RAPID ELECTRODE MANUFACTURE USING STEREOLITHOGRAPHY MODELS - A STATE OF THE ART

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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. In order to reduce the product development time and the cost of tooling, layered manufacturing techniques were developed commonly known as rapid prototyping technology. This technology encompasses a group of manufacturing techniques, in which adding the material layer-by-layer generates the shape of the physical part. Rapid tooling is a progression from rapid prototyping. 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 various methods of manufacturing RT electrodes, using Stereolithography (SL) models, with respect to supplementary processes, are classified in the present work. Recent international research work is reviewed and the results on the performance of RT electrodes are tabulated.

Keywords: EDM, stereolithography, rapid tooling, rapid prototyping

1. Introduction

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.

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 (figure 1) are: material removal rate (MRR, mm^3/min), tool wear ratio (TWR, Vol^{elec}/Vol^{work} (%)), and surface quality of the eroded cavity (μm Ra).

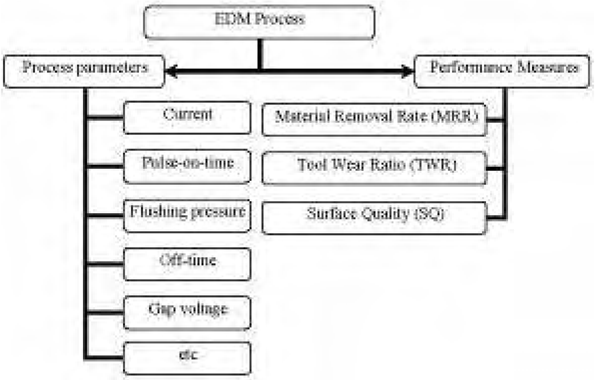

Figure 1. Process parameters and performance measures of EDM process

Generally, depending on the material removal rate, EDM can be characterized as: roughing, semi-roughing, and finishing. Because of the material removal mechanism, 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 thermal and electrical properties, 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, 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.

Rapid tooling (RT) is a progression from rapid prototyping. 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 rapid tooling techniques are direct, indirect and patterns for casting [3]. The direct approaches use a rapid prototyping 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 rapid tooling electrodes by stereolithography (SL) process are classified and a large number of the supplementary processes which integrate each route are reported. 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.

2. Rapid prototyping techniques

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 (figure 2).

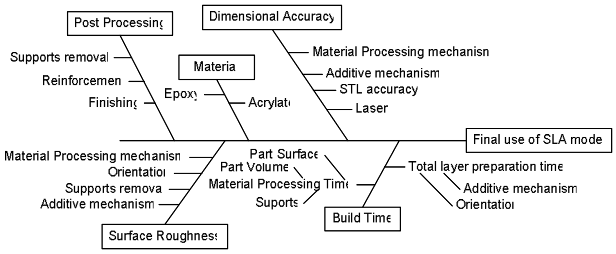

Figure 2. Factors affect the final use of SLA model

The most widespread of RP techniques is StereoLithography (SL), which produces accurate plastic prototypes (±0.15mm) from photocurable resins (figure 3).

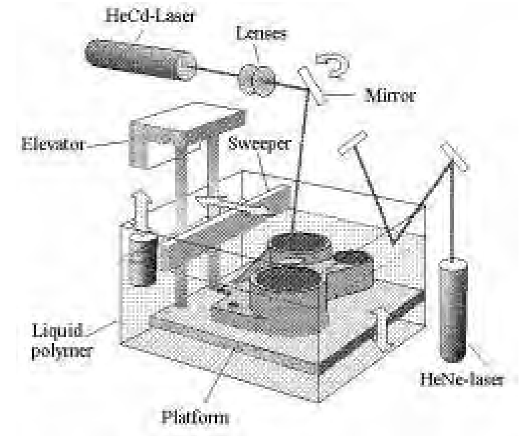

Figure 3. SLA process [2]

In addition to the SLA technique there are a number of RP techniques which can produce both prototypes and functional parts: Selective Laser Sintering, Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), 3D Printing, Thermo Jet Printing (THJ), etc. Although these techniques are oriented on rapid prototyping and manufacturing, many researchers attempted to manufacture electrodes, too [3-7, 23, 32, 33].

3. Electro discharge machining

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 8000 to over 12000°C [1], 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} – 10^{-4} mm^3 and the material removal rate (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 (figure 1). Also, the material of the electrode must have suitable properties to decrease the tool material removal rate and increase the workpiece material removal rate. 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, as well as the dielectric fluid, affect the electrode performance since they define the electric field in which machining takes place (figure 4).

