THERMO-MECHANICAL ANALYSIS OF METALLIZED
STEREOLITHOGRAPHY EDM ELECTRODES

A Thesis by

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THERMO-MECHANICAL ANALYSIS OF METALLIZED
STEREOLITHOGRAPHY EDM ELECTRODES

I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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DEDICATION

Dedicated To My Parents
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ABSTRACT

EDM is widely accepted in tool and die industries for its versatility in machining hardened steels. Its ability to machine heat treated hardened steels eliminates the conventional method of heat treatment after machining which results in distortions. However one drawback of the EDM process, which makes its uses limited, is the high cost and time for the electrode manufacture. The die sinking EDM process employs complex shaped electrodes which require specialized machining operation and often results in high lead times. Solid free form fabrication is found to be an excellent alternative for the conventional all metal electrodes for EDM. Rapid prototyping of the electrode models and electroforming with copper is a fervently studied method of producing cost effective electrodes. However most of the studies have reported premature failure of the electroformed electrodes, limiting its commercial use on a large scale. This study attempts to analyze the failure mechanism of electroformed stereo-lithography electrodes by conducting a finite element analysis of the electrode model using LS-DYNA-970. It has been shown that high temperatures and coefficient of thermal expansion mismatch are the primary reasons for the premature failures experienced in these types of electrodes. The study also proposes some design modifications to improve the electrode performance during repeated thermal loading. The modified electrodes showed significantly improved performance in analysis studies.
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1. INTRODUCTION

Rapid prototyping can be used to produce a model of the complex shape of a part within a short span of time with high accuracy. Rapid tooling is one process of making complex dies, molds and electrodes by rapid prototyping. This technique can substantially reduce the product development cycle in industries. One such application is electrical discharge machining (EDM). EDM is widely used in industry for machining difficult to machine materials. However the complex shapes of the electrodes used in EDM are difficult to be made using the conventional methods. This results in production delays and hence rapid tooling is an excellent solution to this problem. Considerable studies have been conducted in recent years for finding workable methods of producing rapid prototyped electrodes. This work concentrates on understanding the thermal behavior of the rapid prototyped EDM electrode, the knowledge of which could considerably improve the electrode life and machining characteristics.

To make an EDM electrode from stereo-lithography model (SL), the stereo-lithography prototypes of the electrode is electroformed through the required thickness with a conductive metal like copper. These electrodes can then be substituted for an all metal electrode in EDM. However EDM is a thermal process where extreme thermal energy is generated and the electrode undergoes severe thermal loadings during machining. The high temperature results in considerable wear of the electrode. Past experiments have identified high temperature as one of the critical factors affecting the life of the electrode.
The problem is aggravated while using an electroformed stereo lithography electrode, as the resin used for rapid prototyping is inherently nonconductive and has relatively low glass transition temperature. This results in thermal residual stresses along the metal resin interface.

Previous studies have identified that the high temperatures at the interfacial layer and the resultant thermal residual stresses lead to an increase in the sacrificial wear of the electrode. The presence of multilayered heat affected zones necessitates the use of a reliable thermal model of the electrode for predicting its thermal behavior during actual loading conditions. Accurate measurement of temperature along the metal resin interface is not feasible due to practical limitations in employing thermocouples at the metal resin interface. The temperatures at the exact interface could not be measured. However accurate prediction of the thermal behavior of the electrode could permit identifying critical design parameters and optimizing them to enhance electrode life and wear characteristics. Hence an analytical extrapolation is ideal for predicting the precise temperature along the metal resin interface. In this work a finite element model of the electrode is developed to predict its thermal behavior. The model is subjected to actual loading cycles by giving suitable boundary conditions.

Heat flux canals are heat channels tactically placed to relieve the high temperature along the metal resin interface and thereby reducing the thermal residual stresses by reducing the temperature gradients. This work introduces the technique of heat flux canals to enhance the electrode life by channeling the high temperature away from the metal resin interface and seeks to reduce the residual stresses.
A two dimensional finite element model of the electrode is developed to study the effects of heat flux canals on the temperature distribution of the electrode during extreme thermal loading conditions.

1.1 Objective

The primary objective of this work is to accurately predict the thermal behavior of the stereo lithography EDM electrode during machining. The temperature gradients are crucial in identifying zones of high temperatures, and high residual stresses. The accurate prediction of the thermal gradients can significantly improve critical design parameters of the electrode. Finite element analysis (FEM) is used to solve the problem. The results from the FEM analysis are compared with the experimental findings and verified. The thermal residual stresses and strains along the layers of the electrode are studied. Statistical technique ANOVA is used to analyze the interaction between factors and the selected responses. New techniques like heat flux canals are introduced to channel the heat away from the regions of higher temperature. The location of the heat canals is critical and hence knowledge of the thermal behavior of the electrode becomes highly significant.
2 BACKGROUND & LITERATURE REVIEW

Rapid Prototyping can be used to produce an actual prototype of the complex dies, molds, castings and electrodes used in many manufacturing applications. These models can be used for casting purposes, injection molding and for making electrodes for EDM. In a production scenario this can lead to drastic reduction in production delays and production cycle time. Electroformed stereo lithography models are an ideal substitute for the complex electrodes in EDM. The electrodes traditionally used are made of conductive materials like copper and graphite. Producing the required shape of the electrodes with these metals is costly and time consuming and requires sophisticated machining processes. Rapid prototyping and electroforming is an excellent technique of producing these shapes cheaply and in a relatively short span of time. Most of the previous efforts have yielded promising results, however for implementing these techniques commercially; it is indispensable to have a thorough knowledge of the behavior of the electrodes during machining. This chapter gives a brief description of the previous works done in developing rapid prototyped electrodes and analysis techniques used for design optimization. Review of works dealing with metal resin interfacial adhesion during thermal loading and thermo-mathematical models of EDM is also included.

2.1 Rapid tooling

Rapid tooling refers to techniques used for making tools for manufacturing applications with the aid of solid free form fabrication (SFF) or rapid prototyping. In stereo-lithography rapid prototyping a prototype of the required shape is created by layer by layer deposition and subsequent curing of a photosensitive resin. A laser beam directed to the layer being formed is used to photo-polymerize the liquid resin.
The resins used for rapid prototyping or stereo-lithography are photopolymers having a glass transition temperature well below 100°C. The part to be prototyped is first modeled with the help of a 3D modeling CAD software. This 3D model is then sliced into a number of 2D layers. The data is then fed to the rapid prototyping machine where the photosensitive resin is deposited layer by layer and cured. A fully grown model retains all the geometrical features of the part to be machined. Rapid prototyping can thus reduce the lead time and production cycle time in manufacturing industries. The photopolymers currently used for stereo-lithography process are softened by temperatures higher than 100°C; this nature of the resin is a major constraint for the parts to be put to high temperature applications. Considerable research is being done to develop better resins having higher glass transition temperatures.

In processes like injection molding, lead time and production cycle time are very important. Hence there is growing demand for manufacturing techniques which can reduce both lead time and production cycle time. However the injection mould cavities are very difficult to be made with conventional machining methods. Vertical milling and other machining processes require extended machining time and hence are not cost effective. Electro discharge machining is an ideal process for machining these injection molding cavities. However the electrodes which are made of either copper or graphite are difficult to be machined to the required shape. Rapid prototyping can be used to form these shapes within a short span of time. When these resin models are metallized they can be an excellent alternative to the conventional electrodes used in EDM.
There are different systems of rapid prototyping namely liquid polymerization, fused deposition manufacturing, laminated object manufacturing, selective laser sintering and point to point solidification [1]. Each of these techniques is adopted based on the requirement of the industry, the material availability and the manufacturing application for which these parts are served. However in-spite of the intricacies involved in these processes much of its use is driven by the industrial requirement of a reduced lead time, production cycle and cost. The major part of the lead time is the delay in tool making [1].

Rapid tooling can be classified into two types, hard tooling and soft tooling [1]. Soft tooling is characterized by lower cost and volume of production, it uses low hardness materials namely silicones, epoxies, low melting point alloys etc. Hard tooling is associated with higher production cost, volume and hard materials like hardened steel [1]. There are both direct and indirect methods of producing electroformed stero-lithography tools [1]. In indirect method a negative pattern of the shape is developed with rapid prototyping. The resin model is then electroformed with the required thickness of metal. The stereo-lithography model is then separated from the metal shell and another material like zinc or a metallic alloy is used to back fill the mold. In direct method the actual shape of the electrode is developed by rapid prototyping and the cured resin model is electroformed to create the electrode. The effect of back filling on the electrode performance will be discussed later, in detail.

2.2 Electroforming

Electroforming is the process of electroplating a model to produce a solid free form surface. The model required for the process can be created by rapid prototyping. Electroforming uses an aqueous solution of the salts of certain metals as the medium.
The models to be electroplated needs to be conductive and hence ideally are metals. So for electroplating, the stereo-lithography models need to be made conductive. This can be achieved by metallizing the models prior to electroplating. Several techniques are used for achieving this. The reviewed papers discuss methods like chemical reduction of metals from aqueous and non-aqueous solution, electro-less forming, spray coating of the models with a paint permeated with a conductive metallic powder, etc. [1-4].

2.3 Metallized stereo-lithography electrodes for EDM

In the indirect method of producing rapid prototyped electrode, the negative (complementary geometry) of the EDM electrode is prototyped by stereo-lithography to be used as the master [2]. The thin shell of electroplated metal is removed from the stereo-lithography master by applying heat. The resin substrate has a very low glass transition temperature and can be easily removed. However, the amount of thermal stress developed in the metallic shell depends on the glass transition temperature of the resin. If the resin has a high glass transition temperature then the thermal stresses induced due to the burn out process can lead to geometrical distortions of the shell. Sometimes allowance needs to be provided to account for the expansion during the burning out process. The high temperature during the burnout process could cause cracking or deformation in the electroformed metal shell [2]. If the resin has a glass transition temperature below 100°C then softening techniques like immersion in boiling water can be effectively carried out. The backfilling materials are ideally low melting point alloys in the case of metallized stereo-lithography EDM electrodes; this is because there is virtually no contact between the electrodes and the workpiece and hence no mechanically induced stresses.
The process is almost similar to an investment casting or lost wax casting. The low melting point alloy is filled into the electroformed metallic shell. Another backfilling process is powder compaction. The metal shell is filled with a metal powder and binder mixture in a solvent. The mixture is poured into the shell, when the solvent evaporates we get a green compact model. This is then sintered to burn-off the binder [2].

Though the backfilling technique can improve the structural strength of the electrode to a great extent it has its own share of problems as well. During back filling there is a high probability of formation of air pockets and voids. The air pockets can affect the behavior of the electrodes considerably during the EDM process. The air entrapments can increase heat concentrations and accelerate the electrode wear. Again the burn out process and then the back filling results in considerable thermal stress to the metal shell resulting in distortions. Complete incineration of the stereo-lithography master is observed around 560°C [2]. The sudden thermal expansion could lead to cracks or edge failures in the metallic shell. This deformation during the burnout process is largely dependent on the type of backfilling material used. A metal with higher melting point implies higher structural strength for the electrode. However the high melting point alloy gives more thermal stress to the electrode. Casting with a high melting temperature metal tends to generate larger thermal stress which may cause larger deformation in the electroformed metal shell [2].

2.4 Performance and thermal behavior of metallized SL electrodes

The performance of the electro discharge machining process is characterized by the efficiency of material removal or the material removal rate (MRR), electrode wear rate (EWR), and the surface finish of the machined surface.
Considerable data is available on the performance characteristics of all-metal electrodes traditionally used for EDM applications. However sufficient data is not available regarding the performance of metallized stereo-lithography electrodes. This performance characteristics data is vital for optimizing the electrode performance during machining operation. Arthur et al. [3] suggested that the performance attributes are not complementary requiring the machine operator to select process settings to achieve the necessary balance between them. Hence tabulated data regarding the performance of the electrode is crucial for achieving the most acceptable machining characteristics.

