

Dissertation
On
**FINITE ELEMENT MODELING AND
ANALYSIS OF POWDER MIXED ELECTRIC
DISCHARGE MACHINING FOR SINGLE
AND MULTIPLE CRATERS**

Submitted in partial fulfillment of the requirements for the award of degree of

**MASTER OF ENGINEERING
IN
CAD/CAM & ROBOTICS**

Submitted by:

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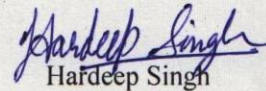
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This Thesis is dedicated to my parents and my teacher Anirban Bhattacharya.

CERTIFICATE

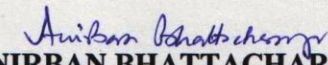
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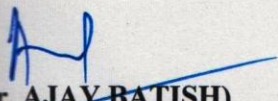
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ABSTRACT

Electrical Discharge Machining (EDM) is one of the most extensively used non-traditional material removal process for very hard, tough, high strength but electrically conductive materials. Mixing of powders into dielectric fluid is a one of the recent advancement in the EDM process to improve its process capabilities and is known as Powder Mixed EDM (PMEDM) process. Present work aimed to study the thermal aspects of PMEDM process using finite element analysis. Temperature distribution and volume removal for single and random multiple craters are analyzed by suitably modeling the process and considering temperature dependent material properties. A gradually growing spark behavior and Gaussian distribution of heat source is used to simulate for both single and multiple craters. Temperature distributions along the radial and depth direction of the crater are analyzed and subsequently used to estimate volume removal at different process settings. Development of different temperature zones like unaffected, heat affected, melting and evaporation zone, shape and size of crater for different current, pulse on and fraction of heat to work piece have been studied. Temperature distribution during simulation is found to be the maximum at the center of spark region and decrease in the radial direction in both cases of single as well as multiple overlapped craters. Peak temperature and total volume removed is found to be more influenced by the discharge current as compared to fraction of heat supplied to work piece. Results also show that after a certain discharge current and heat fraction, proportion of volume removed due to evaporation increases. For multiple spark analysis, variations of temperature after each spark are analyzed and successive removal of volume is analyzed for different parameter settings.

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NOMENCLATURE

a	Crater radius
C	Carbon
C_{ev}	Specific heat for evaporation
C_m	Specific heat for melting
Co	Cobalt
Cr	Chromium
Cu	Copper
F_c	Fraction of total EDM spark going into cathode
Fe	Iron
h	Coefficient of convection heat transfer
h_c	Crater depth
I	Current
I_d	Discharge current
K	Thermal conductivity
K_n	Powder particle size and concentration factor
L_{ev}	Latent heat of evaporation
L_m	Latent heat of melting
Mn	Manganese
Mo	Molybdenum
n	Number of load steps
Ni	Nickel
P	Phosphorous
$q(r)$	Heat flux incident at radius r
$q(t)$	Equivalent heat input at time t
q_o	Maximum heat incident at spark center
$Q_w(r)$	Heat flux incident at radius r
R	Spark radius
r	Distance along spark radius
R_a	Surface roughness
RC	Resistance capacitance
R_{max}	Maximum surface roughness
R_n	Heat source radius
R_w	Fraction of total heat supplied going into work piece
S	Sulphur
S_0	Section of initial plasma channel

Si	Silicon
T	Temperature
t	Time
T_0	Ambient temperature
T_B	Boiling temperature
t_d	Discharge duration
T_{ev}	Evaporation temperature
Ti	Titanium
T_m	Melting temperature
T_m	Melting temperature
T_{off}	Pulse off time
T_{on}	Pulse on time
T_{RC}	Recrystallization temperature
T_U	Unaffected zone temperature
U	Electric potential
V	Vanadium
V	Voltage
V_b	Breakdown voltage
V_c	Crater volume
V_d	Discharge voltage
V_g	Gape voltage
σ	Standard deviation

ACRONYMS

ANOVA	Analysis of variance
APH	Analytic hierarchy process
CLSM	Confocal laser scanning microscopy
CNC	Computer numeric control
CTE	Coefficient of thermal expansion
DC	Direct current
ECDM	Electro chemical discharge machining
EDA	Electro discharge alloy
EDM	Electrical discharge machining
FE	Finite element
FEM	Finite element method
HSFC	High speed framing camera
HSS	High speed steel
MRR	Material removal rate
OPP	Object oriented programing
PFE	Plasma flushing efficiency
PMEDM	Powder mixed electrical discharge machining
SEM	Scanning electron microscopy
SP	Scanning profile-meter
SR	Surface roughness
TWR	Tool wear rate
XRD	X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO NON-TRADITIONAL MANUFACTURING PROCESSES

Industries in the field of aeronautics, nuclear reactors, automobiles, missiles, turbines etc. work with the materials like high strength temperature resistant alloys which have higher strength, corrosion resistance, toughness, and other diverse properties. With rapid development in the field of materials it has become essential to develop cutting tool materials and processes which can safely and conveniently machine such new materials. Besides this industries face problems in manufacturing of components because of several reasons such as the complexity of the job profile or may be due to surface requirements with higher accuracy and surface finish. Consequently, non-traditional techniques of machining are providing effective solutions for the problem raised by the increasing demand for high strength temperature resistant alloys, parts with intricate and compacted shapes and materials so hard which are difficult to machine by conventional methods. The processes are non- conventional in the sense as no conventional tool is employed for the material removal. Non-conventional or advance machining processes can be classified into three basic categories, i.e. mechanical, thermoelectric, and electrochemical machining processes. Some of them can be used only for electrically conductive materials while other can be used for both electrically conductive and electrically non-conductive materials. The range of applications of newly developed machining process is determined by work piece properties like electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. In mechanical advanced machining methods, (abrasive jet machining, ultrasonic machining, and water jet machining) kinetic energy of either abrasive particles or water jet is utilized to remove material from the work piece. In electro-thermal method (plasma arc machining, laser beam machining, and electron beam machining) the energy is supplied in form of heat, light, and electron bombardment which results melting, or vaporization and melting both of work material. In electrochemical & chemical methods (electrochemical machining, chemical machining), is an etching processes which has very narrow range of applications mainly because

of very low material removal rate (MRR) and difficult in finding a suitable etchant for given work material. The selection of a process is depend upon various factors like process capabilities, physical parameters, shape to be machined, properties of work piece material to be cut, and economics of process. As there is no direct contact between the tool and the work piece in the non-conventional machining; hence the tool need not be harder than the job. Today after the huge technical advancements, the conventional machining processes can't produce complex geometrical shapes in the hard and temperature resistant alloys and die steels effectively. So for these requirements, a number of non-conventional methods have been developed.

