WEAR & FAILURE MECHANISMS FOR SL EDM ELECTRODES

Alan Arthur*, Phill Dickens*, Chris Bocking, Richard Cobb***

*Department of Manufacturing Engineering & Operations Management,
The University of Nottingham, UK
**GEC-Marconi Materials Technology, Hirst Division, UK

ABSTRACT

The principle of Electro-Discharge Machining (EDM) electrode manufacture using rapid prototyped StereoLithography (SL) models has been proposed and discussed in previous published material by the authors [1,2,3,4]. Applying a thin electrodeposited coating of copper to SL models has provided a direct route from model to tool cavity. A number of current factors present limitations to the application of these electrodes. This paper outlines and addresses the factors affecting electrode quality and performance. Premature failure of SL electrodes is attributed to a number of wear and failure mechanisms which are being investigated at The University of Nottingham. An overview of experimental and theoretical work is presented.

1. INTRODUCTION & BACKGROUND

The recent emergence of Rapid Prototyping (RP) techniques has provided a route to faster product modelling. A number of commercial process routes from models through to tooling are currently being developed. The integration of RP with established downstream tooling techniques is essential to the continued expansion of the RP application base. This paper focuses on the manufacture of production tooling for injection moulding using RP models. The use of thin coated models as EDM electrodes is discussed. It is intended that the methodology of process optimization being undertaken with SL models can be applied to EDM electrodes manufactured by alternative RP technologies. The potential for application of RP to EDM electrode production has been discussed in previous published material by the authors [1,2,3,4], and it is sufficient to provide only a broad outline here.

The increase in demand for small tools for plastics and rubber component production over the past ten years is likely to continue. This has applied pressure on tooling manufacturers to reduce lead times and costs. EDM is a process widely used in the manufacture of the mould cavities for plastics and rubber. The EDM work typically accounts for 25%-40% of overall production time. A large proportion of the EDM time is consumed by the manufacture of electrodes [5]. The application of RP to electrode manufacture could provide an opportunity to move from product verification to tooling with significant reductions in time and cost. A number of possible routes to RP electrodes have been proposed [3], and classified as 'direct' or 'indirect'. Direct production is the use of RP models as electrodes, whilst indirect routes use RP cavities (or masters) as an intermediate step to electrode manufacture.

To date the various techniques applied to the transformation of RP models to electrodes have not provided a realistic alternative to conventionally machined electrodes. At the University of Nottingham thin electroplated copper coatings have been applied to metallized StereoLithography (SL) models and these have been used as finishing electrodes. The functions of roughing and finishing electrodes for EDM die sinking are fundamentally different. The roughing electrode is an approximation of the geometry required in the cavity, with respect to size and detail. The primary function of this electrode is the bulk removal of material from the workpiece. However, the closer this electrode is to the profile of the required cavity the less work is needed to be done by the finishing electrode. The function of the finishing electrode is to provide a cleaning cut which generates the final profile and detail of the tool cavity. To satisfy their specific functions the roughing and finishing electrodes are manufactured to different specifications.

The finishing electrode is not used to remove substantial volumes of workpiece material but must maintain its geometry through low tool wear. The surface finish of the electrode must be as smooth as possible to reduce the necessity for post processing of the tool surface. It is clear from experimental trials that the SL electrodes are currently unsuitable for mass material removal; where high amperage applied during EDM generates high surface temperatures at the electrode which cannot be dissipated effectively through the SL substrate. This results in premature failure of the electrode. An appropriate thickness for the copper coating has been determined, which will sustain EDM finishing cuts using an optimized machine set-up [4]. Simple electrode profiles have been used to erode cavity depths up to 16mm (Figure 1) far in excess of that usually required of a finishing cut, i.e. up to 1mm. The low Material Removal Rate (MRR) makes the use of the coated electrodes for depths of several millimetres uneconomic with respect to machining efficiency.

The methodology for producing SL coated finishing electrodes is detailed in earlier work [2,3,4] and it is appropriate to provide only a summary of the processing steps here:-

i) Production of SL model in SL5170 epoxy resin, using ACES™ build @ 0.15mm layers
ii) Application of high conductivity silver paint (10μm thickness)
iii) Electrodeposition of copper from acid copper sulphate bath solution (175μm thickness)

2. COPPER COATING SL MODELS

2.1 Sizing of SL models - surface offsetting

Deposition of copper onto SL models causes oversizing, which can compromise geometric accuracy. It is necessary to determine the proposed thickness of deposition and undersize the SL model accordingly. Electrodeposition generates a non-uniform coating, favouring particular features. This variability can be controlled to a degree but it is impossible to completely eradicate the problem.

The requirement for a mean copper deposit of 175μm has been determined through experimental work, to achieve EDM performance. The external surfaces of the CAD and SL model must have a negative offset applied to accept this deposit.

2.2 Controlling copper deposition

The performance of plated EDM SL electrodes is dependant on the accuracy and quality of the applied plating. The uniformity of an electrodeposit over the surface of a plated model will depend in part on the way in which the current density varies from point to point over the surface (primary current distribution). Also the type of solution and operating variables contribute to variability (secondary current distribution or Macro Throwing Power - MTP). Control of plating determines the accuracy of the electrode and its EDM performance. The factors affecting current distribution and MTP are; Geometry, Electrical/Electrochemical, Chance factors.

Geometric considerations relate to the size as well as the shape of the model. Electrical/Electrochemical control concerns the state of the electrolyte and the model. Chance factors are somewhat more difficult to control relating to the condition of the surface of the model, the necessity for pretreatment, and variability during the plating process.