As already discussed, the indirect method for producing metallized stereo-lithography process uses a backfilling material as a substitute for the resin substrate. The primary objective of using the backfiller material is to enhance the thermal conducting property of the electrode and to reduce the concentrated thermal residual stresses. Though the backfilling process is largely successful in conducting the heat away from the surface of the electrode, concentrated wear and failure of the electrode has been noted. Rennie et al. [4] studied the performance characteristics of a backfilled stereo-lithography electrode and tabulated the data for different plating thickness. The electrode wear was tabulated as a percentage wear rate, which is the original electroform dimensions divided by the post sparking dimension and then multiplied by the dimensional difference between the two. Most of the electrodes studied reported earlier failures like edge failure and splitting of the electroplating during roughing operations and a much slower wear rate during the finishing operations. The wear rate was higher at corners and sharp edges which may be attributed to the uneven coating thickness obtained during the electroplating process.
The uneven coating thickness is due to the difference in the strength of the electric field during electroplating. This field strength is a property of the geometry of the electrode and hence a higher coating thickness can be expected at protruded areas and vice versa. During the EDM process the protruded surfaces experienced concentrated sparking and hence excessive heat generation. A part of this heat is conducted through the backfilling material and a portion of it is dissipated through convection. Hence a uniform backfilling material should reduce the thermal stresses by conducting the heat from the surface of the electrode. However Rennie et al. [4] reports that even with the best backfilling process the wear will happen though at a slower rate. It is further stated that in some cases the metallic filler starts to erode much quickly when exposed, resulting in increasing the electrode wear. Electrodes with thicker plating showed an increased life due to the higher time needed for eroding the plating away before the filler material is exposed. So it can be concluded that though the back filling process can improve the strength of the stereo-lithography mold, it has very little effect in reducing the wear rate of the electrode or improving the electrode life. Moreover the thermal stresses to the electrode during the backfilling process and the burnout process can result in major distortions to the electrode. Again there is a possibility of air entrapments or voids created during the backfilling process that can increase the wear rate.

The direct method of developing the electrode involves the metallizing of a stereo-lithography model. However the resin used for the stereo-lithography process usually has a low glass transition temperature usually less than 100°C. The resin material is an insulator by nature; this property seriously impairs the ability of the electrode to conduct the heat generated by the machining process.
The thin electroplating or the metal shell is largely unsuccessful in conducting the heat away from the surface. The thermal transfer through the electrode is insufficient [4]. The heat build up in the metallic shell can result in early failure of the tool. However, very little studies had been conducted to establish the relation between the thermal behavior of the electrode and the performance characteristics of the EDM process. Arthur et al. [3], states that the influence of the performance parameters on the thermal behavior of the electrode is not widely understood. Variation of temperature at the electrode face is likely to greatly affect the performance of the electrodes through changing the material conductivity and hence process efficiency.

The different direct methods of developing the SL electrodes include the use of conductive plastics and metal powder impregnated resin substrates. Studies are being done to develop better thermal and electrical conductive plastics. Such materials could easily act as substitutes for metal electrodes. However no major breakthrough has been reported in this field and studies remain inconclusive. Impregnating the resins with metallic powder is another technique; however it is not possible to cure the composites resin completely. Again the powder in the resin was not found to increase the conductivity of the resin, so the technique is not used anymore [4].

Arthur et al. [3] studied the direct method of forming metallized resin electrodes and used them for EDM applications. The coated electrodes suffered premature damage through rupture of the coating or its delamination from the model. The coated electrodes showed better results when used for semi roughing and finishing operations. These two operations are low current applications. Low current means low energy and low energy means reduced thermal energy release.
Hence it can be concluded that there is a certain relationship between the thermal energy and the rate of electrode wear. With increasing thermal energy the coated electrodes showed a higher rate of electrode wear.

The work done by Tandon [5] investigated the performance of rapid prototyped SL electrodes under various operating conditions. It analyzed the effects of process parameters like pulse time, gap current, and coating thickness on tool life and material removal responses. The data generated from the experimental runs, based on a Box-Behnken design, was used to arrive at optimal levels of the process parameters. Again the temperature measurements along the copper-resin interface were used to explore possible mechanisms of failure of the coated SL electrode.

This study identified five kinds of failures, namely edge failure, peppering, delamination, distortion and rupture, among which rupture was the most commonly observed type. Of all the failure types, except for peppering and edge failure this study identified temperature as having a prominent role. A closer investigation of the rupture failure found that at a certain point into the cutting, a burned area develops on the cutting face which is characterized as a charred dimple. Further into the cutting, this area showed accelerated wear and concentrated sparking. Finally this charred lump is completely chipped off from the cutting face exposing the resin surface; however any damage to the resin surface was not observed.

2.5 Effects of temperature on polymer – metal interface

Polymer – metal interfaces are characterized by a mismatch in the coefficient of thermal expansion (CTE). This mismatch in CTE is attributed to the various failures of polymer metal interfaces.
The major failures associated with polymer metal interfaces are cracking of the layered structures and interfacial delamination. Considerable work has been done in the past to quantify the residual stresses in these joints during thermal loading. Residual stresses develop in these interfaces as a result of the difference in the coefficient of thermal expansion. The metallic surface has a higher coefficient of thermal expansion and for the polymer surface it is comparatively low. The thermal energy conduction through the metallic surface results in a drastic expansion of the metallic lattice, however having a lower CTE the polymer surface fails to produce a uniform expansion rate leading to micro cracks in the metal polymer interface. Residual stresses develop across these micro fissures resulting in failure of the interface. The failure of the metal coating happens when the residual stresses exceeds the yield strength of the thin metallic layer. Yao et al. [6] studied the effects of thermal residual stresses on these metal polymer interfaces. He used several specimens of aluminum pieces bonded together by an epoxy resin. Both experimental tests and finite element method were used to quantify the residual stresses along these joints. The finite element analysis yielded results which directly indicates that the CTE mismatch is responsible for the high residual stresses in these joints. The paper states that the thermal residual stresses can result from both CTE mismatch and stiffness mismatch across the interface [6]. The FEM simulation made it possible to provide artificial elastic modulus to adhesives with same CTE and the energy release rates of different cases compared [6]. The analytical experiments show that CTE mismatch is having the largest influence on the failure of the interfaces. In some cases the residual stresses developed was sufficient enough to cause cohesive or adhesive failure of the interface [6].
The metallized stereo-lithography electrodes contain a polymer resin surface coated with a metal having a higher conductivity. The resin surface is made conductive by applying a conductive paint impregnated with metallic powder. The higher thermal energy during the EDM process can result in the quick expansion of the copper plating as it is having a higher CTE. The CTE mismatch between the surfaces could be a reason for the early failures reported in coated stereo-lithography electrodes. The precise measurement of the metal resin temperature fringes is decisive in validating this theory.

2.6 Analytical models of EDM

Electro discharge machining is essentially a thermal process where high ranges of thermal energy are produced. The high release of thermal energy poses major problems like wear of the electrode, cracking, and poor surface finish. The materials traditionally used in EDM process are good conductors of electrical and thermal energy. However the drastic temperature cycles during EDM can result in catastrophic failures to the electrode as well as the work-piece. Considerable efforts have been made in the recent past to develop mathematical models of the EDM process.

However most of these models aim to predict the performance characteristics like material removal rate (MRR) and electrode wear rate (EWR) for a specific operating condition. Little or very little information is available regarding models that can accurately predict the temperatures and thermal stresses in machining zone. A review of literature indicates that there have been very few theoretical approaches for determination of thermal stresses [7]. Again the available models are based on assumptions like single spark, single material and temperature independent properties, perfectly elastic plastic materials etc.
EDM process on the other-hand is highly non-linear, transient, thermal-mechanical coupling problem with a cyclic energy input curve and random sparking. Both the electrode and the work have temperature dependent thermo-physical properties. In the case of metallized stereo-lithography electrodes the electrode consists of a multilayer configuration of metal and resin. Since the objective is to develop a model that can reliably predict the temperatures and the thermal stresses during the EDM process a more proactive approach is needed. A real time simulation that takes into account the duty cycles, the cyclic load curve and temperature dependent properties are crucial.

Akiyoshi and Imagi of Mitsubishi electric [8] used FEM technique to study the effects of temperature and surface integrity in electro-discharge machining. The objective was to optimize the waveform using thermal analysis and improve the layer hardness of the machined surface. They used a two dimensional axisymmetric model for thermal analysis as shown in Fig: 2.1. Again the model was based on the assumption of single spark. An arc column in the electrode work gap is considered. It is assumed that the energy spent on this arc column expansion balances the total energy transmitted to the dielectric fluid plus the state of the electrical discharge beside the arc column.
The size of the arc column is calculated by the equation,

\[ R \frac{dR}{dt} = C_1 i - C_2 R, \quad \text{Where} \quad C_1 = \frac{\eta v}{2\pi E}, \quad \text{and} \quad C_2 = \frac{h\Delta T}{E} \]

where \( i \) is the discharge current, \( v \) is the discharge voltage, \( R \) is the arc column radius, \( I \) is the gap between the electrodes, \( h \) is the heat transfer coefficient, \( \Delta T \) is the difference in temperature between the arc column surface and the dielectric fluid, \( E \) is the energy required to cause the arc discharge, \( t \) is the duration of discharge and \( \eta \) is the proportion of the electric discharge consumed to increase the size of the arc column. The analysis region is divided into 400 equal units. The governing equation is the 2D heat conduction equation.

\[ \frac{\partial T}{\partial t} = k \left( \frac{1}{r} \left( \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \right) + \frac{\partial^2 T}{\partial z^2} \right) \]
Here k is the thermal diffusivity constant, T is the absolute temperature, r is the distance from the centre of the analysis. The paper states that the FEM technique is able to predict the temperature distribution and a quantitative estimation of the temperature is made. The mathematical technique is claimed to have made a good enough prediction of the temperature fringes. Again finite element technique when used with the help of powerful software with iterative solvers can perform a real time simulation thereby reducing the margin of error considerably and improving the analytical extrapolation.

Yadav et al. [9] used finite element technique to develop a thermal model of the EDM process to predict the Gaussian temperature fringes and the thermal residual stresses during EDM process. The effects of different process variables on the temperature fringes and the thermal stress were also studied. The model was developed based on the following assumptions. The analysis domain is assumed to be two dimensional and axisymmetric. The work-piece is homogenous and isotropic. The material properties are not influenced by the temperature. The heat transfer is purely by conduction. Inertia and body effects are assumed to be negligible. The work-piece is perfectly elastic plastic. The work-piece is stress free before the EDM process. Thermal stresses were evaluated only up to the time for which the transient temperature distribution is known above the dielectric temperature. The analysis is done for a single spark. The analysis model is shown below Fig: 2. 2.
The governing equation is given by:

\[
\rho C \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)
\]

where T is the Temperature, t is the time, \( \rho \) is the density, k is the thermal conductivity, C is the specific heat capacity of the work material and r and z are coordinate axes. In this paper Gaussian heat distribution is used rather than considering a uniformly distributed heat source. However a single spark assumption is used for developing the model. For the computation of thermal stresses the transient temperature distribution in the work-piece, obtained by solving the above heat equation is used. Yadav et al. [9] found that thermal stresses have a damaging nature during the EDM process.
They concluded that considerable levels of compressive and tensile stresses are formed around the sparking zone and that these stresses go beyond the yield strength of the material.