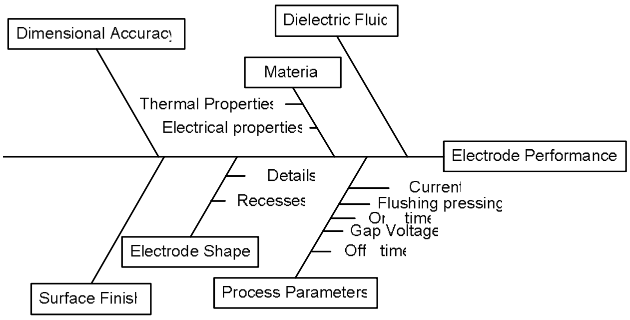

Figure 4. Factors affect electrode performance

4. Rapid tooling electrodes

Electrodes manufactured using SLA technique ought to be of high dimensional accuracy and appropriate surface roughness in order to fulfil EDMing specifications. Thus, post processing of rapid prototyping parts for EDM applications is necessary.

It includes several stages according to the material properties and quality characteristics (dimensional accuracy, surface roughness).

Post processing of non conductive SLA models 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 applied: Backfilling the metal shell cavity with an appropriate material, and RP pattern (mandrel) removal process.

Metal parts made from SLA cast patterns need finishing to improve surface quality and eliminate the stair stepping phenomenon. Also, scaling of the STL file and modification on face small features is necessary [28]. Moreover, cast patterns need post processing, too.

Figure 5 presents all the possible RT electrode manufacturing variations using SLA process.

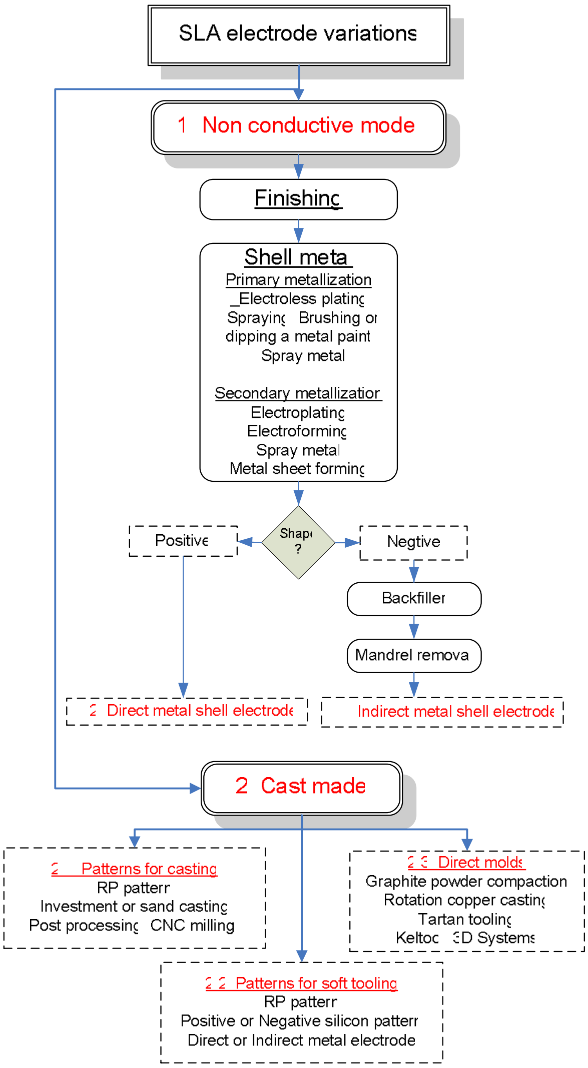

Figure 5. Possible variations of EDM electrode manufacture using SLA process

4.1. Electrodes of non-conductive models

Rapid EDM electrode manufacture of non conductive prototypes or patterns is divided in two subcategories: direct metal shell electrode (positive shape, figure 6), and indirect metal shell electrode (negative shape, figure 7).

Metallization of parts is divided in primary and secondary.

Primary metallization applies a thin metal coat (10-50 μm thickness) to change the non-conductive part to conductive. This can be achieved by electrodes plating, brushing a metal paint, spraying a metal paint, dipping in a metal paint, or direct metal spraying.