1.2 ELECTRIC DISCHARGE MACHINING

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes. In EDM there is no contact between tool (electrode) and part. During process, a series of discrete electrical discharges occur between electrode and work piece in a dielectric medium. During the application of each discharge, local temperature rises at several thousand degrees. As a consequence, part material melts and vaporizes generating craters on the surface of the work piece, and it is removed in the form of debris by dielectric flushing. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage. The electrical discharge machining process is widely used in the aerospace, automobile, die manufacturing and moulds industries to machine hard metals and its alloy.

1.3 HISTORY OF ELECTRIC DISCHARGE MACHINING

In dates back to 1770, English chemist Joseph Priestly discovered the erosive effect of electrical discharges on metal. More than hundred years were elapse before some practical use made of effect. [Lazarenko et al., 1943] investigated the wear of switch contacts, found that spark discharge could be used to machine high strength materials which were difficult to machine by established methods. They developed a controlled process of machining to machine metals by vaporizing material from the surface of work piece. The first British patent was granted to [Rudorff, 1950] USA, Japan and Switzerland developed their machining around 1950. In 1950s The RC (resistance-capacitance) relaxation circuit was introduced, in which first consistent dependable control of pulse times and a simple servo control circuit to automatically find and hold a given gap between the electrode (tool) and the work piece was developed. A machine for spark machining by 'method x'

was patented in USA in 1952. After the investigation of [Lazarenko et al, 1943] the EDM process has attracted worldwide attention as a technique for metal machining. In the 1980s, CNC EDM was introduced which improved the efficiency of the machining operation.

1.4 WORKING PRINCIPLE OF EDM

The basic principle in EDM is the conversion of electrical energy into thermal energy through a series of electrical discharges occurring between the electrode and work piece. Work piece and electrode are immersed in the dielectric fluid, which gives the insulating effect to avoid the electrolysis of electrode while in process. There is a small gap between the electrode and the work piece. A spark is produced at the point of smallest inter electrode gap by a high voltage, overcoming the dielectric strength. Dielectric breakdown and temperature attained in range of 8000 to 12,000 °C. Due to elevated temperature erosion of metal from both electrodes takes place. Duration of each spark is very short and the entire cycle time is usually of few micro-seconds. The frequency of pulsating direct current supply is about 20,000-30,000 Hz. A sudden reduction in the temperature occurs after turning off the DC supply and the circulating dielectric fluid flush the molten material from the work piece in the form of microscopic debris. After each discharge, the capacitor is recharged from DC source through a resistor, and another spark is generated at next narrowest gap (Figure 1.1). Due to the succession of sparks spread over the entire work piece surface erosion take place and the shape generated is the inverse of the electrode or tool.

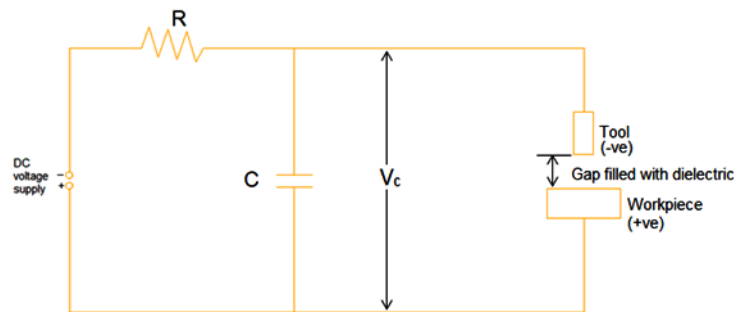


Figure 1.1: The Relaxation circuit

A servo system, which compares the gap voltage with a reference value, is employed to ensure that the electrode moves at a proper rate to maintain the right spark gap, and to retract the electrode if short-circuiting occurs. For supplying the intermittent supply pulse generator is used. A typical wave form is shown in Figure 1.2.

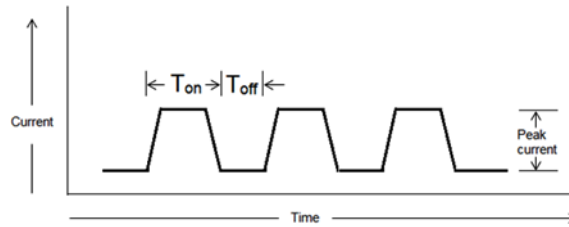


Figure 1.2: Pulse waveform of controlled pulse generator

1.5 ELECTRIC DISCHARGE PHENOMINA

The discharge process during EDM separated into three main phases which are: preparation phase, discharge phase, interval phase.

1.5.1 Preparation Phase

When the generator switches on voltage, the electrical field reaches highest strength in the between the electrode. In the presence of electrically conductive particles in the gap, thin particle bridges are formed. When the strength of the electric field exceeds the dielectric strength of the medium, electric breakdown of the medium takes place. Ionization of the particle bridges takes place and a plasma channel is formed in the gap between the electrodes. A minimum 3A current is needed to start the discharge. The steps in this phase are shown in the Figure 1.3 (a)

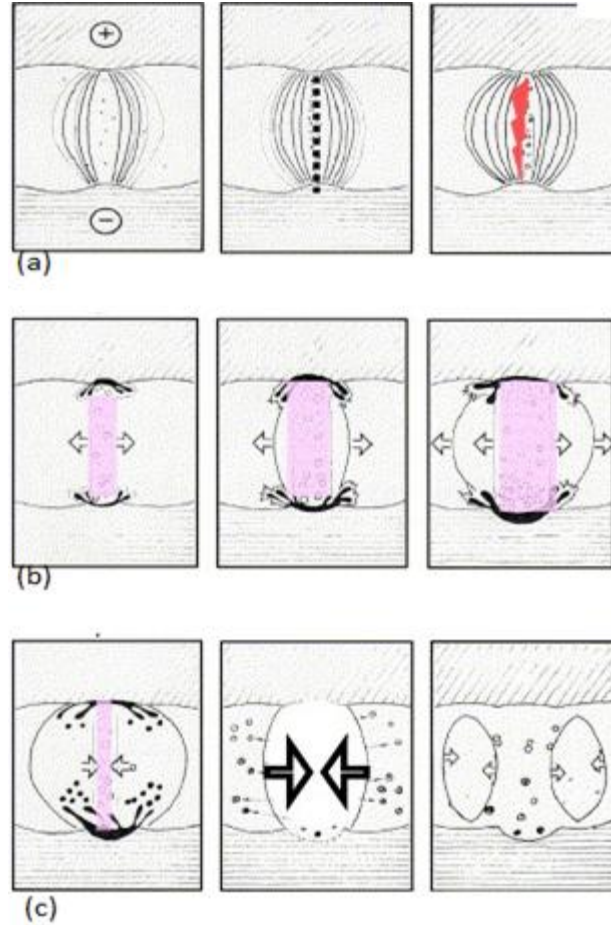


Figure 1.3: Phases of EDM [Schumacher et al., 2004]

1.5.2 Discharge Phase

In this phase plasma channel develop in the shortest time against front of dielectric and a very high pressure inside the channel creating shock wave distribution setup within liquid. High temperature is generated on both electrodes due to current passing through, resulting material in evaporation. The momentum with which positive ions strike the cathode surface is much less than the momentum with which the electron stream impinges on the anode surface, so material removal rate of cathode is less as compared to anode. Current density and temperature decrease quickly with continuous growth of plasma channel. More energy is distributed to cathode where material at plasma spots become molten. Steps, during the discharge phase, are shown in Figure 1.3 (b).