2.3 Achieving coating quality

Simple model geometries used to date have presented few problems of material distribution, however, work is now progressing to more complex surface profiles requiring measures to be taken with respect to copper deposition. A number of techniques are currently commercially used to improve metal distribution on the model during plating :-

- Screens - Screens are physical shielding elements which are used to selectively blind areas of the model thus reducing copper deposition in those areas.
- Robbers - These are additional conductive elements, suitably placed adjacent to regions of the electrode attracting a greater thickness, that "rob" a greater proportion of the current and minimise thickness variations.
- Conforming anodes - Instead of using a simple geometry anode (source) a unit conforming to the profile of the model can be produced. Unfortunately this can be expensive and is unlikely to be practical for one-off prototype plating.
- Anode focusing - This technique employs screening positioned close to the model, focusing the fields through onto the model where required.
- Bi-polar electrodes - These are conducting elements that do not comprise part of the electrical circuit but nevertheless, when suitably placed in recesses or cavities where deposit thicknesses will be low, generate additional plating fields in these regions, again improving the metal distribution.

These techniques are further enhanced by considering size and position of the model relative to the anode and the size and shape of the plating bath, which all affect the polarisation field. Periodic reverse and pulsing are methods of varying the deposition rate to prevent preferential build up. Periodic reverse allows for the removal of excess deposits, whilst pulsing can generate a better quality of deposit through on-off current switching. Further information on current and metal distribution can be found in the literature but a good introduction will be found in reference [6].

To overcome problems associated with material deposition the above techniques are being considered for plating complex SL models. In addition other bath plating solutions are being tested with respect to coating properties and deposition.

3. OBSERVATIONS ON SL ELECTRODE WEAR & FAILURE

3.1 Electrode wear characteristics in EDM

Wear measurement of EDM electrodes is commonly described as Tool Wear Ratio (TWR) which is a volumetric calculation of material removed from the electrode relative to material removed from the workpiece. This TWR is an important comparator but does not identify the variability of electrode wear with respect to geometry. An understanding of the elements or features on an electrode which are subjected to a greater intensity of wear is of fundamental importance to their accuracy and performance. Using SL electrodes, it is important to provide a controlled deposit of copper allowing for sacrificial wear.

The volumetric wear of SL electrodes was measured for a number of tests with different thicknesses of copper coating. The thickness of coating had no apparent influence on the volumetric wear of the electrodes (Figure 2). For erosion of a 4mm cavity the average TWR was calculated as 0.6%. The performance of solid copper under identical EDM conditions was 0.5%. Electrodeposited copper is likely to contain some inclusions or contamination, and plating solutions are often modified with levelling and brightening agents. It is likely that these impurities effect the properties and efficiency of the copper. The difference in wear between deposited and stock copper appear to reflect this.

3.2 Classification of electrode failure

Electrode failure can be expressed as wear or catastrophic. Wear failure describes the loss of geometry of the electrode due to sacrificial material removal. This wear compromises the geometric definition of the electrode outside of its specified tolerance. Catastrophic failure occurs as damage to the electrode which renders it dysfunctional through rupture or distortion.

3.3 Electrode wear failure

As discussed in section 3.1 the general wear characteristics of a SL electrode are similar to a machined solid copper electrode. Currently SL electrodes are being tested for use in finishing cuts which generally will require a cut depth of less than 0.5mm. A shallow cut such as this does not introduce substantial wear at the electrode and therefore wear is not likely to cause failure, unless the copper layer is very thin at the outset. With improved plating techniques and EDM process optimization it may be possible to improve machining efficiency to use them as semi-roughing or roughing electrodes, and therefore apply these SL electrodes to deeper cuts. At that point wear is likely to be a more important factor.

3.4 Catastrophic failure

Catastrophic failure of SL electrodes manifests itself in a number of ways. All damaged electrodes appear to have failed due to overheating. Failure can be classified by the apparent damage. The following definitions are proposed:-

- Edge failure - Here the external edge or corner of an electrode receives a high concentration of spark discharges during EDM causing overheating and results in the copper layer splitting (Figure 3).
- Peppering - This effect is believed to be caused by inclusions or contamination of the copper deposit, which is are highlighted by the EDM process. The defect appears as multiple penetrations of the copper layer (Figure 4). More recent work has highlighted a possible problem with porosity introduced during the plating process, which the acid copper sulphate solution has a tendency to close up (Figure 5). This porosity may form the nucleus for peppering failure.
- Delamination - Delamination is seen as the rippling of the copper layer where it has delaminated from the SL substrate. Adhesion between them two is dependant on the physical bond with the metallizing interface. Differential thermal expansion of SL and copper, and the lack of bonding between materials is the most likely cause of this failure. Where an area of copper is bounded by edges which constrain free movement/expansion, the heat concentration results in a blistering of the copper (Figure 6).
- Rupture - Perhaps the most common damage to be found to date is the rupture of the copper layer (Figure 7). This failure was seen with all early tests using SL electrodes. Having performed a detailed optimization programme of tests with EDM this mode of failure has been virtually eradicated. The use of high amperage in EDM is the primary factor influencing this rupture, causing a spark discharge of an intensity too great for the copper layer to sustain. The excessive heat generated at the discharge explodes the coating where the thermal energy cannot be dissipated efficiently. The inability of the thin copper coating to transmit the spark energy is and will probably remain the single biggest obstacle to high material removal with these electrodes.
- Distortion - The build up of thermal energy in the electrode during EDM is in part due to the insulating properties of the SL substrate. SL resin reaches its glass transition temperature (Tg) around 60°C, above which the material softens. Where the SL model is coated with a relatively thin copper veneer this can result in distortion of the SL electrode. Once this begins to occur there is little support afforded to the copper veneer, and over a short time the composite electrode distorts (Figure 8).