### 2.7 Heat flux canals

The reviewed literature gives strong indication that high temperature concentration and resultant thermal stresses can be a prominent reason for the premature failure of metallized stereo-lithography electrode. As already discussed the backfilling of a metal shell produced by coating a resin electrode and subsequent burnout of the resin could not significantly enhance the electrode life. However an increased thermal conduction from the electrode face was observed with the backfilling of a high thermal conductivity material. Aherns et al. [10] studied the premature failure of stereo-lithography injection moulds. They found that increased temperature has a noted impact on the SL resins mechanical properties. As we have already discussed the photo-polymerized resin substrate has a glass transition temperature well below 100°C. The increase in temperature along the metal resin interface could result in the gradual softening of the resin towards phase transition. The concept of heat flux canals is all about reducing the exposure of the resin to higher temperature leading to a change in its mechanical properties. This directly implies to techniques capable of cooling the resin by ducting the heat away from the high temperature zones. Aherns et al. [10] proposes different methods of cooling a stereo-lithography injection mould. Techniques like an in-situ water circulating duct. However the conductivity of the resin is not favorable for such a technique. The thermal diffusivity of the resin is too low to transfer heat from the resin to the circulating water cooling system.
An FEM analysis is conducted and results were compared to the experimental data. The temperature range of the backfilling material did not show any considerable change with the in-built water cooling technique.

Aherns et al. [10] proposes another technique which seeks to extract heat from the high temperature zones. This works through direct contact with the high temperature zones. The backfilling material and the molded metal is allowed to come to direct contact for efficient ducting away of heat. The design and placement of these channels are vital as they have to be placed close to the high temperature zones. An FEM simulation is performed to determine the regions of higher concentration. The results are used to position the heat flux canals. It is concluded that heat flux canals are thermally more efficient than the other techniques that have been evaluated. Using this technique it is possible to slow down the loss of SL resins mechanical strength [10]. Again numerical simulation is found to be a more cost effective process of determining the thermal behavior of the resin stereo-lithography mold.

After reviewing the papers it seems that a reliable model can effectively predict the thermal behavior of the stereo-lithography electrode. Suitable software with an iterative solver can fine tune the analysis process and enhance the analytical extrapolation. Techniques like heat flux canals can reduce the thermal stresses during the EDM process by channeling the concentrated heat away from the polymer resin interface. Efficient heat ducting can reduce the electrode wear by slowing down the loss of SL resins mechanical properties due to increased exposure to high temperatures.
This work focuses on predicting the thermal behavior of a rapid prototyped EDM electrode. The EDM electrode is made by direct method [1], the electrode is developed by stereo-lithography process, and the cured electrode model is then electroformed with copper to create the EDM electrode.

Experimental results show that the electrode experiences premature failure during repeated thermal loading. Rennie et al. [4] studied the electrodes made using direct method and reported that heat build up in the electrode can be a reason for the early failure of the electrode. Again his paper suggests that the thermal transfer through the electrode is insufficient. This work attempts to explain the early failure of the stereo-lithography EDM electrode. Finite element analysis is used to determine the thermal residual stresses and strains in the electrode during repeated thermal cycles. Reviewed works [7] and [8] suggest finite element analysis as an excellent technique for analyzing EDM operation. This work uses LS-DYNA 3D software to perform a coupled thermo-mechanical analysis on the electrode. The precise evaluation of the temperature fringes is critical in introducing design changes that can improve the electrode performance.
3 MODEL BUILDING AND COUPLED ANALYSIS

3.1 The EDM electrode

The EDM electrode was developed by direct method of stereo lithography rapid – prototyping [5]. The 3D CAD drawing of the electrode is fed to the rapid prototyping machine where the electrode models are grown using stereo lithography rapid prototyping process. RP cure 100 resin is used for the resin bath. Figure 3.1 shows the model of the stereo lithography electrode. Fig 3.2 shows the dimensioned model, the through holes for inserting the thermocouples for temperature measurement is also shown.

Figure 3-1 Experimental model of the EDM electrode with holes for inserting thermocouples [5]

Figure 3-2 Dimensioned model of the electrode (mm) [5]
The rapid prototyped electrodes are inherently non-conductive, hence they are electroformed to be used as EDM electrodes. As the prepared electrodes were non-conductive, it was not possible to carry out copper plating. In this work a conductive silver paint was used to make the stereo-lithography model conductive. The paint was brushed on to the surface of the model carefully and then allowed to dry before being electroplated. Silver paint (solid particles 43% by weight) was found better compared to a copper paint as it is more conductive and has better adhesive properties. A thin layer of approximately 15 µm was applied by brush application and then dried for 1 hour. But the back surface of the electrode was not painted to facilitate the measurement of plating thickness [5].

Once the model was made conductive it was electroplated with copper through the required thickness. Since copper was used for electroplating, copper sulphate solution - (Cu SO₄) was used as the medium. A piece of the parent metal and the resin model were used as the electrodes, namely anode and cathode respectively. A potential difference was supplied to the electrodes; the anode was maintained at a positive polarity and the cathode at a negative polarity. The potential difference causes positive copper ions (Cu²⁺) to migrate to the negative cathode thus forming a smooth coating of copper over the rapid prototyped model. A uniform coating thickness and the surface finish was achieved by altering the process parameters accordingly [5].
3.2 The finite element model

The stereo-lithography electrode consists of three layers as illustrated in Fig 3-3, the inner polymer core, the conductive paint layer and the outer copper coating.

Figure 3-3 The stereo-lithography electrode model

A 2D axisymmetric model of the electrode is developed to reduce the complexity of the model and to substantially reduce the computational time. The quarter model of the electrode is shown in Fig 3-4. The Finite element model of the electrode is created with MSC-PATRAN. Analysis is conducted first on a 2D model and then validated with a 3D model. The preprocessing is done on MSC-PATRAN and LS-DYNA 3D version 970 is used as the solver. The results were post processed in LSPOST. The mesh density is of high importance in thermal analysis. Higher numbers of elements are provided at the regions where increased temperature fringes are expected. 2D Elements of type 14 are used for the 2D axisymmetric model.
The type of the element selected can be set in the *SECTION_SHELL* card in the key file (data file with .key extension). The element type 14 represents 2D axisymmetric (Y axis of symmetry) area weighted elements. The number of integration points (NIP) is set as 4. The number of integration points represent the through thickness integration for the 2D elements. The meshed 2D model of the electrode is shown below.

Figure 3-4 Model with the mesh and details of the individual layers

(1-SL-Resin, 2- Silver Paint, 3-Copper Plating)
Isomesh capability of MSC-PATRAN is used to mesh the three areas, namely, the resin, the silver paint and the copper plating. To facilitate a progressively increasing mesh pattern, provided to have a higher density of elements along regions of interest is achieved by the one way bias meshing technique in MSC-PATRAN.

3.3 Coupled thermo-mechanical analysis in LS-DYNA

LS-DYNA can solve steady state, transient and coupled thermo-mechanical analysis. The options for setting the required type of analysis can be done in the *CONTROL_SOLUTION and *CONTROL_THERMAL_SOLVER card. The EDM process is a nonlinear, thermal mechanical coupled problem. The selection of the required solver is of high interest in getting the accurate result. The control thermal solver card facilitates the option of setting the analysis as linear or non-linear and selecting four different solvers. This work uses solver type 1(ACTOL) symmetric direct solver which is a gauss type profile solver. Since the problem attempted is non-linear *CONTROL_THERMAL_NONLINEAR card is also used. The default LS-DYNA analysis is explicit analysis and is often used for structural analysis. However transient thermal problems are solved by implicit analysis. The implicit time integration is stable and hence larger time steps can be applied for thermal problems. The thermal time step size can be set in the *CONTROL_THERMAL_TIMESTEP card.
The heat conduction model in LS-DYNA is based on the work of Shapiro [15]. The differential equation of conduction of heat in a continuum is given by

$$\rho c_p \frac{\partial \theta}{\partial t} = (k_{ij} \theta_{ij}) + Q,$$

Subject to the boundary conditions,

$$\theta = \theta_s \quad \text{On } \Gamma_1$$

$$k_{ij} \theta_j n_i + \beta \theta = \gamma \quad \text{On } \Gamma_2$$

And initial conditions at $t_0$,

$$\theta_i = \theta_0(x_i) \text{ at } t = t_0.$$  

Where

$$\theta = \theta(x_i, t) = \text{temperature}$$

$$x_i = x_i(t) = \text{coordinates as a function of time}$$

$$\rho = \rho(x_i) = \text{density}$$

$$c_p = c_p(x_i, \theta) = \text{specific heat}$$

$$k_{ij} = k_{ij}(x_i, \theta) = \text{thermal conductivity}$$

$$Q = Q(x_i, \theta) = \text{internal heat generation rate per unit volume}$$

$$\theta_i = \text{prescribed temperature on } \Gamma_i$$

$$n_i = \text{normal vector to } \Gamma_2$$

$$\theta_i = \text{prescribed temperature on } \Gamma_i$$
LS-DYNA uses Shapiro’s approach to solve this equation by finite element method. Brick elements integrated with $2^*2^*2$ Guass quadrature rule, with temperature dependence of the properties accounted for at the Gauss points. Time integration is performed by generalized trapezoidal rule to be unconditionally stable for nonlinear problems. Fixed point iteration with relaxation is used to satisfy equilibrium in nonlinear problems.

3.4 Boundary conditions

![Figure 3-5 Boundary conditions](image)

1) Boundary heat flux zero, 2) Boundary temperature constant, 3) Boundary convection condition, 4) Boundary heat flux input
The 2D model is developed as axisymmetric model. The model with boundary conditions depicted is shown as Fig 3-5. Symmetric boundary condition is given to side 1 and the heat flux in the X direction is specified to be zero along this line. The nodes along the side 2 are kept at a constant temperature of 20°C assumed to be the ambient temperature because this side is clamped to the tool holder. Heat loss through convection is allowed normal to the side 3. The heat transfer coefficient is specified as

\[ h = 100 \text{ W/m}^2\text{ K} \] assumed to be the heat transfer coefficient of water. The power input is heat flux and is applied to the elements on side 4 as a stepped load curve. The nodes along side 2 are prevented in x -translation and y-rotational movement and nodes along side 1 is allowed y–translational degree of freedom. *BOUNDARY_SPC_SET card is used for setting the degrees of freedom. The whole model is assigned an initial temperature of 20°C ambient. Heat flux along the side 1 and 4 is applied by setting the *BOUNDARY_FLUX… card. Two options are available for specifying the element matrix in this card either SEGMENT or SET. In this work SET option is provided. Heat flux can be applied as curve multipliers or varying load curve, in this case a stepped load curve is used for power input along side 4 and curve multiplier is selected as zero along the side1. Three definitions of heat flux are possible. It can be a function of time, a function of temperature or constant values maintained throughout the calculation. Defining multipliers at each node a bilinear spatial variation can be provided. LS-DYNA assumes heat flow in the negative direction of the normal vector hence the curve multiplier in the load curve card should be set to -1.
The convective boundary condition is specified in LS_DYNA by setting the card *
BOUNDARY_CONVECTION_OPTION. This card also allows the option of arranging
the element matrix as SET and SEGMENT. Here a set option is used to arrange the
selected elements. The convection boundary condition is calculated using the relation
given by \( q = h (T - T_a) \), where \( h \) is the coefficient of heat transfer, \( T - T_a \) is the temperature
difference between model and ambient temperature. The constant HLCID in the card or
load curve ID for the heat transfer coefficient is set as ‘0’ to ensure a constant multiplier
value for \( h \). To apply the constant boundary temperature condition *
BOUNDARY_TEMPERATURE_OPTION is used. The initial temperature condition is
set in the * INITIAL_TEMPERATURE_SET card is employed.

Since MSC _PATRAN (structural) does not support thermal boundary conditions
element sets for the boundary heat flux and convection boundary conditions are modified
in the key file. Except for the mechanical boundary condition of degrees of freedom all
the other conditions are applied by modifying the key file.