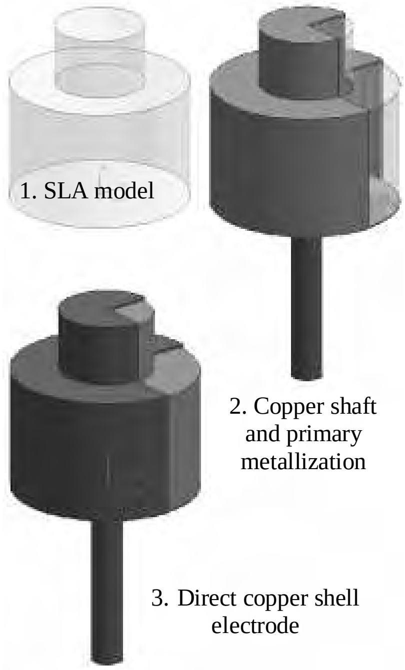

Figure 6. Direct copper shell electrode

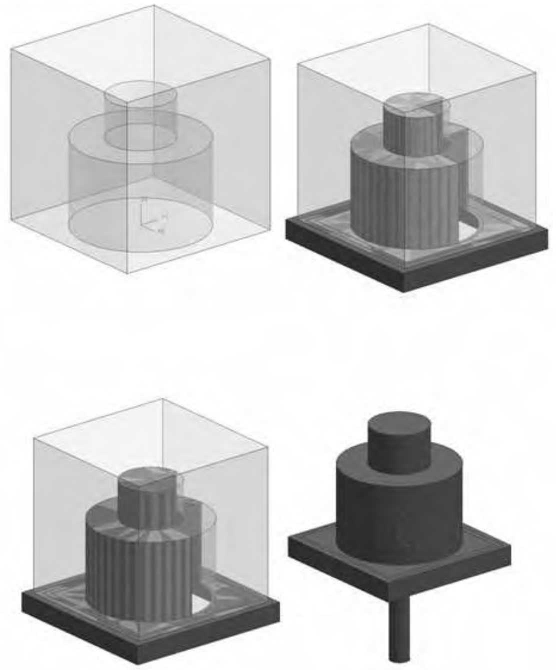

Figure 7. Indirect copper shell electrode

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.

Secondary 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.

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 25μm per hour. Electroforming reproduces the form or mandrel exactly (about 1μm), without the shrinkage and distortion associated with other metal forming techniques such as casting, stamping or drawing.

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 towards 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.

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.

Mandrel removal can be achieved by melting, burning out, or heat softening. Also, backfiller material can be a low melting alloy with good electrical and thermal conductivity.

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.

4.2. Electrodes made using cast methods

Cast made electrodes originating from SLA 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. 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 surface quality. Finish-machining techniques for rapidly manufactured parts were developed [28, 29], which will be incorporated on cast metal parts.

Patterns for metalized electrodes come from soft or hard tooling. This will be necessary if more than one pattern is needed [21].

Direct electrodes come from hard tooling. Many methods have been tested, such as graphite powder compaction [8-10, 30], rotational copper casting and tartan tooling [14], and the 3D Keltool method. The most promising method of these is the latter, which produces compact metal parts replicating the RP pattern.

4.3. Literature review

According to the literature, EDM electrode fabrication attempts, using SLA prototypes or patterns, were made very early, in parallel to RP development [8-11].

Very early [12-17] direct tooling of SL epoxy prototypes were 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 4mm. 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 electrical and thermal conductivity 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 (table 1). 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 [18, 19]. 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 behaviour 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 [20]. 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 and others [16] attempted to use Electro-deposition 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 Electro-deposit 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 SLA 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 [27]. 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^oC during 25 h, at 1 A/dm^2 current. They didn't 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 [14, 20]. In this case, a Stereolithography 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. The total processing time for the electroformed electrodes was about a working day depending on the electrode geometry. Although the backfilled electrodes gave better material removal rates (about $50mm^3/min$) 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 [21]. 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 backfilled 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-time' and 'off-time' 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 [22, 23]. 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.