The effects described above may combine to cause ultimate failure of the electrode. A more detailed understanding of their causes is required, to extend the life of the electrodes and their machining efficiency.

4. HEAT TRANSFER IN SL ELECTRODES

The influence of electrode coating thickness on the machining performance has been examined. Using electrodes of thicknesses in the range 100µm to 300µm the MRR performance was measured, applying an optimized machine set-up (refer to section 5.2).

Tests show electrodes with copper coating thickness of 150µm susceptible to failure. The behaviour and control of the EDM removal mechanism is not finite and there is inevitably some variability in electrode performance at any given coating thickness. Some electrodes with 150µm copper thickness were successfully used to erode the 4mm cavity depth without sustaining damage. However, the likelihood of test failure can be avoided by using coatings of thickness exceeding 175μm. Performance with respect to MRR for electrodes with copper between 175μm and 250μm does not appear to vary significantly. MRR for these thicknesses is typically 3.85mm^3/min (Figure 9). The performance of solid copper tablet electrodes under the same conditions as the above tests generate a MRR of 4.40mm^3/min. It is reasonable to expect the performance of the coated SL electrodes to approach that of the solid copper as layers of progressively greater thickness are tested. This relationship is being investigated with coatings of greater than 300μm thickness.

The effect of coating thickness on MRR and failure is believed to be a function of the efficiency of heat or energy dissipation from the electrode front face, at the spark gap.

4.1 Differential linear expansion at the electrode

The work of Hague [7] established the thermal expansion characteristics of SL5170 resin. Plotting the data for SL5170 against copper an accelerating deviation is seen between the two materials with increase in temperature (Figure 10). Using copper coated SL electrodes inefficient heat dissipation induces stresses at the material interface, where the mechanical bond is subject to shear forces as the copper restricts the free expansion of the SL substrate. This results in delamination, thinning or tearing of the copper.

4.2 Heat dissipation

At the electrode

The ability of an SL electrode to absorb or dissipate energy during EDM is directly related to thickness of the conductive coating. Figure 11 shows the calculation of 'theoretical thermal conductivity' of test tablets. Composite coatings of 10μm Silver with 100μm, 150μm, and 200μm copper are plotted for energy absorbtion against temperature in the range 20°C to 140°C. The rate of theoretical energy absorbtion (Watts) increases with greater copper thickness. The actual thermal conditions at the electrode coating during EDM are being investigated. Using thermal labels it has been established that electrode temperatures during EDM do not exceed 100°C, applying an optimized machining set-up described below. This measurement has been taken at the interface of SL substrate and metallizing layer, by countersinking thermal labels into the SL model viewable through the back of the model face.

In the dielectric

The dielectric used in EDM is multi-functional its primary tasks being the clearing of the spark gap, and suppressing/containing the spark by forming an enclosed channel between electrode and workpiece which collapses as the spark is absorbed. The secondary function of the dielectric is the dissipation of thermal energy from the machined surface. The dielectric acts as a heat sink for both the electrode and workpiece, transferring high heat intensity from the spark gap to the circulating dielectric. This function is of less importance during EDM with solid machined electrodes but is a crucial factor when using SL models as excess heat is seen as the main cause of failure at the electrode. The dielectric flow is used to best effect by incorporating direct flushing at the spark gap during electrode 'off' times. This is referred to as pulse flushing from a point source. In this way the debris can be ejected and heat removed in the most efficient manner.

At the tool/workpiece

The heat generated at the tool surface is dissipated both into its body and into the dielectric. the workpiece is generally metallic and solid, fixed to the EDM machining table. This system ensures efficient thermal conduction, provided sufficient dielectric flow and low ambient tank temperature are maintained. Using electroplated SL electrodes the MRR is low and therefore the heat emissions do cause excessive temperature gradients. Temperatures measured during EDM at the workpiece do not differ substantially from the dielectric.

5. ENHANCING SL ELECTRODE PERFORMANCE

The key to exploiting the full potential of SL electrodes is a double edged sword, requiring optimization and balance of electrode and process. The quality and physical properties of the electrode must be matched effectively with the applied machining conditions. Application of the electrodes demands a detailed understanding of the EDM factors which influence its performance.

5.1 Controlling copper quality & distribution

Deposit quality

It is clear from the work carried out to date that one of the routes to catastrophic failure of the electrode results from defects within the copper coating. Electrodeposits have a different microstructure to bulk metals due to the nature of the deposition process. In the case of the acid copper electrolyte, in order to produce smooth deposits, certain organic additives are introduced to the electrolyte that modify the grain structure. The grains produced in the presence of these additives tend to be columnar, with grain boundaries normal to the substrate surface. If the deposition process is not adequately controlled in terms of electrolyte composition, contamination and deposition conditions, then the structure of the deposit will become variable. The grain boundaries then become regions of weakness which allow rapid localised degradation of the deposit during the machining process. Even with the best process control conditions, it is unlikely that columnar microstructures would be ideal coatings for EDM electrodes. This is because such a structure tends to promote the continuity of any porosity initiated at the metallised surface. Sites of such intrinsic porosity then become zones where the discharge spark rapidly weakens the coating leading to its failure.

It is therefore very important that a very tight control of the plating electrolyte and its conditions of use is exercised. Organic additives are decomposed during the plating process and can form compounds that interfere with the growth of the deposit, leading to the development of high internal stress or other forms of deposit degradation e.g. nodule formation and powdery deposits. Organic contaminants may be removed using activated carbon but this also necessitates the analytical control of the original additives to ensure that these are not removed also.