3.5 Assumptions for the FEM simulation

EDM process, by nature is highly complex involving random sparking and high
localized temperatures. In the case of using stereo-lithography electrodes the problem
becomes more complex due to difference in coefficient of thermal expansion in the
multiple layers of materials involved in the production of the electrode. Hence certain
assumptions are made to tackle this problem and to solve it using finite element analysis.
1. The finite element domain is considered axisymmetric.

2. The heat transfer to the domain is purely by conduction.

3. The electrode material is considered to be elastic-perfectly plastic. The yield stress is the same in tension as in compression.

4. The electrode material is considered stress free before the EDM.

5. The electrode is at an initial ambient temperature of 20°C.

6. Thermo-physical properties of the electrode materials are independent of temperature.

7. The interface between the layers is always continuous and does not hinder heat conduction.

3.6 Material models

The stereo-lithography electrode consists of three separate materials. The thermo-physical properties of these materials are substituted in two different thermal models supported by LS_DYNA. While selecting the thermal material models it is ensured that they account for the thermal expansion coefficient and yield criteria. Two cards are selected *MAT_ELASTIC_PLASTIC_THERMAL,*MAT_THERMAL_ISOTROPIC. The *MAT_THERMAL cards allow thermal properties to be defined for coupled structural/thermal analysis. All the shell and solid elements is defined with the thermal properties. The thermal material identification number is specified in the in the *PART card along with the material identification number.
The thermal isotropic card can be used to specify thermo-physical properties like heat capacity and thermal conductivity. Mat elastic plastic thermal card allows a maximum of eight different temperatures with data to be defined. Hence temperature dependent properties can be applied to this particular material model. To use this model it is necessary to activate the coupled analysis. Properties like coefficient of thermal expansion, yield stress and plastic hardening modulus can be applied in this material model. The thermo-physical properties of all the three materials used in this model are shown below.

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Temp 0 to 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Material Density gm/cc</td>
<td>8.96</td>
</tr>
<tr>
<td>2</td>
<td>Modulus of Elasticity GPa</td>
<td>110</td>
</tr>
<tr>
<td>3</td>
<td>Poissons Ratio</td>
<td>0.343</td>
</tr>
<tr>
<td>4</td>
<td>Coefficient of thermal Expansion µm/m °C</td>
<td>16.4</td>
</tr>
<tr>
<td>5</td>
<td>Heat Capacity J/g.°C</td>
<td>0.385</td>
</tr>
<tr>
<td>6</td>
<td>Thermal Conductivity W/m-K</td>
<td>385</td>
</tr>
</tbody>
</table>

Table 1 Thermo-physical Properties of Copper
<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Material Density gm/mL</strong></td>
<td>1.10</td>
</tr>
<tr>
<td><strong>2. Modulus of Elasticity MPa</strong></td>
<td>3117</td>
</tr>
<tr>
<td><strong>3. Poissons Ratio</strong></td>
<td>0.3</td>
</tr>
<tr>
<td><strong>4. Coefficient of thermal Expansion μm/m °C</strong></td>
<td>79</td>
</tr>
<tr>
<td><strong>5. Yield Stress MPa</strong></td>
<td>64-65</td>
</tr>
<tr>
<td><strong>6. Thermal Conductivity W/m-K</strong></td>
<td>0.15-0.2</td>
</tr>
</tbody>
</table>

Table 2 Thermo-physical Properties of SL resin

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Material Density gm/mL</strong></td>
<td>4 E10</td>
</tr>
<tr>
<td><strong>2. Modulus of Elasticity P</strong></td>
<td>0.35</td>
</tr>
<tr>
<td><strong>3. Coefficient of thermal Expansion μm/m °C</strong></td>
<td>30</td>
</tr>
<tr>
<td><strong>4. Heat Capacity J/g-C</strong></td>
<td>0.30</td>
</tr>
<tr>
<td><strong>5. Thermal Conductivity W/m-K</strong></td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 3 Thermo-physical Properties of Silver paint
3.7 Mesh sensitivity of the FEM model

Thermal problems ideally are sensitive to the meshing. Substantial variation in the temperature distribution was observed when the number of elements varied. Hence to identify a converging model for analysis, several models were tested with an increasing number of elements. The resultant temperature at a predetermined point on the model is plotted against the element number.

![Figure 3-6 Verifying model convergence](image)

The convergence plot is shown as Fig 3-6. The mesh sensitivity is also tested on models without the silver layer. The element numbers of the silver coating is varied keeping the polymer core intact. A variation in temperatures within the range of 60°C to 35°C is observed and a convergence is obtained around 4000 elements.
Next the element numbers on the silver coating is kept intact and the polymer core element numbers are changed. A variation in temperature from 160°C to 25°C is found and a convergence is observed around 4000 elements. Hence it is concluded that the optimal model should have element numbers around 4000. All further analyses were done with element numbers around 4000 with higher densities of elements along the regions were greater temperatures are expected.

3.8 3D Model of the stereo-lithography electrode

The 2D model of the electrode is to be tested for various operating conditions like varying duty cycles, current and coating thickness. Once the optimal 2D model is used to analyze the fringe pattern and stress-strain variations a 3D model is developed. The objective of the 3D model was to validate the results obtained by conducting the analyses on the 2D model. The mesh densities provided on the surfaces are highly significant for getting the precise results, Hence while developing the 3D model care was taken not to upset the progressively increasing mesh pattern on the 2D model. By using the ‘SWEEP’-‘ELEMENT’ option in the MSC-PATRAN the 2D elements were swept through the required angle. MESH CONTROL option was used to realize the through thickness element numbers. Fig 3-7 shows the 3D finite element model of the stereo-lithography electrode.
Figure 3-7 Model of the stereo-lithography electrode

It is noteworthy that only a sector of the cylindrical electrode is considered. This configuration is adopted to reduce the computational time considerably. Again while developing the 3D model the ISOMESH mesh pattern along the polymer surface is replaced by the PAVERMESH. The change in the mesh pattern is to eliminate singular points and resulting element distortion during the SWEEP process. The PAVER pattern which is mainly used on curved surfaces successfully avoids singular points. The sector is one eighth the full periphery and entails four elements along the through thickness direction.
3.9 Boundary conditions for the 3D model

The 3D model is considered as an axisymmetric model and one eighth sector of the full model is considered. Heat flux or boundary flux option is applied to the bottom surface and heat flux is applied in a stepped load curve. A convection boundary condition is provided to the curved face with the heat transfer coefficient $h$ being 100 W/mm$^2$K. Symmetric boundary conditions are provided for the two side faces and a zero heat flux is applied normal to these surfaces. The uppermost nodes are supplied with a constant temperature boundary condition and are kept at 20°C, assumed to be the ambient temperature. The entire model is given an initial temperature condition of 20°C. The uppermost nodes are fixed and are prevented in X translational and Y rotational movement. The nodes on side 2 are allowed Y translational movement. For the 3D model * ELEMENT_SOLID option is used to provide solid elements to the model. This card defines three dimensional solid elements including 4 noded tetrahedral elements and eight noded hexahedrons. The * SECTION_SOLID card is used to input the element type for the 3D model. Here element type 1 is selected these elements are constant stress solid elements. Type 1 elements are much more accurate and are often used for implicit calculations.
3.10 Load Curve

![Diagram of Heat Flux vs Time](image)

**Figure 3-8 Analytical load curve**

To simulate the electro-discharge machining process a stepped load curve is used. The power input in EDM follows a stepped wave form and hence an input load curve as in Fig 3.8 is adopted. The energy input in each cycle is approximately equal to the real time values. The time is in milliseconds and the heat flux unit is in Watts/mm². The input energy and the pulse on time are varied to test the finite element models for various operating conditions. Since the analysis is run to obtain a steady state, it was often necessary to simulate the analysis around 60 sec. To generate a load curve that simulate time steps in milliseconds was manually taxing. Hence a code patch was developed in VB (Visual Basic-6 Enterprise Edition) to write the load curve in the required LS_DYNA format into a text file. With this program it is possible to generate load curves of any levels of pulse-on, pulse-off or power input.
The flux value or the step height is calculated using the relation,

\[ Q = \frac{(V \times I)}{A} \]

Where \( Q \) is the heat flux in Watts/mm\(^2\), \( V \) is the voltage in Volts, \( I \) the current in Amperes and \( A \) is the electrode bottom surface area in mm\(^2\). During the experimental trials a variation in the gap voltage was observed. The gap voltage showed variation in the range of 50 to 80 V. However once the tool begins cutting the voltage stabilizes to 60 to 65 V [5]. Hence during analytical runs the gap voltage was fixed to be 65 V. Table 4 shows the power values calculated for the analytical load curve for the different combinations in combination matrix.

<table>
<thead>
<tr>
<th>Si No</th>
<th>Pulse on time</th>
<th>Pulse off time</th>
<th>Current</th>
<th>Power (V * I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Milli-sec</td>
<td>Milli-sec</td>
<td>Ampere</td>
<td>Watts</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>10</td>
<td>2</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
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<tr>
<td>8</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>65</td>
</tr>
</tbody>
</table>

**Table 4 Flux Values for the runs in the combination matrix**
The total power going into the electrode is calculated as the product of the gap current and gap voltage. The calculated power value is then divided by the number of elements and the resultant value is then applied to discrete elements.
4 RESULTS AND DISCUSSIONS

4.1 Steady state analysis

A steady state analysis is first done on the 2D model. LS-DYNA can perform a steady state two dimensional thermal problem. This facility can be activated by setting the *CONTROL_SOLUTION card, again *CONTROL_THERMAL_SOLVER is used to activate the ACTOL solver which is an iterative gauss type profile solver. Figure 4-1 shows the temperature contour plots of the analysis. The analysis is done for a 2A current and a coating thickness of 300 micrometers.

![Steady State Analysis](image)

A maximum temperature of 43.37°C is observed at the bottom center of the electrode. This simulation gives a clear indication that higher values of temperature can be expected along the center.

Figure 4-1 Steady state analysis showing temperature contours in °C

(2A current and Coating thickness 300um)
More over the outer copper coating having a higher thermal conductivity is largely unsuccessful in conducting the higher concentration of temperature away from the center. Again the polymer core having a lower rate of thermal diffusivity and conductivity is inhibiting thermal diffusion from the polymer metal interface to the polymer inner core resulting in the build up of a high temperature zone along the centre. A higher concentration of temperature can hence be observed along this interface.

A steady state analysis implies that there is no consideration of time in the analysis, however the fringe title in the figure 4-1 shows Time =1. This is actually the termination time for the analysis and not to be mistaken that the analysis follows any variation with time.

4.2 Transient analysis

LS_DYNA performs a transient thermal analysis by implicit integration. This option can be set in the *CONTORL_SOLUTION card. Again ACTOL solver can be selected from the *CONTROL_THERMAL_SOLVER. Since implicit time integration is used, larger time steps can be provided. *CONTROL_THERMAL_TIMESTEP card is used to specify the thermal time steps. The boundary conditions are kept the same apart from the input heat flux, which is applied with a load curve. Initially a ramp load curve is applied to validate the analysis. Again the same analysis is performed with a stepped load curve for a low termination time. The temperature outputs of both the analysis are plotted in figures 4.3 and 4.4, and the results are compared.
Figure 4-2 Transient analysis showing temperature conditions for ramp load

(2A current, 300 um, Time-1sec)

Figure 4-2 shows the transient thermal analysis contour plots of temperature. A ramp load curve is provided. A maximum temperature of 30.34°C is obtained. The plot of time versus temperature obtained along the copper resin interface at node 128 is shown as figure 4-3. A nonlinear variation of temperature with increasing time is observed.
Figure 4-4 shows the transient analysis with a stepped load curve. A maximum temperature of 26.68°C is observed. The plot of time versus temperature obtained along the copper resin interface plotted at node 128 is shown below Fig 4-5. A stepped nonlinear variation of temperature can be observed with increasing time.