Table 1. Performance measures of metal shell electrodes

	Arthur et al, 1996 [14]	Booking et al, 1997 [20]	Yarlagadda et al, 1999 [21]	Yang & Leu, 1999 [24]	Rennie et al, 2001 [23]	Dilma et al, 2004 [31]	Gillot et al, 2005 [27]
Model material	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy/SL7540	CNC/copper
Shape	Positive	Negative	Negative/ Soft tooling	Negative	Negative	Positive	Positive
Shape complexity	Simple	Simple	Medium	‘H’ shape	Complex part	Complex part	Complex part
XY dimensions (mm)	15X15	R=80 Chord length=4	80X80	60X60	-	200X200	80X100
Primary metallization	Conductive paint (10µm)	Conductive paint (10µm)	It is not reported	Electroless plating	Spraying paint (5-40µm)	Spraying silver paint (3-10µm)	No
Secondary metallization	Electroplating Cu (180µm)	Electroforming Cu (2-3mm)	Electroforming	Electroforming Cu (1 - 2mm)	Electroforming Cu (0.4 - 3mm)	Electroplating Cu (10-180µm)	Electroplating Cu (0.25mm)
Electrolyte solution	CuSO4	CuSO4, Cu pyrophosphate	CuSO4	CuSO4 with additives	CuSO4 with additives	CuSO4	alcaline copper (45 oC)
Core/ backfill material	Epoxy	Epoxy, copper shaft	Zink	Tin-lead alloy	i) Polyurethane with Fillite sand, ii) tin bismuth alloy	Epoxy	Copper
Separation method	-	Thermal	It is not reported	Burned	Boiling water	-	-
Eroded material	Tool steel	Tool steel	H13 grade tool steel	Hard steel	Hard steel	-	-
Cut depth (mm)	4	8.7	5	10	up to 15	-	-
MRR (mm^3/min)	up to 3.7	Up to 50	prefixed EDM parameters	It is not investigated	5-50	Copper shell thickness is investigated. Uneven copper deposition in inner cavities. (20-180µm)	Copper shell thickness is investigated. Uneven copper deposition in inner cavities
TWR (%) (V^{elec}/V^{work})	0-100	0-100			0.002-0.18% (Normalized percentage WR)		
Workpiece Roughness (µm, Ra)	Up to 1.6,	up to 1.6,			up to 1.6,		
Total time	model (1/2), Coating(1/2)	model (1), Coating (1)	Several days	It is not reported	24h		24h

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 air brush was used to spray even amounts of silver paint on each model especially on recesses. The coating thickness was between 5 to 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 electroforms was between 0.4-3.0 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 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. The material removal rates 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 EDMing 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, figure 8).

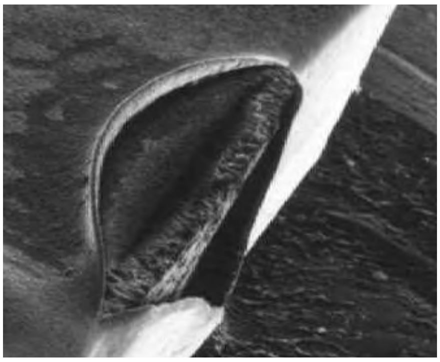

Figure 8. Edge split failure [19]

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 7mm for each category. The plating time of the mandrels was between 24 h and 86 h. The average shell thickness of the electroforms was between 0.5 mm 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 40h and 80h was needed to produce electroforms of an average shell thickness of 0.6 mm, which was critical to erode a 6mm 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 [24]. 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 [25, 26]. 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 [9, 17]. It was found to have inferior characteristics to electroplated and electroformed electrodes. Bocking et al [20] 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.

5. Conclusions and future prospects

Since EDM is one of the most extensively used non-conventional material removal processes and SLA technique has become well documented, many attempts have been made to manufacture copper electroplated or electroformed electrodes for roughing, semi-roughing and finishing EDM applications.

Researchers improve the dimensional accuracy of SLA systems by suggesting new materials with better properties as well as optimizing the process parameters of the SLA systems available.

On the other hand, the additive mechanism which is used of SLA technique 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. Additionally, the supports removal process affects part surface quality too.

For hard surface epoxy parts, after supports removal, post curing and finishing, electrodes 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 $10mA/cm^2$) and the solution must have appropriate organic additives. Otherwise, porosity of copper substrate may be caused (porosity and peppering failure modes, [19]).

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

However, the dimensional accuracy of the 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 (edge split failure during sparking [19], figure 8).

Also, the different thermal conductivity, electrical resistance, and thermal expansion coefficient of the resin and the copper affect the electrode performance (delamination, rupture, and distortion failure modes [19]).

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.

Experimental investigations have shown that under strict conditions simple shaped metal shell electrodes can compared to conventional electrodes (table 1).

Also, electroformed electrodes seem to have better performance on rough EDMing and electroplated ones on finishing applications.

Soft tooling of RP patterns could also be an alternative to produce more than one similar electrode for sequential EDMing [21].

Finally, cast made metal electrodes do not meet the specifications of EDMing 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 EDMing specifications. Also, it must produce the technological program for CNC finishing automatically. These programs will be useful for other RT electrode methods too.

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