It is important to ensure that particulates do not contaminate the electrolyte as these could become incorporated into the deposit. Particulate inclusions can easily act as preferential erosion sites during discharge machining leading again to early and random failure. Continuous filtration can minimise this but ultimately, the best form of cure is prevention of the contamination by employing very clean environments.

Finally, to ensure a consistent deposit, chemical analysis of the electrolyte components carried out on a regular basis, combined with appropriate deposit testing is essential.

Deposit distribution.

The distribution of metal over a complex geometry is dependent on many factors as has previously been mentioned. Whilst it is possible to formulate an acid copper electrolyte to exhibit an improved distribution, other formulations of copper electrolytes are available that offer a significant improvement over even the best acid copper system. These electrolytes are based on copper compounds in the form of chemical complexes. Unfortunately, these are required to operate at temperatures close to the Tg of the SL model (55 - 60 ^{o}C). Work is being carried out to evaluate the properties of these electrolytes under conditions more suited to the SL models. Besides improved distribution, these electrolytes produce finer grained equiaxed deposits and should reduce the tendency to pore continuity. By using these electrolytes in conjunction with the physical methods of improving metal distribution, the difficulty of obtaining a uniform deposit can be minimised. As with the acid copper electrolyte, these electrolytes require tight analytical control and the exclusion of contaminants to offer optimum performance.

5.2 Controlling the EDM process

Efficiency of EDM with the SL electrodes was sought through optimization of MRR using a series of Fractional Factorial Experiments (FFE's). The L18 test array prescribed by Taguchi [8] provided a suitable structure for examination of seven adjustable EDM parameters at three levels. The performance data for these tests is described by Figure 12. Details of these tests have been presented in earlier published material [3,4]. Fixing parameters where their performance was seen to be optimized a specification for machine set up was derived. This set-up has formed the basis for testing of more complex model electrode profiles and the continuing evaluation of electrode performance. The relationships between the various adjustable EDM parameters are complex, however the use of FFE's as outlined above has determined a start point from which improvement in coating techniques should offer potential for improvements in both machining efficiency (MRR) and electrode wear.

Improving the quality and distribution of the copper deposit is likely to yield greater resilience against electrode failure, providing an opportunity for enhanced EDM performance. A cycle of continual improvement has been established.

6. CONCLUSIONS & FURTHER WORK

The potential for application of copper coated SL models is currently limited by a number of factors. Work at The University of Nottingham is seeking to identify and address the limitations. The efficiency of the SL electrodes depends on the quality of the electrodeposited copper coating and the EDM machine set-up. Optimization of both areas is being sought through an on-going research programme.

The inefficient heat/energy dissipation from the front face of the electrode during EDM causes catastrophic failure. Classification of failure modes associated with this heat 'burn out' have been proposed. The factors contributing to failure are being investigated. A thermal model is to be developed, providing a means of predicting electrode behaviour.

The principle of manufacturing electrodes for EDM using SL has been demonstrated. Further work should provide an opportunity for greater machining efficiency.

7. ACKNOWLEDGEMENTS

The authors would like to thank the following for their support and assistance in this research work; UK Engineering and Physical Science Research Council (EPSRC), Rolls Royce (Aerospace) plc, GEC-Marconi Materials Technology - Hirst division, Nuns Street Platers (Derby), and fellow workers at the University of Nottingham

8. REFERENCES

[1] A.Arthur & P.M.Dickens, *"Rapid Prototyping of EDM electrodes by StereoLithography"* Presented at the International Symposium for ElectroMachining (ISEM) XI, Lausanne, Switzerland, April 17-20 1995

[2] A.Arthur & P.M.Dickens, *"The potential for Rapid prototyped EDM electrodes using StereoLithography models"* Presented at the 1st National Conference on Rapid Prototyping and Tooling Research, Buckinghamshire College (Brunel University), UK, November 6-7 1995 pp 221-235

[3] Alan Arthur, Phillip Michael Dickens, & Richard Charles Cobb, *"Using rapid prototyping to produce electro discharge machining electrodes"* Rapid Prototyping Journal, Vol 2, No.1, February 1996, pp 4-12. ISSN 1355-2546

[4] A.Arthur & P.M.Dickens, *"Material removal & tool wear rates in EDM with StereoLithography electrodes"*, Presented at the 5th European Conference on Rapid Prototyping and Manufacturing, Espoo, Helsinki, Finland, June 4-6 1996 pp 157-169 ISBN 0-9519759-5-1

[5] Semon, G. A practical guide to Electro-Discharge Machining (2nd ed.), 1975 (Publ. Ateliers des Charmilles, Geneva), Chapter 9 pp 63-76

[6] Vagramyan, A.T. , Solov'eva, Z.A. Technology of Electrodeposition, 1961, (Robert Draper, UK) pp 308-384

[7] Hague, R. Dickens, P.M. Stresses created in ceramic shells using Quickcast™ models, Proceedings First National Conference on Rapid Prototyping and Tooling research, Buckinghamshire College UK, 6th-7th November 1995. ISBN 0852989822 pp 89-100.