Figure 4-4 Transient analysis showing temperature contours for stepped load

(2A, 300 um, 1sec)

Figure 4-5 Temperature Vs Time Plot (Step load curve)
It is clear from the analysis that a ramp load is giving higher values of temperature. However a real time electro discharge machining process involves a stepped load curve and hence for all the subsequent analysis a stepped load curve is employed.

4.3 Coupled thermo-mechanical analysis

A coupled thermo-mechanical analysis can be done in LS_DYNA by setting the *CONTROL_SOLUTION card. Again *CONTROL_THERMAL_SOLVER card is set to select the required solver and the type of analysis. The thermal time step is always set to be higher than the mechanical time step. This is because LS_DYNA uses explicit time integration for structural analysis and implicit time integration for thermal analysis hence it is advisable to set large thermal time steps to ensure adequate thermal conduction. Heat transfer takes place on a longer time scale than mechanical deformation. Apart from the thermal boundary conditions; structural boundary conditions are also specified. In this work all the nodes on the upper side are restricted in the X and Y translational and rotational degrees of freedom. The nodes along the left side are given Y –translational degree of freedom. A stepped load curve is applied and initially the analysis was done for one second. After validating the results and comparing it with the experimental results the analysis is done for a steady state. A saw tooth pattern of the resultant time versus temperature is expected.

Figure 4-6 shows the contour plots for the coupled thermal structural analysis. The analysis is done for one second. The coating thickness is 300um, current is 2A and pulse on time is 30ms. A plot of the time versus temperature is obtained indicating a saw tooth pattern as shown in Fig 4-8. Fig 4-7 shows the fringes of thermal $\sigma_x$ stress obtained from LSPOST output.
Figure 4-6 Coupled structural thermal analysis showing temperature contours after 1 second (2A, 300um, 30)

Figure 4-7 Coupled structural thermal analysis after 1 second
(Contours of $\sigma_x$ –stress MPa)
Figure 4-8 Temperature versus time plot for coupled analysis

The analysis indicates that higher concentrations of temperatures are obtained at the center. However the contour of X-stress indicates that maximum levels of stresses are located away from the center towards the edge. This trend is studied in detail in later analysis under different operating conditions and varying coating thickness. This trend of shifting stress patterns called for closer observation along three specific regions namely the center radial (between the edge and the center) and the edge. All the following studies are concentrated on the temperature fringes and stress patterns along these regions.

The analysis run time was increased to obtain steady state conditions as shown in Fig 4-9. Fig 4-10 shows the steady state temperature versus time taken along the center, radial and edge regions. A steady state condition is observed around 20s. However the analysis is carried out for 60s. All of the subsequent analyses focus on contour plots and graphs obtained at the steady state condition at 60 seconds.
Figure 4-9 2D Coupled structural thermal analysis

(Steady state temperature contours in °C)

Figure 4-10 Temperature versus time plot (Coupled analysis-steady state)

Taken along the area of interest (center, radial, and edge)
4.4 3D Coupled thermo-mechanical analyses

Figure 4-11 Coupled structural thermal analysis after 1 second

(2A, 300um, 1sec)

Figure 4-12 Temperature versus time plot (Coupled 3D analysis after 1sec)
A three dimensional model was developed to validate the results of the coupled analysis. Fig 4-11 shows the coupled analysis of the 3D model. A stepped load curve similar to the 2D analysis was applied. Fig 4-12 shows the temperature versus time plot for the 3D coupled analysis for 1 sec. This result shows similar trend to the 2D analysis Fig 4-8.

4.5 Heat flux boundary condition on selected elements

The real time electrical discharge machining process is characterized by random sparking. The sparks are generated in a random manner between the electrode and the work piece. Hence inputting the heat flux boundary condition to the model was a cause of concern. Predicting the points which are receiving the hits at a specific time is difficult to analyze and might require a stochastic approach. However to eliminate the complexities involved in stochastically analyzing the problem a unique way of inputting the heat flux was adopted.

Figure 4-13 Electrode face after 300 sec

Figure 4.13 shows the electrode surface after receiving the spark hits at a certain stage (300sec) of the machining process. This image when scanned under a microscope revealed erosion points through out the surface.
These points can be assumed to be the ones which are taking the maximum number of hits. Since a quarter model of the electrode is used for analysis, a region from the center of the electrode to the edge was scanned and a total of 25 prominent hit points were identified along the radial direction. The optimal 2D model used for finite element analysis consists of 75 elements along the bottom face; hence it is assumed that every third element along this face is subjected to the analytical power input. Heat flux was applied at these selected elements using the same stepped curve, (i.e.) all at once. This technique aims to bring the analysis process closer to the real time process, and to make the chaotic sparking phenomenon during the EDM process in to a more logical and manageable one.

![Contour of Temperature](image)

**Figure 4-14 Contours of temperature (Flux applied on selected elements)**

Figure 4.15 shows the temperature fringes of the above analysis when the flux is applied to the selected elements only.
Though the fringes do not indicate significant variation from the uniformly distributed flux analysis, there are subtle changes in the width of the fringe ranges. Again since this is closer to the actual process, for all the further analysis the flux load curve was applied to selected elements only.

4.6 Stress analysis and matrix

![Figure 4-15 Electrodes with 400 and 300 micrometers coating thickness](image)

To analyze the performance of the metallized SL electrode model under different operating conditions a combination matrix consisting of various levels of the process parameters is selected. The main factors of interest are the current, pulse on time and coating thickness. Two levels of each of these factors are considered, namely high and low levels. Since there are three factors at two levels the combination matrix is actually a $2^3$ factorial design comprising of eight combinations. The two levels of coating thickness are 400 and 300 micrometers. The pulse-on times are 20 and 30 milli-seconds and the pulse current are 2 and 4 Amperes, respectively. The selections of range of the process parameters are based on the experimental approach and findings of an experimental study [5]. The analytical results from the combination matrix are subjected to two kinds of studies.
1) The contour plots of X-stress, maximum shear stress and maximum shear strains obtained from LS-POST are studied for the stress distributions and stress patterns. Again a specific region of concentrated maximum shear stress is identified and the stress values are plotted against time using LSPOST.

2) The values of maximum temperature, maximum shear stress and maximum shear strains and maximum Y displacement are tabulated and subjected to statistical analysis. This is done to determine the effects of the process parameters on the selected responses.

<table>
<thead>
<tr>
<th>Sl-No</th>
<th>Pulse – On (ms)</th>
<th>Current(A)</th>
<th>Coating Thickness(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
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</tr>
<tr>
<td>8</td>
<td>10</td>
<td>1</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 5 performance parameters combination matrix
The combination matrix comprising a total of eight experiments is shown as Table 5. As already mentioned the experimental results showed inconsistent wear patterns [5]. The concentrated wear was observed along the center, radial and edge region. However, majority of the electrodes experienced wear at the radial region. The result (maximum shear stress) from the matrix is studied for identifying locations of concentrated wear and is correlated with the experimental findings.

4.7 Stress patterns along the metal–resin interface

The review of previous works indicated that during EDM process the electrodes experience localized wear when subjected to frequent thermal loading. In this case the experimental results showed localized wear patterns and the wear was commonly experienced along the center, radial and edge regions with majority falling in the radial region. One of the principal objectives of this analysis is to identify the stress patterns and distribution along the metal resin interface and its relationship to the electrode failure. A specific case from the combination matrix having high levels for all the factors is considered. The first run in the matrix for pulse on time of 30 ms, current 2A and 400 microns coating thickness, hereafter referred to as the worst case, is analyzed.

Figure 4.16 and 4.17 show the shear and X-stress distributions in the model for this worst case. The whole of the copper coating is experiencing higher levels of stress compared to the silver and the resin layers. However concentrated regions of X-stress and maximum shear stress are visible along the radial region which is shifted from the edge and more towards the centre. The maximum value of the maximum shear stress obtained for this case is 17.13 GPa which is closer to the yield limit of the copper coating.
The location of these higher stress concentration regions is shifted more to the center in this case; this is in good agreement with the experimental results where a localized wear pattern is obtained at the center for similar operating conditions.

The contour plots of maximum temperature, maximum shear stress, maximum shear strain, X-stress, maximum X-displacement, maximum Y-displacement, maximum principal stresses and maximum principal strains are given in appendix-A for all the runs in the matrix.

Figure 4-16 Contours of Maximum Shear Stress in MPa for 30ms, 2A, 400um
The reviewed literature indicated that mismatches in the coefficient of thermal expansion values are the major cause of failure in polymer metal interfaces. The stereo-lithography EDM electrode is also characterized by a similar interface. Hence a closer evaluation of the performance of the individual layers of the electrode to cyclic thermal loading becomes indispensable. Copper is a good conductor of heat and is having a high value for the CTE. The polymer core in comparison is inherently nonconductive and is characterized by a very low value for the CTE. Figure 4.18 and 4.19 show the X and Y displacement of the electrode for 30ms pulse-on, current 2A, and 400um coating thickness (worst case). The analysis shows that there is considerable movement of the corresponding layers in the X and Y directions respectively.
The displacements are scaled to a factor of 100. The fringes indicate that the copper layer experiences the maximum displacement to the order of 5 to 6 micrometers.

The structural boundary conditions are specified such that the nodes along the top surface are restricted in X, Y and Z rotation and translation movements. The nodes along the left side are restricted to X, Y, Z rotation and X, Z translation, giving Y translation degree of freedom. This is in close conformity with the real time process. This non uniform movement of electrode layers was observed in all of the analytical runs in the combination matrix. The contour plots of the X and Y displacement of all the runs are added in appendix A.
Figure 4-19 Contours of Y-Displacement in mm for 30ms, 2A, 400um

The resultant analysis indicates that due to the X and Y translational movement the electrode is experiencing an outward expansion becoming prominent as a bulge along the centre of the tool (Results scaled with a scale factor of 100). Again the copper layer experiences maximum X directional displacement compared to the polymer and silver layers. These inconsistent displacements also add up to the shear stresses in the electrode layers leading to the failure of the copper coating.
4.9 Stress and strain plots for the combination matrix

The values of shear stress, shear strain and X-stress along a line in the region of maximum shear stress are plotted against time. The line considered covers all three layers of the model. The values of X-stress, X-strain and maximum shear stress are plotted for all the cases in the combination matrix. Figure 4.20 shows the contour plot of maximum shear stress for the worst case.

Figure 4-20 Contours of maximum shear stress in MPa for the worst case

Figure 4.22 shows the X-stress values plotted versus time. A line along the region of maximum shear stress is considered and the elements along the line are selected. The graph indicates that the copper elements are experiencing tensile stress where as the silver and the polymer elements are showing compressive stresses.
Figure 4-21 Region of interest (the selected nodes along the three layers)

Figure 4-22 Plot of Time versus X-Stress in MPa for

Case 1: Pulse on -30us, Current – 2A, Coating thickness 400um (worst case)
Figure 4-23 shows the maximum shear stress values plotted against time. The graph indicates that the copper elements are experiencing higher values of shear stress. The shear stress values for the silver and the polymer elements show a sudden increase and then stabilize as the solution reaches steady state. The stress values for the copper elements show a constant upward trend throughout the analysis period. Again the maximum shear stress value is obtained at the element at the bottom surface.