1.5.3 Interval Phase

When the discharge is ended by switch off the generator, the plasma channel is de-ionize. The gas bubble collapse and material is ejected out from the surface of electrodes in the form of vapors. The evaporated material solidifies quickly when it comes in contact with cold dielectric and debris particles are flushed away from the discharge gap.

1.6 SINKER EDM

Sinker EDM sometimes is also referred to as cavity type EDM or volume EDM. It consists of an electrode and work piece that is submerged in an insulating liquid called dielectric fluid like kerosene oil. The power supply connected to electrode and work piece generates an electrical potential between the two parts. As the electrode approaches the work piece, dielectric breakdown occurs in the fluid forming an ionization channel, and a small spark is generated in the gap. Due to heat generated work material vaporizes and electrode also evaporates to some extent. These sparks strike one at a time in huge number of different locations between the electrode and the work piece. The spark gap increases after the erosion of the work piece. Then electrode is lowered down by servo system to maintain the gap voltage. Several hundred thousand sparks occur per second in this process.

The numerical control monitors the gap conditions (voltage and current) and synchronously controls the different axes and the pulse generator. The dielectric liquid is filtered to remove debris particles and decomposition products

1.7 EDM PROCESS PARAMETERS

1.7.1 Polarity

Polarity, in EDM process determines the direction of current flow relative to electrode. Polarity of electrode can be either positive or negative depending on applications. In positive polarity work piece is positive and tool electrode is negative. The negative polarity work piece is negative and tool is positive. Polarity is also termed as normal and reverse polarity.

With the discharge taking place between work piece and electrode, electriferous particles and electrons from the cathode in the dielectric arouse the ionization which produced ionized channel. The particles with positive charge bombard the cathode while electrons bombard the

anode in ionized channel. In this process, electrons, which are smaller and lighter, thus accelerate faster and reach higher speed, whereas the particles with positive charge accelerate more slowly and do not reach high speed. As a result, electrons transfer more energy to anode than positive charged particles to transfer to the cathode. This difference leads to material removal in anode that is greater than material removal in the cathode. Polarity is determined by tool material, work material, current density and pulse length.

1.7.2 Pulse on Time

Pulse on-time is the time period during which machining takes place. MRR is directly proportional to amount of energy applied during pulse on-time. The energy of spark is controlled by the peak amperage and the length of the on-time. Long pulse on time will increase the material removal rate and broader and deep crater than short pulse duration will be produced. These large craters will create a rougher surface finish. Extended on times gives more heat to work piece, which means the recast layer will be larger and the heat affected zone will be deeper. Excessive on times exceeding the optimum on time for each electrode-work material combination can reduce the material removal rate.

1.7.3 Pulse off Time

Pulse off-time is the time during which re-ionization of dielectric takes place and no energy is applied on the work piece surface. The discharge between the electrodes leads to ionization of the spark gap. Before another spark can take place, the medium must de-ionize and regain its dielectric strength. This takes some finite time and power must be switched off during this time. Too low values of pulse off time will increase the top surface temperature of the work piece and may lead to short circuit. A large value on the other hand will decrease the material removal rate. Each cycle has an on-time and off-time that is that expressed in units of microseconds.

1.7.4 Peak Current

This is the amount of power used in discharge machining, measured in units of amperage. Current is a function of heat energy transferred to work piece. In each on-time pulse, the current increases until it reaches a preset level, which is expressed as the peak current. Higher value of peak current leads to rough surface finish operations and wider craters on work materials. Its higher value improves MRR, but at the cost of surface finish and tool wear. Hence it is more important in

EDM because the machined cavity is a replica of tool electrode and excessive wear will hamper the accuracy of machining.

1.7.5 Discharge Current

The discharge current (I_d) is a measure of the power supplied to the discharge gap. A higher current leads to a higher pulse energy and formation of deeper discharge craters. This increases the MRR and the surface roughness (R_a) value. Similar effect on MRR and R_a is produced when the gap voltage (V_g) is increased. Once the current starts to flow, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and work piece. Higher voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cut.

1.7.6 Pulse Wave Form

Different wave forms are supplied by different generators. In case of rotating impulse generators the rectified sinusoidal voltage wave form is give across the spark gap to produce the spark. Due to inductive circuitry there is a spark oscillation even after the pulse is withdrawn give rise to extremely high tool wear and arcing become frequent if the second pulse comes before complete damping of oscillation. In relaxation generator, the spark oscillation is reduced. Tool wear (TWR) will be less and charging time is equal to ignition delay, so the ionization process is slower and depends on changing time. Pulse wave form, generated by the square pulse generators, is such more defined and easily controllable. Using a generator, which can produce trapezoidal pulses, one can reduce relative tool wear to very low values.

1.7.7 Type of Dielectric Medium

Mineral oil exhibiting high dielectric strength and a low viscosity is preferred because of their higher performance. For safety reasons oils with a high flash point are usually used. The fluids used as dielectric are generally hydrocarbon oils. The kerosene oil, paraffin oil, lubricating oil is very common. Water based dielectric are extensively used in Wire EDM because water has high specific heat capacity which leads to better cooling effect required for Wire EDM. In comparison to mineral oils and water, air has lowest dielectric strength, viscosity, thermal conductivity. Air provides high accuracy and better surface finish due to its low viscosity. Whereas MRR using air as dielectric is low and low thermal conductivity and thermal capacity cause higher damage to the work piece. A good dielectric fluid should have following properties:

- a. It should have dielectric strength (i.e. behave as insulator until the required breakdown voltage between the electrodes is attained).
- b. It should provide effective cooling during operation.
- c. When the breakdown voltage is attained it should take minimum possible time to breakdown, once the break down voltage is attained.
- d. It should able to deionise the gap immediately after the spark has occurred.
- e. It should remain electrically non-conductive until the required breakdown voltage has been reached.
- f. It should have high degree of fluidity.