[8] Ross, P.J. Taguchi techniques for Quality Engineering, 1988, (McGraw-Hill, UK) pp 228 ISBN 6100897425

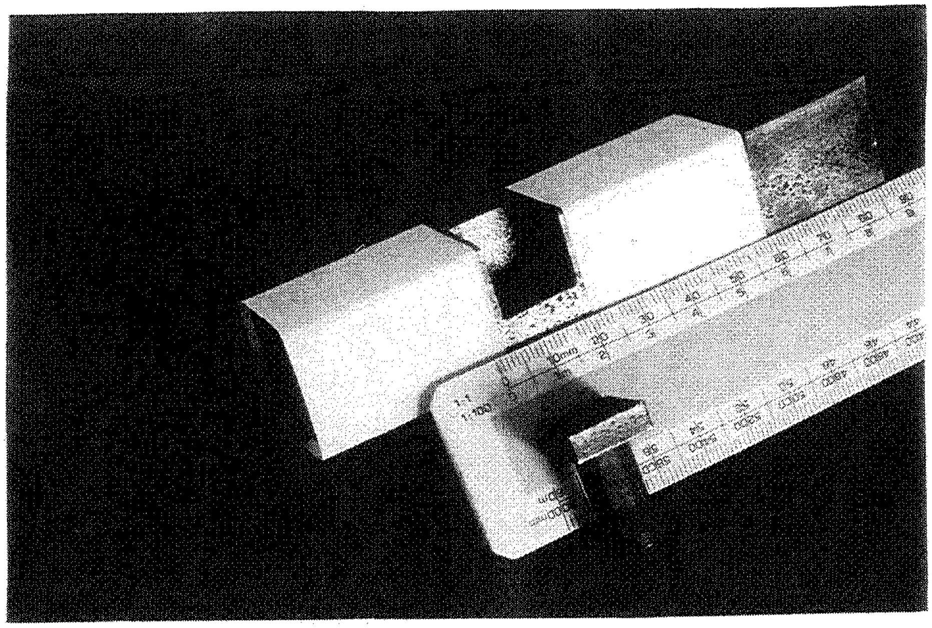

Figure 1 SL 'tablet' electrode and 16mm deep EDM cavity in tool steel

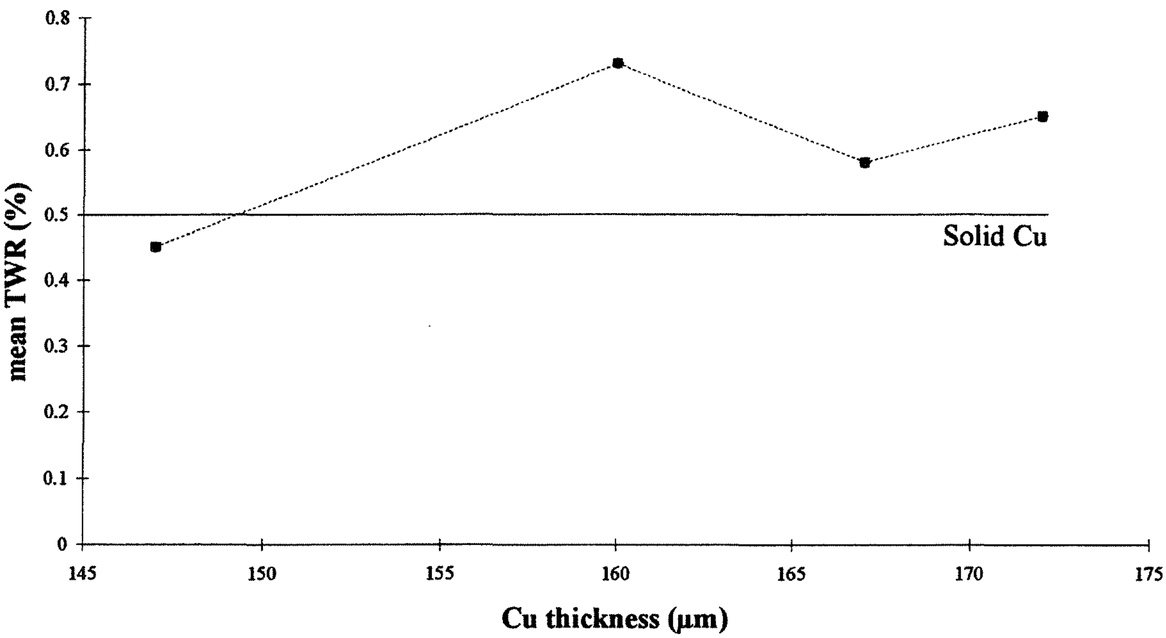

Figure 2 SL EDM electrode TWR versus copper thickness

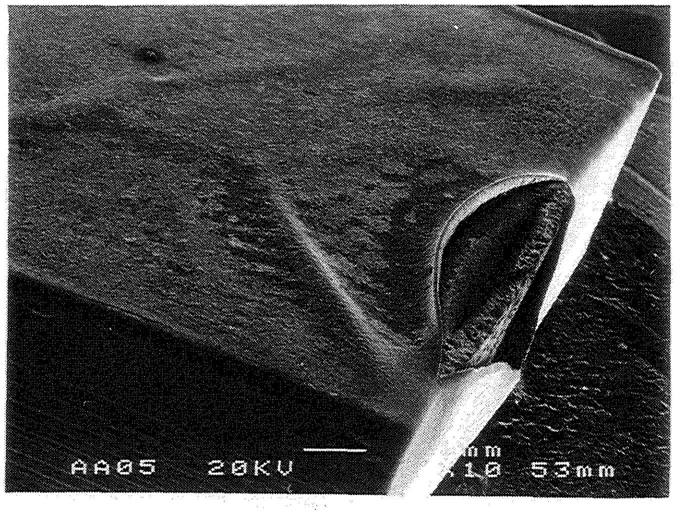

Figure 3 Electrode failure - Edge failure (15mm x 15mm SL 'tablet' electrode)