Figure 4-23 Plot of Time Vs Maximum Shear Stress in MPa

Figure 4.24 shows the X-strains plotted against time. Maximum X-strain values are obtained for the copper elements.
Figure 4-24 Plot of Time versus X-Strain

Similar graphs are plotted for all the cases in the combination matrix and the graphs are given as appendix B. Table 6 shows summary results from the combination matrix analysis.
<table>
<thead>
<tr>
<th>S1 No</th>
<th>P-On (ms)</th>
<th>Current (A)</th>
<th>Coat thick (um)</th>
<th>Max Temp (°C)</th>
<th>X-Stress-Radial (GPa)</th>
<th>Shear Strain (GPa)</th>
<th>Shear Stress (GPa)</th>
<th>X Displacement (um)</th>
<th>Y Displacement (um)</th>
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</thead>
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<tr>
<td></td>
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<td></td>
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<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
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<td>1.147e-5</td>
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<td>10</td>
<td>2</td>
<td>400</td>
<td>47.05</td>
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<td>27.15</td>
<td>1.008e-5</td>
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<td>400</td>
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<td>17.55</td>
<td>6.14e-6</td>
<td>1.764e-3</td>
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<td>1</td>
<td>400</td>
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<td>-11.61</td>
<td>18.23</td>
<td>3.33e-6</td>
<td>1.66e-3</td>
<td>0.08</td>
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</tr>
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<td>1.687e-3</td>
<td>0.09</td>
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</table>

Table 6 Results from the combination matrix analysis
4.10 Statistical analysis

The data obtained from the FEM analysis is statistically analyzed with the design of experiment technique (DOE). Stat Ease Inc, Design Expert software is used to perform the analysis. A $2^K$ factorial design is chosen, factorial designs are used to evaluate two or more factors simultaneously. The different treatments are combinations of the levels of factors considered. The factorial designs permit detection of interactions among the factors and hence make careful study of them possible. The interaction signifies how the mean differences for different levels of one factor vary over different levels of the other factor. The Analysis of Variance (ANOVA) is the technique used for analyzing and interpreting the interaction among factors.

In this case a $2^3$ factorial design is used. This implies that there are three factors treated at two levels, a high level and a low level. Pulse on time, gap current and coating thickness are the three factors selected.

1. Two levels were selected for the pulse-on time, $10 \, \mu s$ (low), and $30 \, \mu s$ (high).
2. The two levels for gap current chosen are, $1 \, A$ (low), and $2 \, A$ (high).
3. Likewise two levels for copper plating thickness selected are $300 \, \mu m$ (low), and $400 \mu m$ (high).

This study is focused mainly on determining the temperature, residual stresses, strain distribution and the deformation in the stereo-lithography electrode during the electro discharge machining process, and hence the four responses chosen are the maximum temperature, maximum shear stress, maximum shear strain and the maximum Y displacement (bulging). With the finite element model it is possible to perform analysis on all the eight treatment combinations in the $2^3$ design.
The gap current can be set in the flux value; the pulse on time can be set in the load curve and the coating thickness by modeling one model with 300 \( \mu \text{m} \) copper thickness and the other with 400 \( \mu \text{m} \) thickness. Figure 4-25 shows the design matrix as entered in the design expert software.

<table>
<thead>
<tr>
<th>Stbl</th>
<th>Run</th>
<th>Block</th>
<th>Factor 1 Pulse Ons (s)</th>
<th>Factor 2 Current A (A)</th>
<th>Factor 3 Current B (A)</th>
<th>Response 1 Temperature °C</th>
<th>Response 2 Max Shear Stress MPa</th>
<th>Response 3 Max Shear Stress MPa</th>
<th>Response 4 Max Y Displ. (\mu m)</th>
</tr>
</thead>
<tbody>
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<td>1.00</td>
<td>300.00</td>
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<td>9.0</td>
<td>0.001656</td>
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<td>50.23</td>
<td>17.1</td>
<td>0.003164</td>
<td>5.49</td>
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</table>

**Figure 4-25 The 2\(^3\) Factorial design matrix**

The data is then analyzed and the ANOVA table is obtained for each of the four responses under consideration. The ANOVA table indicates the significance level of the model terms and their interaction. A confidence level of 95% is sought in this particular analysis. The ANOVA table also gives values for the mean, the standard deviation, R-squared and adjusted R-squared. Since a 95% confidence interval is expected values of “Prob >F” less than 0.0500 indicate that the model terms are significant. The different plots obtained are the normal probability plot, residuals versus factor plots, residuals versus predicted plot, plot of outliers, the interaction graphs, the contour plots and the 3D surface interaction plot. In this section only the normal plot of residuals, interaction plot and contour plots are given all the other plots are provided in appendix C.
4.10.1 Effect on maximum temperature

Table 6 shows the ANOVA table for the maximum temperature. A model F-value of 323.89 implies the model is significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of “P > F” less than 0.0500 indicate model terms are significant. In this case A and B and AB are the significant model terms.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Prob &gt; F</th>
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</thead>
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<td>Model</td>
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<tr>
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<td>6.68</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>Cor Total</td>
<td>311.47</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6 ANOVA table for temperature

Adjusted R-squared of 0.9928 is in reasonable agreement with the predicted R-squared of 0.9836. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 35.267 in this case indicates an adequate signal. The final equation of the actual factors is given by:

Temperature = 25.33250 – 0.085250 * Pulse-On + 9.90750 * Current + 0.11775 * Pulse-On * Current
4.10.2 Residual analysis: temperature

The residual analysis is done to detect any violations to the ANOVA assumptions. The residual plots and other relevant plots indicate deviations from the basic assumptions made while performing the ANOVA.

The normal probability plot checks the normality of the residuals. Fig 4.26 shows the normal probability plot for the factor temperature. The lack of trends implies that the model is following the constant variance assumption.

![Figure 4-26 Normal probability plot (Temp)](image-url)
4.10.3 Factor effects: temperature

Figure 4-27 Interaction graph (Temp)

Figure 4.27 shows the interaction graph for the response temperature. It is clear from the graph that gap current is having the major influence on temperature. Higher ranges of temperatures are observed at higher levels of gap current. It is obvious from the plot that there is significant interaction between pulse on time and gap current at high level of gap current. Whereas at low level of current there is not considerable interaction among the factors. The maximum temperature is obtained for the high level of pulse on time and current and vice-versa. Figure 4.28 shows the contour plot of the surface generated by the prediction equation for the temperature. It can be inferred from the contour plot that there is a linear variation of temperature with increasing values of both the factors. The response surface plot shown as Fig 4.29 validates this conclusion.
4.10.4 Contour plot and response surface: temperature

**Figure 4-28 Contour plot (Temp)**

**Figure 4-29 Response surface (Temp)**
4.10.5 Effect on maximum shear stress

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
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<td>Model</td>
<td>274.54</td>
<td>3</td>
<td>91.51</td>
<td>251.59</td>
<td>&lt; 0.0001 significant</td>
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<tr>
<td>B</td>
<td>132.03</td>
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<td>362.97</td>
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<tr>
<td>C</td>
<td>141.96</td>
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<td>390.27</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Residual</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>276</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 ANOVA table for shear stress

Table 7 shows the ANOVA table for the maximum shear stress. A model F-value of 251.59 implies the model is significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of “P >F” less than 0.0500 indicate model terms are significant. In this case B and C are the significant model terms. Adjusted R-squared of 0.9908 is in reasonable agreement with the predicted R-squared of 0.9789. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 40.038 in this case indicates an adequate signal. The final equation of the actual factors is given by:

Maximum Shear Stress = (+35.38750-0.026250* Current-0.084250* Coat-Thick ) GPa
4.10.6 Residual analysis: max shear stress

The residual analysis is done to detect any violations to the ANOVA assumptions. The residual plots and other relevant plots indicate deviations from the basic assumptions made while performing the ANOVA.

The normal probability plot checks the normality of the residuals. Fig 4.30 shows the normal probability plot for the factor temperature. The lack of trends implies that the plots model is following the constant variance assumptions.

Figure 4-30 Normal Probability plot (Shear stress)
4.10.7 Factor effects: max shear stress

Figure 4-31 Factor-Current (Shear stress)

Figure 4-32 Factor-Coating thickness (Shear stress)
Figures 4.31 and 4.32 show the interaction graphs for the response shear stress. It is clear from the graph that there is no significant interaction between the significant model terms. However both current and coating thickness has major influence on shear stress. Higher ranges of shear stress are observed at higher level of gap current and lower level of coating thickness.

4.10.8 Contour plot and response surface (Shear stress)

Figure 4-33 Contour plot (Shear stress)
Figure 4-34 Response Surface (Shear stress)

Figure 4.33 shows the contour plot of the surface generated by the prediction equation for the shear stress. It can be inferred from the contour plot that as the level of coating thickness increases the shear stress values decreases. The response surface shown as Fig 4.34 also validates this point.
### 4.10.9 Effect on maximum shear strain

Table 8 ANOVA table for shear strain

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3.53E-06</td>
<td>3</td>
<td>1.18E-06</td>
<td>1743.94</td>
<td>&lt; 0.0001 Significant</td>
</tr>
<tr>
<td>A</td>
<td>3.92E-08</td>
<td>1</td>
<td>3.92E-08</td>
<td>58.18</td>
<td>0.0016</td>
</tr>
<tr>
<td>B</td>
<td>3.48E-06</td>
<td>1</td>
<td>3.48E-06</td>
<td>5160.5</td>
<td>&lt; 0.0001</td>
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<td>AB</td>
<td>8.85E-09</td>
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<td>8.85E-09</td>
<td>13.13</td>
<td>0.0223</td>
</tr>
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<td>Residual</td>
<td>2.70E-09</td>
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<td>6.74E-10</td>
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<td></td>
</tr>
<tr>
<td>Cor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3.53E-06</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8 shows the ANOVA table for the maximum shear strain. A model F-value of 1743.94 implies the model is significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of “P > F” less than 0.0500 indicate model terms are significant. In this case B and C are the significant model terms.

Adjusted R-squared of 0.9987 is in reasonable agreement with the predicted R-squared of 0.9969. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 79.640 in this case indicates an adequate signal. The final equation of the actual factors is given by:

\[
\text{Maximum shear strain} = +4.51250\text{E-004} - 2.97500\text{E-006}\times\text{Pulse-On} + 1.18550\text{E-003}\times\text{Current} + 6.65000\text{E-006}\times\text{Pulse-On}\times\text{Current}
\]
4.10.10 Residual analysis: maximum shear strain

The residual analysis is done to detect any violations to the ANOVA assumptions. The residual plots and other relevant plots indicate deviations from the basic assumptions made while performing the ANOVA.

The normal probability plot checks the normality of the residuals. Fig 4.35 shows the normal probability plot for the response maximum shear strain. The lack of trends implies that the plots model is following the constant variance assumptions.

![Figure 4-35 Normal probability plot (Shear strain)](image)
4.10.11 Factor effects: maximum shear strain

Figure 4-36 Interaction plot (Shear strain)

Figure 4.36 shows the interaction graph for the response shear strain. It is clear from the graph that gap current has major influence on shear strain. There is significant interaction between gap current and pulse on time at low level of current. However at high level of current there is no significant interaction between the model terms.
4.10.12 Contour plot and response surface: maximum shear strain

**Figure 4-37 Contour plot (Shear strain)**

Figure 4.37 shows the contour plot of the surface generated by the prediction equation for the shear strain. It can be inferred from the contour plot that there is a linear variation of shear strain with current and pulse on time. Lower shear strains are observed at low level of current and pulse on time. The response surface plot shown as Fig 4.38 validates this point.
Figure 4-38 Contour plot (Shear strain)

4.10.13 Effect on maximum Y- displacement

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Prob &gt; F</th>
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<td>Model</td>
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<td>16.1312</td>
<td>154.2303</td>
<td>&lt; 0.0001 significant</td>
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<tr>
<td>B</td>
<td>16.1312</td>
<td>1</td>
<td>16.1312</td>
<td>154.2303</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Residual</td>
<td>0.62755</td>
<td>6</td>
<td>0.104592</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>16.75875</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
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<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9 ANOVA table for max Y displacement

Table 9 shows the ANOVA table for the maximum Y displacement. A model F-value of 154.23 implies the model is significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of “P > F” less than 0.0500 indicate model terms are significant. In this case B is the significant model term.
Adjusted R-squared of 0.9863 is in reasonable agreement with the predicted R-squared of 0.9755. Adequate precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 17.286 in this case indicates an adequate signal. The final equation of the actual factors is given by:

$$\text{Max Y displacement} = +0.66250 + 2.84000 \times \text{Current}$$

4.10.14 Residual analysis: max Y displacement

The residual analysis is done to detect any violations to the underlying ANOVA assumptions. The residual plots and other relevant plots indicate deviations from the basic assumptions made while performing the ANOVA.

