlimited theoretical possibilities that RP techniques have in producing complex parts, promotes them as the ideal alternative for low cost EDM electrode manufacture rather than multi axis CNC milling which currently exists.

The additive mechanism which is used of all RP techniques not only gives the possibility of manufacture free form parts but also, affects part quality. For example, in sloped surfaces which exhibit the ‘stair stepping’ phenomenon; an effect caused basically by layer thickness of the material layers.

Also, the support removal process affects part quality and therefore demands very experienced personnel. Having experience in the manufacturing of three RP systems (LOM 1015, FDM 1600, and SLA 250) the authors strongly believe that each RP system is suitable for different applications [54]. For example, big parts are better to be built by LOM, accurate delicate parts with SLA and test parts with FDM machines. None of these parts has yet the appropriate accuracy to be used as copper shell electrodes for EDM without finishing or polishing.

Although industrial fabrication of RT electrodes is until now inappropriate many perspectives will develop if the RP systems become more accurate and the ‘stair stepping’ phenomenon is eliminated.

Researchers improve the dimensional accuracy of RP systems by suggesting new materials with better properties as well as optimizing the process parameters of the RP systems available. Also, the ‘stair stepping’ phenomenon would be eliminated if a hybrid technology, which will combine RP with milling processes, is developed in the future.

Thus, in experimental conditions RT electrodes tested on EDM show hope that the obstacles can be overcome.

The most promising RP process, SLA, is used first to produce RT electrodes in different variations by several researchers, due to its high dimensional accuracy of the epoxy materials and the excellent surface roughness in vertical and flat up surfaces. Thus, having built simple parts, for example cubes, RT electrodes can be manufactured.

For hard surface epoxy parts, after post-curing and finishing, electroless plating seems to be the most convenient process to change the conductivity of plastic articles. It gives the most uniform coating especially in recesses and on details. Then electroforming or electroplating is proposed for hard metal shell metallization. Although many metal choices exist, copper is recommended for epoxy metal shell electrodes due to its good electrical properties. Moreover, shell metallization must be applied at ambient temperature to avoid distortions of the copper shell due to the epoxy having a higher shrinkage factor. Also, due to the uniform deposition of copper during electroplating or electroforming, the current must have low strain values (about 10 mA/cm^2) and the solution must have appropriate organic additives.

If all the above is taken into account, an average electroplated copper shell of 0.6 mm will be produced in about 24 h, which is capable of eroding a 6 mm deep cavity in a typical tool steel part without being damaged.

However, the dimensional accuracy of electroplated electrodes is decreased due to the uneven copper shell thickness. The electroplated shell thickness is affected by the electric field which is also affected by the shape of the part. Thus, a strictly controlled electrodeposition method must be used for an even shell thickness; a problem that has not been solved so far. Even if the STL model is scaled to compensate for the shell thickness, a certain dimensional inaccuracy occurs because of the uneven shell thickness. This problem is more evident on edges as well as on recesses of copper shell electrodes. This is the main reason for the premature damage of RT electrodes.

On the other hand, the electroformed electrode method, theoretically gives a better dimensional accuracy due to the fact that no shell thickness compensation is needed. But in this process, disengagement between the mandrel and the metal shell is a further problem. For epoxy materials, thermal disengagement could distort the copper shell, thus it is to be applied after the back filling process. This causes problems too. The most common procedure is to preheat the copper shell and use a low melting alloy material as backfiller, and then to remove the mandrel by heating. Even if the above is taken into account, the uneven copper shell thickness causes premature wear to this kind of electrode too.

In addition to the above problems, the 'stair stepping' problem must be considered for complex electrodes.

Experimental investigations have shown that under strict conditions simple shaped metal shell electrodes can compared to conventional electrodes. Also, electroformed electrodes seem to have better performance on rough EDM and electroplated ones on finishing applications.

The potential of using other RP techniques to produce RT electrodes has been investigated too. Even though some of them give faster prototypes than SLA, the dimensional accuracy and surface roughness of these processes are not appropriate for EDM. Nevertheless, if these processes are chosen to be used for RT electrode fabrication, some modifications of the above-mentioned procedures must be made. For example in this case it is better to apply the first metallization by brushing or spraying.

Soft tooling of RP patterns could also be an alternative to produce more than one similar electrode for sequential EDM.

On the other hand, direct metal electrodes which are produced by RP techniques [3, 55–59] demonstrate the same disadvantages; poor surface roughness and dimensional accuracy.

DLMS and IMLS seem to give the most accurate prototypes. Thus, these techniques were tested for metal tools and final parts.

Simple shaped electrodes were fabricated and tested in several EDM applications such as roughing, semi-roughing and finishing.

The results have been disappointing until now for industrial production of RT electrodes. But investigations of MMC selective laser sintering electrodes were promising indicating that if the RP part final quality is improved then MMC electrodes will give a better EDM performance. DMLS also promises better material powder systems that will overcome porosity and uncontrolled shrinkage issues.

Until now infiltration or electroplating of copper on RP metal parts has not given the appropriate quality for industrial use either.

Finally, cast made electrodes do not meet the specifications of EDM yet. The development of an appropriate S/W, which will manipulate an STL file of an RP pattern for EDM use, is needed. This S/W will incorporate features like scaling, cutting, joining, etc., of the STL part taking into account the EDM specifications. Also, it must produce the technological program for CNC finishing automatically. These programs will be useful for other RT electrode methods too.

Although variations of RT electrodes were developed and research was performed extensively, until now the results of RT electrode performance have shown that they do not meet the desirable standards for use as an alternative to conventional CNC or high speed machining (HSM) milling electrodes.

RP techniques need improvement and redesign as manufacturing processes rather than as prototyping processes. Also, the mechanical properties of RP available materials must be investigated more extensively and the material systems must be expanded.

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