1.7.8 Type of Flushing

Flushing is the circulation of the dielectric fluid between tool electrode and work piece during operation. In EDM when discharge occurs the debris are produced in the gap reducing dielectric strength, which results in unwanted discharges which can damage to both tool and work piece. To remove unwanted debris from the gap effective flushing is required. TWR and MRR are affected by the type of dielectric and the method of its flushing. Flushing plays a very important role when deep and complex shapes are machined. Flushing can be achieved by following methods:

Suction flushing

In this, dielectric may be sucked through either the work piece or the electrode. To avoid any tapering effect due to sparking between machining debris and the side walls of the electrodes, this technique is well suited. Suction flushing through the tool rather than through the work piece is more effective.

Injection flushing

In this technique, dielectric is fed through either the work piece or the tool which are pre-drilled to accommodate the flow. With the injection method, tapering of components arises due to the lateral discharge action occurring as a result of particles being flushed up the sides of electrodes.

Flushing by dielectric pumping

This method is particularly suitable in deep hole drilling. Electrode pulsation movement is used for flushing. When the electrode is raised, clean dielectric is sucked into mix with contaminated fluid, and as the electrode is lowered the particles are flushed out.

Side flushing

Side flushing is employed when the flushing holes cannot be drilled either in the work piece or the tool.

1.7.9 Electrode Gap

The servo feed system is used to control the working gap at a proper width. Electromechanical and electro-hydraulic systems are used to respond to average gap voltage. Larger gap widths cause longer ignition delays, resulting in a higher average gap voltage. The feed control must maintain a movement of electrode towards the work piece at such speed that working gap does not change which results in changing the average gap voltage. Values of gap size range between 0.005 to 0.05 mm.

1.7.10 Electrode Material

The shape of electrode will be basically same as that of the product is desired. The electrode materials are classified as metallic material (copper, brass, tungsten, aluminum), non-metallic material (graphite), combined metallic and non-metallic copper-graphite), and metallic coating as insulators (copper on moulded plastic, copper on ceramic) etc. Materials having high melting-point, good electrically conductivity, low wear rate and easily machineability are usually chosen as tool materials for EDM. High density graphite is used in pulsed EDM equipment as it gives low wear due to its high melting temperature. Brass as a tool material has high wear. Copper has the qualities for high stock metal removal. Copper-boron and silver tungsten both exhibit extremely low wear.

1.7.11 Material Removal Rate

The material removal rate is defined as volume of metal is removed per unit time. This depends on large range of properties of the work piece material, melting point and latent heat. It also influenced by the properties of the tool electrode and geometric factors such as the shape and dimensions of the tool and work piece.

1.8 POWDER MIXED EDM

Mixing of suitable material in powder form into the dielectric fluid is new advancement in EDM process to improve the process capabilities. This process is known as powder mixed EDM (PMEDM). In this process, the electrically conductive particles are mixed in the dielectric fluid,

which reduces its insulating strength and increases the spark gap distance between the tool and work piece. This leads to spread the electric discharge uniformly in all directions. As a result; the process becomes more stable thereby improving MRR and surface finish.

Fig 1.4 shows that in PMEDM there is a separate tank for the dielectric fluid. Reason of using separate tank is because every time when new experiment is conducted, concentration of powder and its type may be different. So in this case tank need to be leaned and again refilled with new dielectric medium and powder particle type and concentration. A motorized stirrer is used to circulate the powder mixed dielectric.

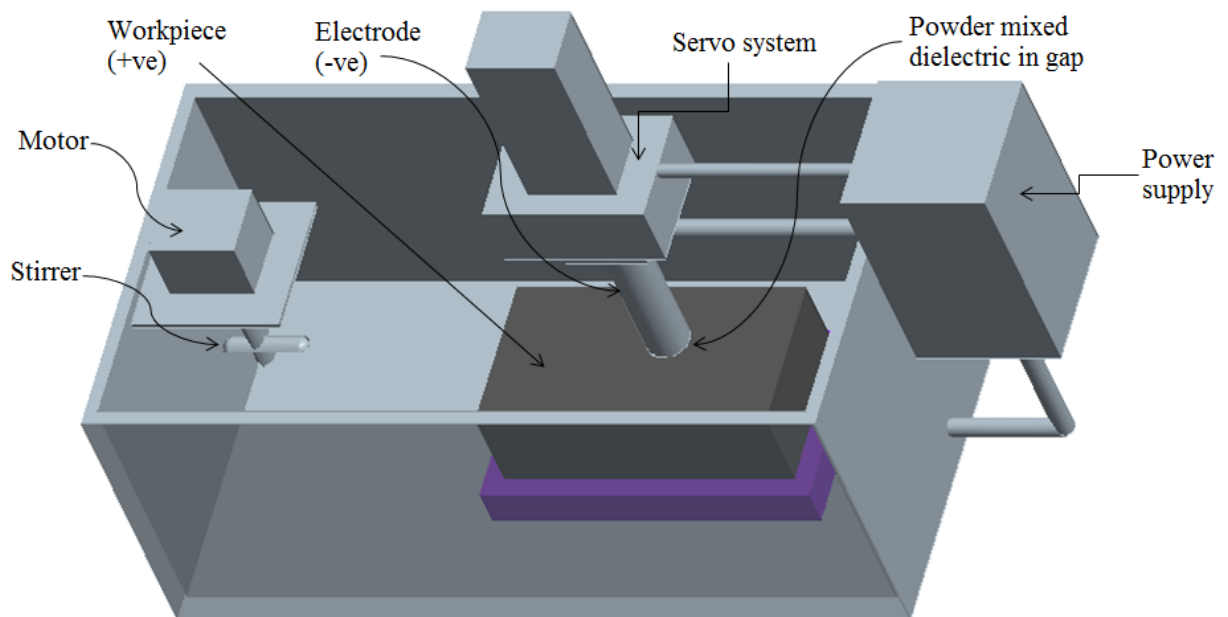


Figure 1.4: Schematic illustration of PMEDM setup

CHAPTER 2

LITERATURE REVIEW

In this report, literatures are reviewed in four categories. These four categories are:

1. Material transfer mechanism
2. Optimizing parameters
3. Simulation of EDM
4. Simulation of PMEDM

2.1 MATERIAL TRANSFER MECHANISM

Min et al. [2007] investigated a new method to improve the surface integrity of electro-chemical discharge machining (ECDM) process by use of conductive particles in the electrolyte. In conventional ECDM processes the generation of fine sparks with uniform energy has been most desired technique to improve the machining efficiency and the surface quality. However, precise control of the spark generations in ECDM process has been a challenging problem. In EDM an process, which is thermal erosion machining process using spark energy similar to the ECDM, PMEDM fluids have been used to improve machining quality. Although the exact role of the conductive particles in the EDM process could not be clearly explained yet, it has been reported that the powder stabilizes discharge current as a result of discharge energy dispersion. Considering the similarity of the ECDM process compared to EDM where electrical sparks are utilized, powder mixed electrolyte was introduced to create similar effects. In this paper fine graphite powder (which has good thermal and electrical conductivity) mixed with electrolyte has been applied to the ECDM process. Borosilicate glass, which is frequently used as a material for micro structures, was used as a work piece. To investigate effectiveness of the proposed method pediments were conducted. The experiment results demonstrated that the breakdown voltage was reduced and the peak current during the process was decreased by ten percent. Discharging pattern was modified such that a single discharge pulse was branched into two or three. As a result, the surface quality was improved compared to that from the conventional process. Various experiment results of product quality with respect to powders volume ratio are also presented.