The normal probability plot checks the normality of the residuals. Fig 4.39 shows the normal probability plot for the factor maximum Y displacement. The lack of trends implies that the plots model is following the constant variance assumptions.

![DESIGN-EXPERT Plot](image)

**Figure 4-39 Normal probability plot (Max Y displacement)**
4.10.15 Factor effects: maximum Y displacement

Figure 4-40 Normal probability plot (Max Y displacement)

Figure 4.40 shows the factor current interaction graph for the response maximum Y displacement. It is evident from the graph that there is considerable variation in the Y displacement with change in levels of the factor current. At lower ranges of gap current the maximum Y displacement is low and vice versa.
4.10.16 Contour plot and response surface: Maximum Y displacement

![Contour plot](image)

**Figure 4-41 Contour plot (Max Y displacement)**

Figure 4.41 shows the contour plot of the surface generated by the prediction equation for the maximum Y displacement. It can be inferred from the contour plot that as the level of current increases the maximum Y displacement value increases. The response surface plot shown as Fig 4.42 validates this point.
Figure 4-42 Contour plot (Max Y displacement)
4.11 Summary and discussion

Using finite element software LS-DYNA, the FEM model of the stereo-lithography electrode was subjected to a range of operating conditions. The process parameters like pulse on time, gap current and coating thickness were changed and the results are tabulated. The temperature, stress (both x-stress and shear stress), shear strain, x and y direction nodal displacements were obtained. The x-stress, shear stress and shear strain values along a line in the region of maximum shear stress are plotted against time and compared. The x and y displacement contour plots scaled to a factor of 100 are also taken. A statistical analysis of the tabulated values of temperature, shear stress and shear strain was performed with a $2^3$ factorial design. Design expert software was used for the purpose.

The experimental results had shown that localized wear was the most common type of wear observed in the stereo-lithography electrode [5]. Again the catastrophic failure of the electrode was preceded by a dimple or a tiny protrusion of the copper plating and accelerated wear of the electrode in this region. Due to the deformation of the copper plating the gap between the electrode and the work piece reduces and finally due to the concentrated sparking and erosion the copper plating wears out.

The FEM results indicate that there is wide discrepancy in the temperature fringes obtained. Higher values of temperatures are obtained along the copper plating and the polymer-metal interface with very less thermal diffusion into the polymer layer. This variation in the fringe pattern could be due to the very low thermal conductivity of the polymer material when compared to the copper layer.
Again the thin copper plating is largely unsuccessful in channeling the heat away from the polymer-metal interfacial region leading to increased levels of temperature along the copper coating and the metal-resin interface. It can be clearly seen from the temperature fringe plot that there is very less thermal diffusion into the polymer layer and increased temperature levels at the centre of the electrode.

There is considerable amount of nodal displacement in the x and y directions. The model experiences an outward expansion and it becomes prominent as a bulge along the centre of the model. Again the copper plating is experiencing the maximum amount of displacement compared to the silver and the polymer layers. The increased nodal displacements in the copper region can be attributed to the high coefficient of thermal expansion of copper. The deformation of the electrode was observed as a prominent bulge in the center. In EDM protruded parts and edges receive more spark hits and hence are subjected to accelerated wear. Hence it is quiet obvious that the deformed portion of the electrode will receive concentrated sparking and will wear out rapidly. However in experimental trials the wear was located more towards the edges [5]. The table shows that the wear happens at the centre, radial and edge locations, however mostly at the edge. This anomaly in the wear location can be a locating problem. The experimental setup did not have a locating mechanism to ensure that the electrode and the workpiece are aligned properly. The manual alignment of the electrode and the workpiece is prone to errors, this skewing of the electrode and subsequent difference in the electrode gap explains the irregularity in the wear location.
The X-stress plots indicate that the copper plating is experiencing tensile stress levels whereas the silver and the polymer regions are in compression. In other words the polymer and the silver layers are expanding more than copper, and the copper is holding them in compression. This phenomenon as already explained is begot by the coefficient of thermal expansion mismatch in the polymer-metal joints. The CTE mismatch is the primary reason for failure in most of the polymer metal joints subjected to thermal loads. The shear stress plots indicate that the copper layer is experiencing more shear stress when compared to the silver or the polymer layers. The contour plots show concentrated shear stress regions along the copper plating shifted more towards the surface. These concentrated shear stress regions might experience surface cracking which aggravates the sacrificial wear of the electrode during machining.

For the statistical analysis, maximum shear stress, maximum shear strain, maximum temperature and maximum Y displacement at the region of interest were selected as the responses. The factors chosen were the gap current, pulse on time and the coating thickness. The ANOVA of temperature shows that higher temperature values are obtained with high level of pulse on time and gap current, with gap current being the most influential factor. The temperature values are showing a linear variation with increasing levels of gap current. The shear stress values are influenced by the gap current and the coating thickness. The shear stress values are higher at high level of gap current and lower at low levels of gap current. However shear stress values are high at low level of coating thickness and shear stress values are low at high level of coating thickness. This explains why the copper plating experiences surface cracking and increased wear with the thinning of plating during machining.
Again the shear strain values are influenced by pulse on time and the gap current. High values of shear strains are obtained at high level of pulse on time and gap current. The factor which is having the most influence on the maximum Y displacement value is the gap current. The values of maximum Y displacement show considerable variation with different levels of gap current. The maximum Y displacement value increases with increasing level of gap current and vice versa.

These results give strong inference that reduced thermal diffusion owing to the low thermal conductivity of the polymer layer, the CTE mismatch between the polymer and copper layers and the buckling of the electrode could be the reason for the premature and localized failure of the electroformed stereo-lithography EDM electrode.
4.12 Comparison of experimental and analytical results

In this section the experimental results from [5] are compared with the analytical results for specific cases. As already explained the three regions of interest are the centre, the radial and the edge. The nodal temperature along the polymer resin interface in these regions are plotted against time and compared with the experimental results. The experimental values of the temperatures were obtained by using thermo-couples placed along the interface. Fig 4.43 shows the contours of temperature for a pulse on of 10us, current of 1A and coating thickness of 400 um. Fig 4.44 shows the analytical time versus temperature plot for 60 seconds. The temperature values show a steady increase till 15 seconds and then achieve a steady state. Maximum temperature is obtained at the center, and decreasing towards the edge region.
Figure 4-44 Time versus temperature (centre, radial and edge)

Figure 4-45 Temperature vs. time experimental and analytical represented symbolically
Figure 4-46 Contours of temperature (30us, 2A, 300um)

Figure 4-47 Contours of Temperature (centre, radial and edge)
Figures 4-45 and 4-48 shows the experimental temperature versus time distribution, the analytical temperature distribution is represented symbolically. The plots indicate that the analytical temperature values are lower when compared to the experimental ones. For pulse on time of 10us, current of 1A and coating thickness of 400 um, the maximum steady state temperature recorded at the center, radial and edge were 42°C, 38°C and 35°C, respectively, whereas the analytical results showed 38°C, 35°C, and 32°C, respectively. For pulse-on time of 30us, current of 2A and coating thickness of 300um, the experimental readings were 50°C, 45°C and 40°C, respectively, whereas the analytical results showed 48°C, 45°C, 40°C, respectively.
Again it can be seen that the analytical plots show the temperature readings attaining a steady state condition very early around 10 to 20 seconds, whereas the experimental plot seems to attain a steady state at around 100 seconds. Again the experimental plot show variation in the temperature values till the cutting is over. This difference in the temperature values of analytical and experimental can be attributed to the different uncontrollable factors in the experimental setup. The thermocouples where inserted into the electrode by drilling holes into the electrode, which raises the possibility of air entrapments. The air being an insulator takes longer time for heating up and will result in fairly higher values in the recorded temperature. Again the thermocouples could not be inserted to have contact with the outer copper layer. Thus the time lag in the experimental plots in attaining steady state can be attributed to the time needed for the resin layer remaining between the thermocouple and the electrode to heat up.
5 HEAT FLUX CANALS AND EFFECT ON THE RESPONSES

The studies performed on the finite element model of the stereo-lithography EDM electrode indicates that temperature plays a major role in the premature failure of the electrodes. Hence it is quite obvious that efficient cooling techniques capable of either cooling down or channeling the heat away from the failure region can significantly improve the performance characteristics of the electrode. In this work such a procedure is selected, heat ducts are placed in-situ in the region of maximum thermal gradients to enhance the thermal diffusion to the regions which has the lowest coefficient of thermal conductivity.

Copper wires are to be used as the heat ducts or channels. To study the effectiveness and feasibility of this procedure is one of the objectives of this study. Previous results have identified that gradients of higher temperature tends to focus around the centre of the electrode, and regions of concentrated residual stresses are observed along the centre and the radial regions. Thus the FEM model is modified with an in-situ heat channel. Two cases are analyzed, one with the heat channel in the center and one in both center and the radial position. The dimension (diameter) of the heat channel is set equal to the coating thickness. Again the heat channel diameter is changed to twice the coating thickness and the results are plotted. The responses of interest are the maximum temperature, maximum shear strain, maximum shear stress and maximum Y-displacement.
The whole idea of using heat flux canals is to mitigate the effects of higher gradients of temperature on the mechanical properties of the resin. Again the flux canals are expected to reduce the higher rate of expansion of the copper layer by allowing thermal diffusion into the polymer regions. In this study only the worst case from the combination matrix is modeled. The preliminary analysis has shown the worst case phenomenon exists at high level of current and pulse on time. Hence all the subsequent analysis will focus on this worst case with current 2A, pulse on time 30 us and a coating thickness of 400 um.

5.1 Heat flux duct positioned at the centre (twice the coating thickness)

![Heat Duct in the Centre](image)

Figure 5 - 1 Electrode modified with heat duct in the centre
Figure 5.1 shows the modified electrode with the heat canal placed at the centre, the dimension of the canal is specified to be twice the coating thickness and hence 800um. Since a 2D model is used the duct dimension is 400um. The boundary conditions were kept the same with similar loading conditions and a cyclic load curve.

The analysis results showed a drastic drop in the temperature gradients observed in the electrode. The original case showed maximum temperature to be around 50°C where as the modified model showed 26°C which is almost a drop of fifty percent. Again the all the other responses of interest namely the maximum shear stress values and shear strain showed considerable reduction. Figure 5.2 shows the contour plots of temperature of the modified electrode with the heat flux canal along the centre, it is noteworthy that the bulge along the centre is shifted to the radial position.

![Figure 5 - 2 Contour plot of the temperature °C (modified electrode)](image)

Figure 5 - 2 Contour plot of the temperature °C (modified electrode)
Figure 5 - 3 Contour plot of Y-displacement in mm (modified Electrode)

The Y-displacement plot shown as Fig 5.3 indicates that the displacement values show significant reduction with the modified electrode. The maximum shear stress plot and the shear strain plot also show the same decreasing trend.