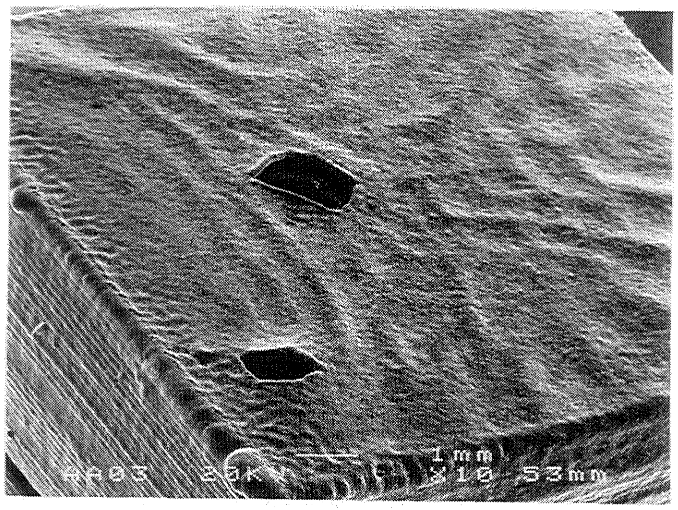

Figure 4 Electrode failure - Peppering (15mm x 15mm SL 'tablet' electrode)

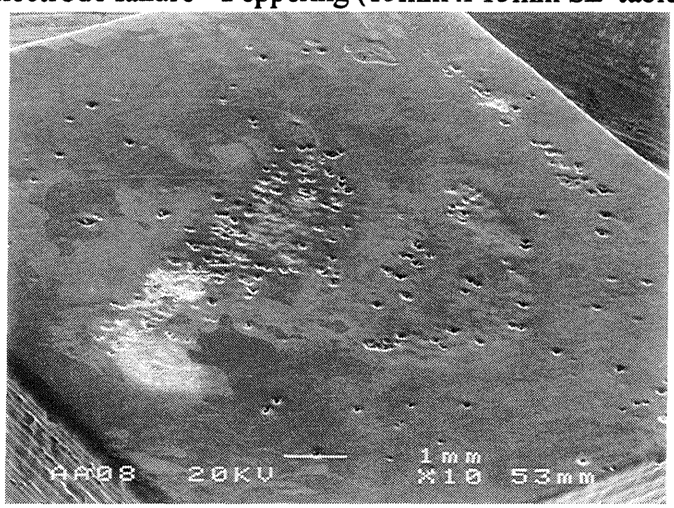

Figure 5 Porosity in electrodeposited copper, highlighted by pyrophosphate plating (15mm x 15mm SL 'tablet' electrode)

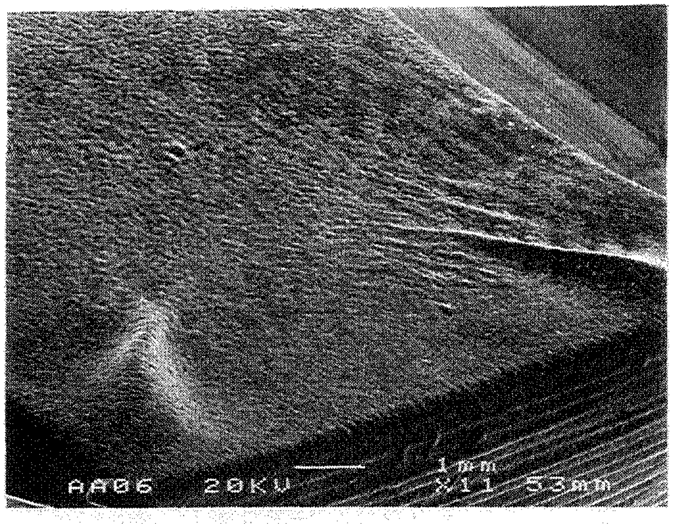

Figure 6 Electrode failure - Delamination (15mm x 15mm SL 'tablet' electrode)

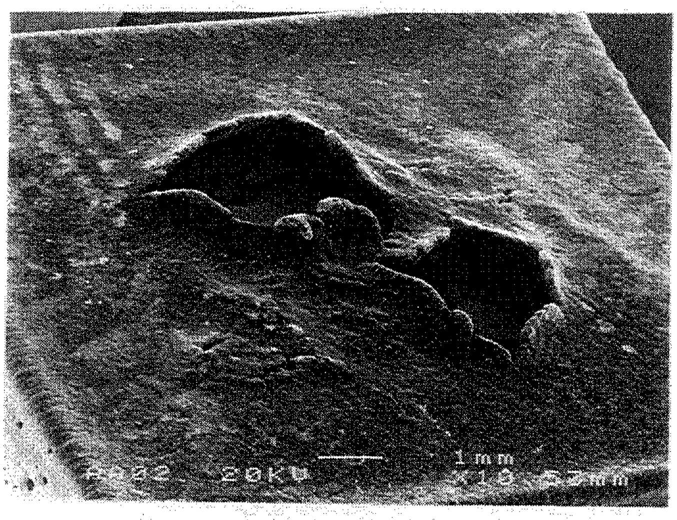

Figure 7 Electrode failure - Rupture (15mm x 15mm SL 'tablet' electrode)