Kumara et al. [2011] investigated the response of three die steel materials to surface modification by EDM method with tungsten powder mixed in the dielectric medium. Taguchi experimental design technique was used to conduct the experiments on each work material independently. Peak current, pulse on-time and pulse off time were taken as variable factors and micro-hardness of the machined surface was taken as the response parameter. X-ray diffraction (XRD) and spectrometric analysis show substantial transfer of tungsten and carbon to the work piece surface and an improvement of more than 100% in micro-hardness for all the three die steels. Presence of tungsten carbide (WC and W₂C) indicates that its formation is taking place in the plasma channel. Machining parameters for the best value of micro-hardness for each work material were found to be the same.

Batish et al. [2012a] studied material transfer mechanism in die steels using PMEDM. They investigated the effect of process parameters and mechanism of material deposition in PMEDM on surface properties of EN31, H11, and High Carbon High Chromium (HCHCr) die steel materials. Samples were analyzed for XRD followed by microstructure analysis using a scanning electron microscope (SEM). Surface modification was measured in terms of the micro-hardness, and results showed that there was almost 80% increase in micro-hardness after PMEDM and the results also showed significant material transfer from the electrode as well as powder, either in free form and/or in compound form. Current, powder and interaction between work piece and electrode affected the micro-hardness significantly. Copper electrode was found best for EN31 and H11 die steel, whereas tungsten-copper electrode was better suited for HCHCr steel to achieve higher micro-hardness. Graphite powder was found to be more suitable compared to aluminum in improving the micro-hardness of all three materials. The XRD analysis shows creation of largely amorphous structure because of high temperature coupled with rapid cooling.

Bhattacharya et al. [2012] investigated about surface modification of HCHCr, EN31 and HDS using PMEDM process with different electrodes (graphite, tungsten copper), powder (copper, tungsten), dielectric (kerosene, EDM oil) at different pulse on, pulse off time and current values. Current and powder mixed with certain electrode were observed as significant parameters affecting the micro-hardness of the work pieces. The mechanism of material deposition was observed from the suspended powder and/or tool electrode as well. Amongst the two electrode materials, copper-tungsten along with tungsten powder had the best micro-hardness. Selected

samples were analyzed for XRD followed by microstructure analysis using a SEM. The results showed significant material transfer from the electrode as well as powder either in free form or in compound form.

Batish et al. [2012b] discussed about the mechanism of material deposition from powder, electrode and dielectric for surface modification of H11 and H13 die steels in EDM process, properties measured in terms of the micro-hardness of the machined surface. Three different electrode materials (Cu, W-Cu and graphite), four different powder materials (aluminum, copper, graphite and tungsten) and three different dielectrics (kerosene, EDM oil and refined mineral oil) with other suitable parameters were used. Powder mixed and current was found as significant process parameter. Maximum increase in micro-hardness was observed with addition of tungsten powder and with tungsten-copper electrode even at lower current. At relatively higher current settings significant amount of material transfer takes place from the electrode material and breakdown of the dielectric material takes place offering a possibility of material deposition from dielectric. This is definitely attributed to the material migration from powder suspended and/or electrode and/or dielectric. Kerosene was found a superior choice for consistently good machining and surface improvement. Use of graphite electrode provides much possibility of material deposition from electrode and in most of the cases helped in carbide formation thereby increasing the hardness and wear resistance property of the machined surface. Due to rapid cooling generally amorphous structures formed in the machined surfaces and cracks were observed.

2.2 OPTIMIZING PARAMETERS

Wong et al. [1997] presents a study of the near-mirror-finish phenomenon in EDM when fine powder is introduced into the dielectric fluid as a suspension at the tool–work piece or inter electrode gap during machining. For this study, the dielectric flushing system of a conventional die-sinking EDM machine was specially modified to inject and distribute the powder into the dielectric fluid, especially at the gap between the tool and the work piece. Machining was performed on various types of steel with different types of powder suspensions at a peak current of around 1 A. Particular combinations of powder-mixed dielectric and work piece have been found to produce mirror-finish or glossy machined surfaces. Close scrutiny of the mirror-finish surfaces reveals shallow overlapping re-solidified discs with smooth rims, unlike typical EDM

surfaces, which are typically covered with deep craters, pock marks and globules. The various factors affecting the generation of the mirror-like surfaces are discussed. The appropriate settings of electrode polarity and pulse parameters and the correct combination of work piece material and powder characteristics have a significant influence on the mirror-finish condition. The use of negative electrode polarity (i.e. with the tool as the negative electrode, which is a condition normally used for finishing EDM) is necessary to achieve the mirror-finish condition. Other features of the powder-mixed dielectric EDM are shorter machining time, more uniform dispersion of the electrical discharges, and stable machining. Based on the results of the experimental investigation, the types of material composition, powder properties and machine setting in bringing about near-mirror conditions are discussed.

Klocke et al. [2003] examined effects of micro Joule-range discharge energies on the recast layer in combination with powder suspended working. The effects of a capacitor connected parallel to the gap were investigated in relation to the recast layer formation. In addition, transverse section pictures show the morphology and the depth of the thermal influenced zone. The aim was to investigate the influence of the powder particles in micro-sinking-EDM and especially in the gap, on the thermal spread in the dielectric and on the influenced zone. Pictures were taken during the spark generation in different suspended dielectrics with a high speed framing camera. Furthermore, a complete qualitative and quantitative analysis of an EDX spectrum has been performed in order to examine the changes of the recast layer composition by using powder suspended dielectrics at the work piece surface.

Kansal et al. [2005a] optimized PMEDM by response surface methodology. They worked with EN-31 tool steel in kerosene dielectric with Si mixed powder. Variables like pulse-on time, peak current, duty cycle and concentration of Si powder in dielectric were selected as process parameters in terms of MRR and SR. They concluded that addition of Si powder in dielectric increase MRR and better surface finish. MRR increases with increase in concentration of Si powder improving surface finish as well. Concentration and peak current individually affect the MRR and SR as well as their combination also is significant.