Figure 5 - 4 Contour plot of maximum shear stress MPa (modified electrode)
Figure 5 - 5 Contour plot of maximum shear strain (modified electrode)

5.2 Heat flux duct positioned at the centre and radial region (twice coat thickness)

Figure 5 - 6 Modified electrode with heat ducts (twice the coating thickness) at the center and radial region
The electrode when modified with a single heat canal placed along the centre showed decreasing values for all the responses considered. However the y – directional displacement seems to shift from the centre location to the radial region. This shifting of the protrusion is further indication that temperature is the key player in determining the deformation of the electrode. The placing of the heat canal along the centre region facilitated the channeling of higher thermal gradients to diffuse into the polymer regions and resulted in the shifting of the bulge from the region. Hence it is evident that a second heat canal placed in the radial region can improve the performance and obviate the protrusion from occurring along the radial region. In the subsequent analysis a second heat canal is placed in the radial region and the analysis is repeated with the boundary conditions being the same.

![Figure 5 - 7 Contour plot of temperature °C](image)

Figure 5 - 7 Contour plot of temperature °C
Fig 5.7 shows the temperature fringes of the modified electrode with the heat flux canals at the centre and radial regions. There is considerable reduction of temperature ranges from the original worst case. Again the maximum temperature zone is more uniformly distributed when compared to the maximum temperature at the centre in the worst case. The bulge in the radial region observed with the heat canal at the centre is reduced significantly and the electrode profile at the bottom appears to be more even. Fig 5.8 shows the maximum displacement in the Y direction. The values show considerable reduction and the contour plots show no prominent bulging of the electrode in the Y direction. The maximum shear stress value in the plot Fig 5.9 also shows considerably reduced values.

Figure 5 - 8 Contour plot of y-displacement in mm
Figure 5 - 9 Contour plot of max shear stress in MPa

Figure 5 - 10 X-stress Vs Time with heat flux canal 2 * coat thickness
Figure 5 - 11 Max shear stress Vs Time with heat flux canals 2 * coat thickness

Figure 5 - 12 Max shear strain Vs Time with heat flux canals 2 * coat thickness
5.3 Heat flux duct positioned at the centre and radial region (equal coat thickness)

![Figure 5 - 13 Modified Electrode with heat ducts (equal to the coating thickness) at the center and radial region](image)

The model of the electrode is again remodeled with heat canals of dimension same as that of the coating thickness, placed on the centre and radial locations. This analysis is done to study the effect of different duct dimensions on the main responses namely the temperature, Y-displacement and maximum shear stress. Fig 5.14 show the temperature contour plots, the values are much lesser than the original worst case however there is a one degree increase in the maximum value compared to the model with ducts having twice the coating thickness. Again the y-displacement plot shown as Fig 5-15, indicates reduced bulging and y-directional movement however the values are higher when compared to the model with ducts of dimension twice the coating thickness. The same trend is also reflected in the maximum shear stress plots.
Figure 5 - 14 Contour plot of temperature °C

Figure 5 - 15 Contour plot of max y-displacement in mm
Figure 5 - 16 Contour plot of max shear stress in MPa

<table>
<thead>
<tr>
<th>2A,30us,400um (worst case)</th>
<th>Max Shear Stress</th>
<th>Max Temperature</th>
<th>Max-Y displacement (um)</th>
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</thead>
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<tr>
<td>With out HFC</td>
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<td>50.23</td>
<td>6.49</td>
</tr>
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<td>HFC at Center (2CT)</td>
<td>9.8</td>
<td>27.88</td>
<td>1.78</td>
</tr>
<tr>
<td>HFC at Cnter &amp; Radial (2CT)</td>
<td>6.8</td>
<td>26.24</td>
<td>.373</td>
</tr>
<tr>
<td>HFC at Center &amp; Radial (CT)</td>
<td>10.75</td>
<td>29.71</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 9 Comparison Table for the worst case with and without HFC (CT and 2 CT)
This clearly indicates that by increasing the dimension of the ducts employed in the model the deformation of the electrode during repeated thermal loading can be controlled to a good extend. The experimental and analytical studies indicate that the deformation of the electrode and the subsequent concentrated sparking as the primary reason for the premature failure of the electrode. Hence reducing the pronounced protrusion of the electrode by employing heat ducts can significantly improve the performance characteristics and life of the electrode.
6 CONCLUSION AND FUTURE WORK

It has been shown that temperature plays a lead role in the premature failure of rapid prototyped electrical discharge machining electrode. The multi material configuration of the electrode stymies efficient heat conduction during repeated thermal cycles. This results in high temperature zones concentrated mainly towards the centre along the polymer metal interface. The higher thermal gradients cause the electrode to deform as a pronounced bulge or protrusion, often characterized as a ‘dimple’ during experiments. This region invites concentrated sparking and increased electrode wear leading to the premature failure of the electrode.

Again higher levels of thermal stress were observed along the copper layer. This can be attributed to the high inconsistency in the coefficient of thermal expansions of the materials. The CTE mismatch causes the copper plating and the resin layer to expand quickly, the CTE for the resin is very high as compared to the copper or the silver layers with silver layer having the lowest CTE. Hence the rapid expansion of resin is prevented by the surrounding copper plating invoking compressive stresses in this region. The copper plating being the outermost layer is free to expand and hence experiences tensile stress levels. The analysis results also indicate that the silver layer fails to match the high levels of CTE of both resin and copper and produces a holding up effect between the layers inducing higher stress levels throughout the polymer metal interface. These stress variations can be a reason for the surface cracking and detachment of plating from the polymer core observed in some higher level factor experiments.
The statistical analysis studied the effects of the performance parameters like pulse on time, pulse of time and coating thickness on the main responses, namely temperature, maximum shear stress, maximum shear strain and maximum Y displacement. The results indicate that temperature is influenced by current and pulse on time with current being the most influential factor. A linear variation of temperature is observed with increasing gap current. The maximum shear stress values are influenced by current and coating thickness. Maximum shear stress values reduced with increasing coating thickness. The maximum shear strain values are influenced by current and pulse on time. Higher level of factors yielded increased values of maximum shear strain. The maximum Y displacement values are influenced by both current and coating thickness. A higher value of maximum Y displacement is obtained at higher levels of gap current and lower levels of coating thickness. Hence it can be concluded that optimum performance and electrode life can be achieved at lower levels of pulse on time and current and higher coating thickness.

The study of the modified electrode with in-situ heat flux canals showed reduced values for all the main responses when analyzed for the worst case. The temperature and maximum shear stress values showed noted reduction and very less movement in the y-direction. The profile of the electrode on the sparking face is found to be even showing very little movement or expansion in the y-direction.
6.1 Future work

- The FEM analysis can be extended to involve more complex shaped electrodes. The main objective of substituting ordinary EDM electrodes with metallized rapid prototyped electrodes is to reduce the high lead time involved in the production of complex shaped metallic electrodes. Hence it is most essential that complex electrodes are involved in the analytical studies.

- A failure criteria can be incorporated in the FEM model to analyze the crack propagation in the in the polymer metal interface. Incorporating a failure criterion would enable closer examination of the failure mechanism; moreover such an analysis can shed light on the adhesive strength of the resin, paint, metal bond.

- Experimental studies can be performed on the modified rapid prototyped electrode grown with in-situ heat flux canals to validate the FEM findings. The model grown with in-situ heat flux canals will avoid the problem of air entrapment between the electrode and the resin thus eliminating the anomalies resulting from this. Again with out the presence of air, these flux canals can give optimal performance by increasing the thermal diffusion into the resin substrate.
REFERENCES


APPENDIXES
6.2 Appendix A

CONTOUR PLOTS OF ANALYSIS CASES IN THE COMBINATION MATRIX

a) Temperature

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
b) Max Shear Stress

30us, 2A, 400um  
10us, 2A, 400um

30us, 1A, 400um  
10us, 1A, 400um
c) Maximum Shear Strain

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
30us, 2A, 300um

10us, 2A, 300um

30us, 1A, 300um

10us, 1A, 300um
d) X-Stress

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
e) Max X-displacement

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
30us, 2A, 300um  
10us, 2A, 300um  
30us, 1A, 300um  
10us, 1A, 300um
f) Max Y-displacement

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
30us, 2A, 300um

10us, 2A, 300um

30us, 1A, 300um

10us, 1A, 300um
g) Maximum Principal Stress

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
30us, 2A, 300um

10us, 2A, 300um

30us, 1A, 300um

10us, 1A, 300um
h) Maximum Principal Strain

30us, 2A, 400um

10us, 2A, 400um

30us, 1A, 400um

10us, 1A, 400um
30us, 2A, 300um

10us, 2A, 300um

30us, 1A, 300um

10us, 1A, 300um
6.3 Appendix B

STRESS, STRAIN PLOTS OF CASES IN THE COMBINATION MATRIX

Case 1: Pulse on -30us, Current – 2A, Coating thickness 400um (worst case)

Plot of Time versus X-Stress

Plot of Time Vs Maximum Shear Stress
Case 2: Pulse on -10us, Current – 2A, Coating thickness 400um

Plot of Time versus X-Strain

Plot of Time versus X-Stress
Plot of Time Vs Maximum Shear Stress

Plot of Time versus X-Strain
Case 3: Pulse on -30us, Current – 1A, Coating thickness 400um

Plot of Time versus X-Stress

Time Vs Max Shear Stress
Case 4: Pulse on -10us, Current – 1A, Coating thickness 400um

Plot of Time versus X-Strain

Plot of Time versus X-Stress
Plot of Time Vs Maximum Shear Stress

Plot of Time Vs X- Strain
Case 5: Pulse on -30us, Current – 2A, Coating thickness 300um

Plot of Time Vs X-Stress

Plot of Time Vs Maximum Shear Stress
Plot of Time Vs X-Strain

Case 6: Pulse on -10us, Current – 2A, Coating thickness 300um

Plot of Time Vs X-Stress
Plot of Time Vs Maximum shear stress

Plot of Time Vs X- Strain
Case 7: Pulse on -30us, Current – 1A, Coating thickness 300um

Plot of Time Vs X-Stress

Plot of Time Vs Maximum Shear stress
Plot of Time Vs X-Strain

Case 8: Pulse on -10us, Current – 1A, Coating thickness 300um

Plot of Time Vs X-stress
Plot of Time Vs Maximum Shear Stress

Plot of Time Vs X- Strain
6.4 Appendix C

STATISTICAL ANALYSIS GRAPHS

Temperature

![Outlier plot (Temp)](image)

Residual Vs Predicted (Temp)
Residuals versus Run (Temp)

Residuals versus Pulse on (Temp)
Residuals versus Current (Temp)

Shear stress

Outlier plot (Shear stress)
Residual versus Predicted (Shear stress)

Residual versus Run (Shear stress)
Residual versus Coating thickness (Shear stress)

Shear Strain

Outlier plot (Shear strain)
Residual versus Predicted (Shear strain)

Residual versus Current (Shear strain)
Residual versus Pulse-on (Shear strain)

Max Y displacement

Outlier plot (max Y displacement)
Residual versus Predicted (max Y displacement)

Residual versus Pulse on (max Y displacement)
Residual versus Current (max Y displacement)

Residual versus Coat-thick (max Y displacement)
6.5 Appendix D

CONTOUR PLOTS OF MODIFIED ELECTRODES WITH THE FLUX CANALS

1. Flux canal at the centre (twice coating thickness)

1-1 Maximum Y-displacement

1-2 Maximum Principal Stress

1-3 Maximum Principal Strain
2. Flux canal at the centre and radial (twice coating thickness)

2-1 Maximum Y-displacement

2-2 Maximum Principal Stress

2-3 Maximum Principal Strain
3. Flux canal at the centre and radial (equal to coating thickness)

3-1 Maximum Y-displacement

3-2 Maximum Principal Stress

3-3 Maximum Principal Strain