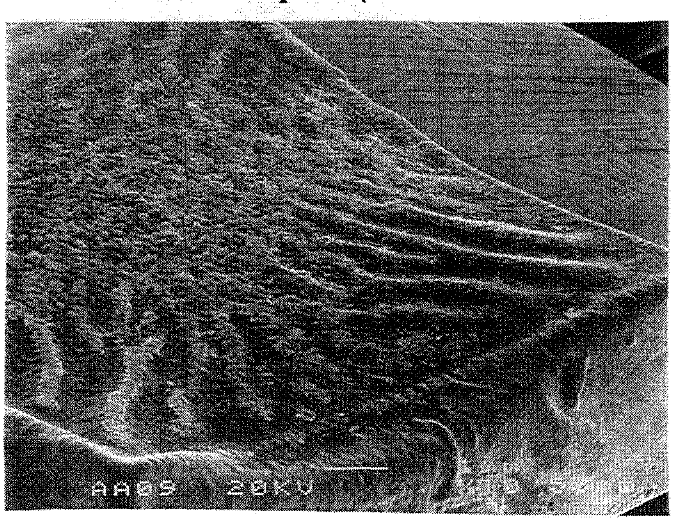

Figure 8 Electrode failure - Distortion (15mm x 15mm SL 'tablet' electrode)

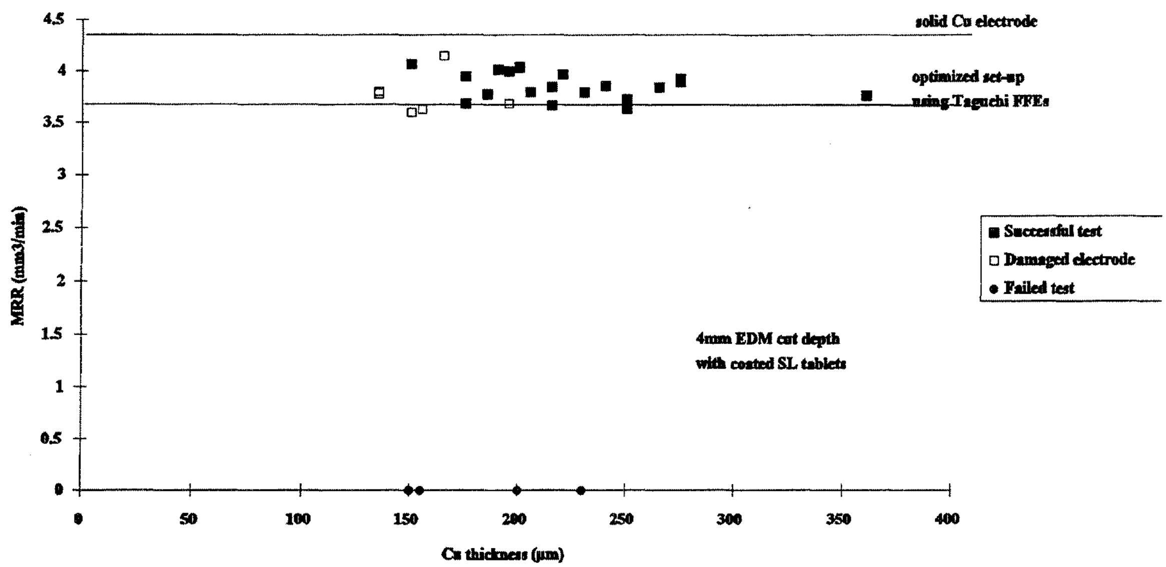

Figure 9 SL EDM electrode MRR versus copper thickness

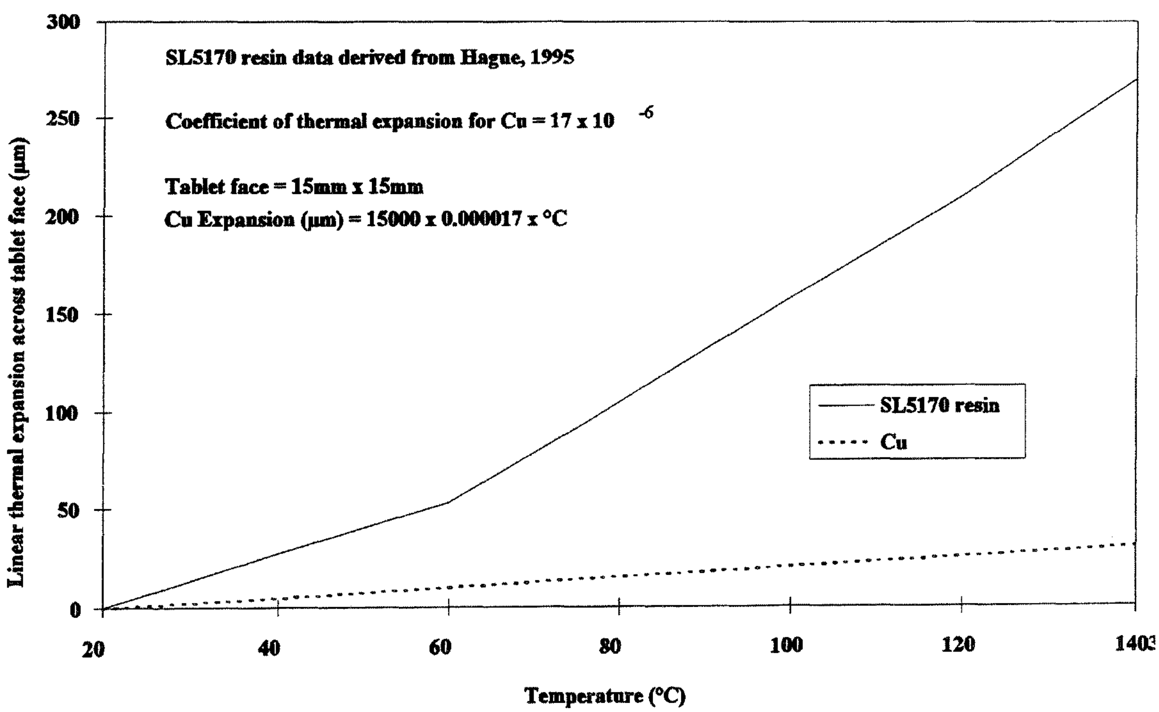

Figure 10 The differential linear thermal expansion of SL tablets and applied copper coatings at elevated temperature