Kansal et al. [2005] optimized the process parameters of PMEDM. Response surface methodology has been used to plan and analyze the experiments. Pulse on time, duty cycle, peak current and concentration of the silicon powder added into the dielectric fluid of EDM were

chosen as variables to study the process performance in terms of material removal rate and surface roughness. Experiments are performed on a newly designed experimental setup developed in the laboratory. The results identify the most important parameters to maximize material removal rate and minimize surface roughness. The recommended optimal process conditions have been verified by conducting confirmation experiments.

Kansal et al. [2007] presents a tutorial introduction, comprehensive history and review of research work carried out in the area of PMEDM. The machining mechanism, current issues, applications and observations are also discussed.

Kansal et al. [2007] discussed the effect of silicon powder mixing into the dielectric fluid of EDM on machining characteristics of AISI D2 (a variant of high carbon high chrome) die steel has been studied. Six process parameters, namely peak current, pulse on time, pulse-off time, concentration of powder, gain, and nozzle flushing have been considered. The process performance is measured in terms of machining rate (MR). The research outcome will identify the important parameters and their effect on MR of AISI D2 in the presence of suspended silicon powder in a kerosene dielectric of EDM. The study indicated that all the selected parameters except nozzle flushing have a significant effect on the mean and variation in MR (S/N ratio). Optimization to maximize MR has also been undertaken using the Taguchi method. The ANOVA analysis indicates that the percentage contribution of peak current and powder concentration toward MR is the maximum among all the parameters. The confirmation runs showed that the setting of peak current at a high level (16 A), pulse-on time at a medium level (100 μ s), pulse-off time at a low level (15 μ s), powder concentration at a high level (4 g/l), and gain at a low level (0.83 mm/s) produced optimum MR from AISI D2 surfaces when machined by silicon powder mixed EDM.

Pecas et al. [2007] presents a research work within the objective to acquire deep knowledge on EDM technology with powder mixed dielectric and to compare its performance to the conventional EDM when dealing with the generation of high-quality surfaces. In particular the analysis of the effect of the electrode area in the surface quality measured by the surface roughness and craters morphology was carried out for both technologies. The results achieved evidenced a linear relationship between the electrode area and the surface quality measures as well as a significant performance improvement when the powder mixed dielectric is used.

Ojha et al. [2010] presents a review of EDM research work related to MRR improvement along with some insight into the basic EDM process and material removal mechanism. The major research development resulting in improvement in material removal rate is summarized in Table 1 in chronological order. It is found that the basis of controlling and improving MRR mostly relies on empirical methods. This is largely due to stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters along with their complicated interrelationship. Being an important performance measure, the MRR has been getting overwhelming research potential since the invention of EDM process, and requires more study/experimentation/modeling in future.

Singh et al. [2010] analyze the effect of electrical parameters on the performance of PMEDM process. Peak current, gap voltage, pulses on time and duty cycle are taken as machining parameters. Material removal rate, tool wear rate, % wear ratio and surface roughness are taken as response parameters to measure process performance. The experimental investigations are carried out using copper electrode. Nineteen experiments are performed on hastelloy using electronica make smart ZNC electric discharge machine tool. Variations of response parameters are plotted against input machining parameters. The study indicates that all the input machining parameters strongly affect the machining performance of hastelloy.

Bhattacharya et al. [2011a] carried out experimentation for setting optimal parameters for rough and finish machining of die steels (EN31, H11 and HCHCr) in PMEDM. Seven different parameters along with their interactions were evaluated using dummy-treated experimental design and ANOVA (L_{27} Orthogonal Array). Suspending powder showed surface modification. EN31 showed maximum MRR as compared to the other two materials at similar process settings, then H11 and lowest MRR was observed for HCHCr. Copper (Cu) electrode with aluminum suspended in the dielectric maximized the MRR, while graphite powder showed low MRR but better finish. The MRR was observed to be dependent upon pulse off, pulse on time and current. The interaction between tool material and suspended powder was observed to be significant. The electrode material independently had no effect on MRR but in combination with the suspended powder affected the MRR significantly. HCHCr required higher current and pulse on settings for initiating a machining cut and worked best in combination with tungsten–Cu electrode and

graphite powder for improved finish. On the other hand, SR was significantly affected by pulse on time, current, and powder and the combined effect of work piece, powder, and electrode.

Ojha et al. [2011] carried out a study on parametric optimization (MRR & TWR) of the powder mixed electrical discharge machining (PMEDM) using EN-8 steel. Response surface methodology (RSM) has been used to plan and analyze the experiments. Average current, duty cycle, angle of electrode and concentration of chromium powder added into dielectric fluid of EDM were chosen as process parameters to study the PMEDM performance in terms of MRR and TWR. Experiments have been performed on newly designed experimental setup developed in laboratory. Most important parameters affecting selected performance measures have been identified and effects of their variations have been observed.

Bhattacharya et al. [2011b] dealt with optimization of powder mixed electric discharge machining using dummy treated experimental design with analytic hierarchy process with seven different process parameters, i.e., work piece (HCHCr, Hot Die Steel, EN31), dielectric (kerosene and EDM oil), powder (Copper, Tungsten), electrode, pulse on and pulse off time and current with L_{27} array for optimization of MRR, TWR and SR. The process conditions that affected the three responses were identified and optimized together using AHP for HCHCr, EN31 and HDS work piece. Addition of powder in the dielectric improved the MRR as well as SR. Three factors, current, electrode material, and pulse-on time were found to be the most significant factors affecting MRR. Current, powder, and electrode material significantly affected the TWR. Kerosene as dielectric was observed to be a superior alternative than EDM oil. Graphite electrode worked best for HCHCr and EN31 and W-Cu electrode worked best for HDS as they globally optimize the three output variables. Also, Cu powder suspended in the dielectric resulted in an optimal solution for HCHCr and HDS and tungsten powder was seen to be a better choice for EN31 to globally optimize the responses. Arcing was observed at high current settings with low pulse on time during addition of more electrically conductive copper powder. Current and pulse-on time influenced the SR of the finished work surface.

2.3 SIMULATION OF EDM

Salah et al. [2006] concluded the importance of temperature variable thermal conductivity in the process of EDM simulation. They use 2D model for their simulation. In numerical section of the paper they first take thermal conductivity as constant and use Difference scheme to solve the

heat transfer equation, then iterate it by Gauss-seidal method up to N^{th} iteration and then use GMRES method for further iterations. Now in the next step they take temperature variable thermal conductivity and solve it by using a five step iterative algorithm. And in the last while validating the results with AISI316L as a working material for 100 μ s they find that temperature sensitive thermal conductivity gives more realistic result and they suggested that the error between the experimental and simulated data may be due to re-solidification of hot ejected metal in the form of spherical particles of different sizes on the surface due to hydrodynamic effect.

Marafona and Chousal et al. [2006] developed a thermal-electric model for spark generated by electric discharge machining in a liquid media. Shape used was cylindrical for the discharge channel between electrodes. It was certified that discharge channel being electrical conductor will dissipate heat, which can be explained by Joule heating effect. Joule heating arises when energy dissipated by an electric current following through a conductor is converted into thermal energy. The amount of heat dissipated varied with the thermal-physical properties of the conductor; as a result, as a result maximum temperature reached was different. In this model, the radii value of the conductor is a function of the current intensity and pulse duration. The thermal physical value used in the model was the average of both the ambient and melting value. Copper and iron was used for anode and cathode, respectively. The Finite Element Analysis results were compared with the experimental values of the table of the table of AGIE SIT used by other researchers. The TWR and MRR as well as surface roughness results agree reasonably well with the researcher's values. Joule heating effect was considered in the EDM electrodes and discharge channel. Heating source for both the electrodes was given by the current intensity flux transformed into thermal energy due to Joule heating effect, which reached 50% of the pulse power. In this equivalent heat input radius, dependent of current intensity (I) and pulse duration (t), was used

$$[R] = 2.04 * 10^{-3} I^{0.43} t^{0.44} \quad (2.1)$$

This is a virtual radius (constant) for each current intensity case used to get a static thermal electric model. The supply of the heat to the parts of the model was variable with the thermal-electric properties of the vaporized dielectric and both electrodes. The heat flux fractions used in the modeling of EDM varies from the different approaches. This model used a Joule heating factor of 50%

Schulze et al. [2004] concluded that comparison of measured crater geometry with simulated one is a very important method to determine the connections of the physical processes and the parameters of the process energy source. An analytical relation between pulse parameters and roughness was achieved and a difference between single discharge and a series of discharges were described. Simulations of the thermal effected zones were identified for a single discharge and a sequence of discharges. The characteristics describing the charged gap conditions of the discharge types in the simulation model were shown. For the test confocal laser scanning microscopy (CLSM) was used. Specific crater geometry analyses of the electrode arrangements were accomplished with the SEM. The CLSM is faster and has an accuracy of $\pm 0.5\mu\text{m}$. 3D patterns of the crater configurations were drawn up. High speed framing camera (HSFC) permitted temporal resolutions of discharge from 5 to 200ns. Results of the different research methods (CLSM, HSFC and ANSYS) were combined in order to extend the real physical conditions for the discharging process and surface heating. The change of the pulse parameters also leads to purposeful changes in the plasma channel parameters which could be determined partially from HSFC images. The physical effects such as Pinch effect, temperature and pressure dependence of the enthalpy, specific heat capacity, heat conductivity, and distribution of energy parts in plasma channel and on the electrode faces were considered.

Shabgard et al. [2013] studies the effect of different parameters on the Plasma flushing efficiency of EDM process. The temperature distribution on the surface of work piece and tool during a single discharge in the electrical discharge machining process has been simulated using ABAQUS code finite element software. The temperature dependency of material properties and the expanding of plasma channel radius with time have been employed in the simulation stage. The profile of temperature distribution has been utilized to calculate the dimensions of discharge crater. Based on the results of FEM and the experimental observations, a numerical analysis has been developed assessing the contribution of input-parameters on the efficiency of plasma channel in removing the molten material from molten puddles on the surfaces of work piece and tool at the end of each discharge. The results show that the increase in the pulse current and pulse on-time have converse effects on the plasma flushing efficiency, as it increases by the prior one and decreases by the latter one. Later, the introduced formulas for plasma flushing efficiency based on regression model were utilized to predict the cardinal parameter of recast layer thickness on the electrodes which demands expensive empirical tests to be obtained.

2.4 SIMULATION OF PMEDM

Zhao et al. [2005] presents a method that can be used to forecast the surface roughness in the PMEDM process with the application of artificial neural networks (ANNs). ANNs with back propagation (BP) algorithm coupled with an orthogonal design was applied to the modeling of the PMEDM system and simulation of experimental conditions. An orthogonal design was utilized to design the experimental protocol, in which peak current, pulse-on time discharging area, servo voltage and no-load voltage were varied simultaneously. The results showed that the ANNs model reflected the complex relationship of PMEDM and had high predicting accuracy.

Kansal et al. [2008] developed an axis-symmetric two dimensional model for PMEDM using the Finite Element Analysis (FEM). The model utilizes the several important aspects such as temperature sensitive material properties, shape and size of heat source (Gaussian heat distribution), percentage distribution of heat among tool, work piece and dielectric fluid, pulse on/off time, material ejection efficiency and phase change (enthalpy) etc. to predict the thermal behavior and material removal mechanism in PMEDM process. The developed model first calculates the temperature distribution in the work piece material using ANSYS (version 5.4) software and then MRR is estimated from the temperature profiles. The effect of various process parameters on temperature distributions along the radius and depth of the work piece has been reported. Further validation of was done by comparing the theoretical MRR with the experimental one obtained from a newly designed experimental setup developed in the laboratory. The model was developed for single spark. The material flushing efficiency is assumed to be 20%. It was investigated that powder particles suspended into the dielectric fluid increase the electric conductivity of the dielectric fluid and help to spread the discharge uniformly in all directions resulting in increased energy transfer to work piece compared to EDM. 9% of total of the total heat lost to the work piece was assumed.

Specific heat of melting and evaporation was considered. It was found that craters are shallow and smaller in size compared to EDM. A new parameter K_n was introduce into the heat flux equation to take into account the effect of powder on spark frequency and breakdown voltage. Equation used for heat flux was given by:

$$Q_w(r) = \frac{4.57K_n V_b I R_w}{\pi R^2} e^{-4.5(r/R)^2} \quad (2.2)$$

The modeling and simulation of the results for PMEDM were performed using ANSYS software. Meshing of the work piece domain was done using mapped meshing technique. AISI D2 die steel was considered as the work piece material and copper as a tool material. It was observed that top surface temperature goes on increasing with increase in current and the increase in pulse duration, the surface temperature also increases. The effect of pulse of time was studied by keeping the pulse duration constant. It was clear from the curves that the top surface temperature of the work piece increases as the pulse off time decreases.

Bhattacharya et al. [2012] reports the results of a finite element simulation of powder mixed electric discharge machining process for H11 Hot Die steel material using relevant boundary conditions and reasonable assumptions. The crater shape was developed using simulated temperature profiles to estimate the volume removed in a single crater. The temperature distribution on the work piece was used to predict the cooling rate and calculate the stresses generated due to thermal loading. Subsequently, the simulation results were experimentally validated by physically measuring the crater shape and volume. From the results it was concluded that about 25% of heat is transmitted to the work piece during machining at the process conditions used in the experiment. The microscopic pictures showed bigger craters with increase in current. The machined surface showed overlapping craters with surface cracks suggesting a high cooling rate.