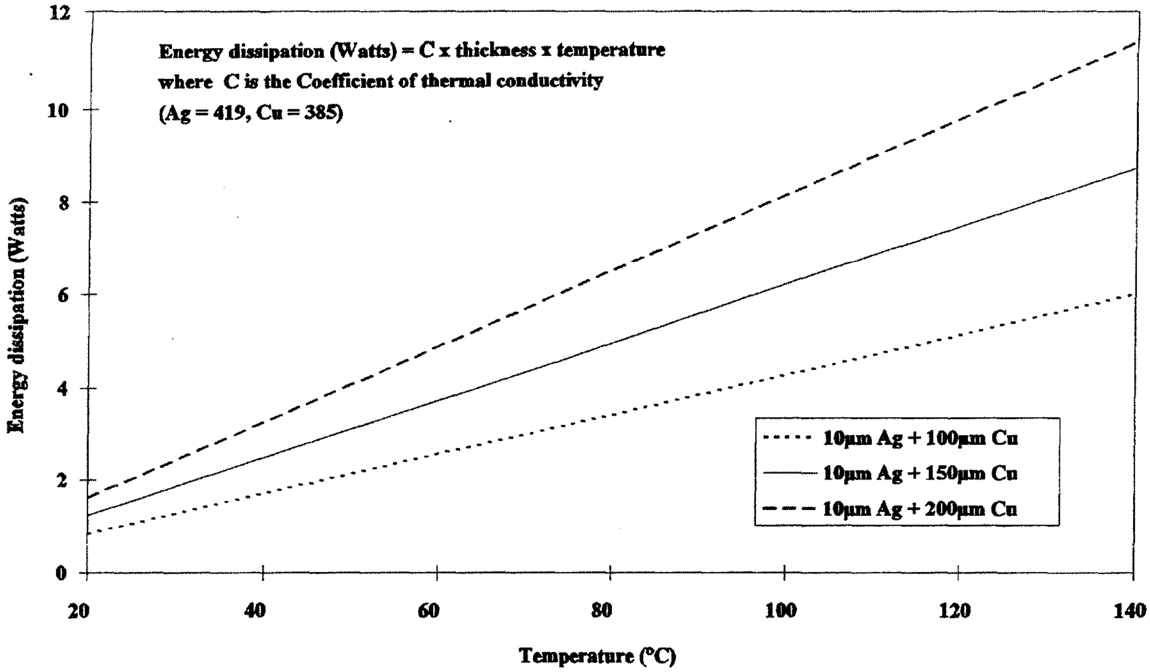

Figure 11 SL EDM electrode capacity for energy dissipation versus coating thickness

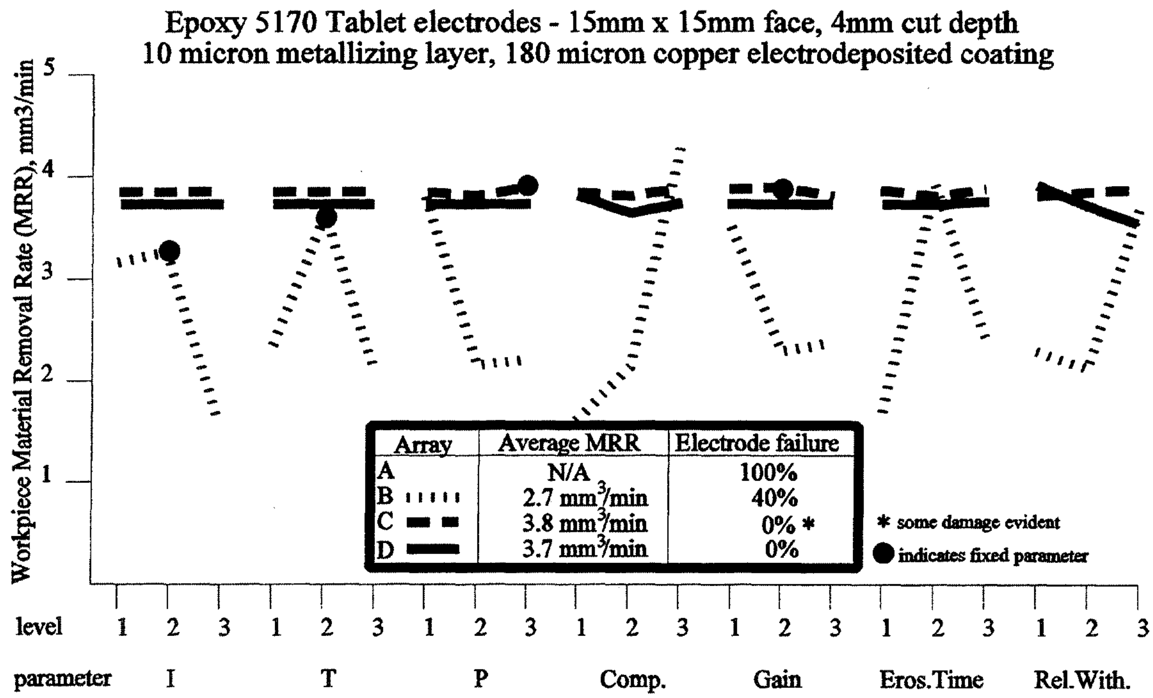

Figure 12 SL EDM electrode Material Removal Rate (MRR) optimization