2.5 GAPS IN THE LITERATURE

A lot of work has been done on different aspects of PMEDM process. Some of researchers are studying the material deposition mechanism during PMEDM process and observing micro harness improvement by using different methods, some are finding optimizing parameter settings by varying different parameters like pulse on time, discharge current, amount of heat transfer to work piece, materials of tool, work and powder used, dielectric and many others parameters and some are doing simulations by using different methods and using different mathematical models. Out of them very few of researchers are working on FE simulation of PMEDM process. Still there is a large scope of work on FE simulation of Powder mixed EDM process. Sufficient work has not been done to predict the temperature distribution generated in the work material, total volume removed and types of volume removed during process. Some of the researchers have studied the FE approach on simulation of single spark of PMEDM process. But no work has

been done to model and simulate the multiple overlapped craters as it actually happened during PMEDM process.

2.6 OBJECTIVE

Based on detailed literature survey the objectives of the present work are as follows:

- 1) To develop a transient thermal model for analysis of PMEDM process for a single and multiple overlapped sparks.
- 2) To study the temperature distribution in work piece due to the heat flux of the spark assuming a Gaussian heat distribution inside the spark.
- 3) To find out the volume removal from crater during single and randomly oriented multiple sparks at different values of current, pulse on time and fraction of heat entering to work piece.
- 4) To estimate and compare the proportion of volume removal by melting and vaporization at different process settings and realize the effect of process variables.

CHAPTER 3

METHODOLOGY

This chapter explains the detailed modeling steps, boundary conditions and simulation methodology used in the study. It consists of the two different sections: Modeling of PMEDM process and Simulation methodology. In prior section the basic modeling principles and methods along with general assumptions are explained for both single and multiple overlapped crater study. The later section explains each step of FE simulation for both the cases.

3.1 MODELING OF PMEDM PROCESS

Methodology used for the modeling of PMEDM process is explained here along with certain assumptions, so as complex PMEDM process can be mathematically feasible without sacrificing the basic principle of the process. Assumptions used during simulation, thermal model of PMEDM, properties and applications of material used during simulation, heat transferred to the work piece, domain discretization, heat flux calculations, heat flux discretization, boundary conditions and growing of spark radius with the time are explained in the following sections.

3.1.1 Assumptions for modeling

- i) Model is developed using both single and multi-spark study.
- ii) Material is considered as homogeneous and isotropic.
- iii) Transient thermal analysis has been considered.
- iv) Gaussian distribution of heat flux is used as a heat source.
- v) Temperature variable thermal properties have been considered.
- vi) Material flushing efficiency is assumed to be 100%.
- vii) Increase of plasma channel with respect to time is considered.
- viii) Condition of zero initial stress is considered.
- ix) Convection is taken beyond the spark radius ' R ' on the top surface.

3.1.2 Thermal Model

Discharge phenomenon of PMEDM process can be modeled as heating of work piece by incident plasma channel. Many researchers have tried modeling of PMEDM process using uniform distributed heat source [Snoues et al., Erden et al. and Jilani et al.]. Actually the assumption that

heat source is uniform is not true. In actual, intensity of heat is the maximum at the center of the spark and goes on decreasing in the radial direction while moving away from spark [Bhattacharya et al.]. In present work, work piece is being subjected to a heat load with Gaussian distribution as shown in figure 3.1. If the maximum heat intensity is Q_o at center of spark and spark radius R is known then heat intensity for PMEDM process at any value of r (radial distance from spark center) is given by

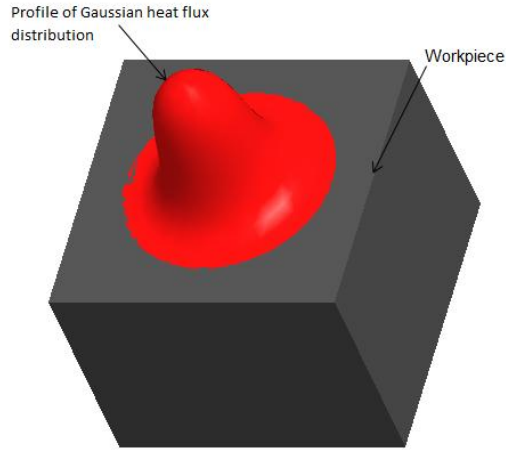


Figure 3.1: Gaussian heat distributions used for PMEDM process simulation

$$Q_w(r) = Q_o e^{-4.5(r/R)^2} \quad (3.1)[Kansal et al., 2010]$$

3.1.3 Work piece

Work piece of cuboid shape is used for the simulation of single and multi-sparks study of PMEDM process. Material for both the cases is H13 hot die steel. Material taken for the simulation is H13 hot die steel. Table 3.1 shows the chemical composition of the work material. Mechanical and thermal properties of the work material are also listed in the table 3.2.

Major applications of H13 hot die steel are as follows:

- Forging dies
- Die casting dies
- Bolt dies

- Hot piercing punches
- Forming punches
- Aluminium extrusion dies

Table 3.1: Chemical composition of work piece material

C (%)	Si (%)	Cr (%)	Mo (%)	V (%)	Fe (%)	Mn (%)	P (%)
0.368	0.91	5.04	1.28	0.915	90.7	0.38	0.0219
S (%)	Ni (%)	Co (%)	Cu (%)	Mo (%)	Ti (%)	W (%)	
0.0118	0.162	0.0206	0.0909	0.0185	0.0055	0.0389	

Table 3.2 gives mechanical and thermal properties of the work material.

Table 3.2: Mechanical and thermal properties of the work material

Density (g/cc)	7.8	
Tensile strength, ultimate (M Pa)	1990	
Tensile strength, yield (M Pa)	1650	
Young's modulus (G Pa)	210	
Elongation at break (%)	9	
Poisson's ratio	0.30	
Bulk Modulus (G Pa)	140	
Machinability (%)	50	
Shear Modulus (G Pa)	81.0	
Specific Heat Capacity (J/g-°C)	0.460	
T_b (°C)	3045	
T_m (°C)	1454	
T_{rc} (°C)	970	
T_u (°C)	Below 970	
Temperature variable Thermal conductivity	Temperature (°C)	Thermal conductivity (W/m-K)
	215	24.3
	475	24.3
	350	24.4
	605	24.7

3.1.4 Heat transferred to work piece

In some research works of EDM process it is assumed that no heat is lost to tool electrode and dielectric medium [Jilani et al. and Snoyes et al.] i.e. 100% heat is transferred to the work piece. But this assumption is not realistic. Patel et al. [1998] and DiBitonto et al. [1989] has predicted that for EDM process 8% of the total heat goes to anode and 18% to cathode and remaining heat is lost in dielectric medium. But in case of PMEDM process heat given to anode (i.e. work piece) should be more as compared to EDM process due to presence of conductive powder particle in dielectric medium. So in the present work different levels of R_w are considered for the simulation. For single spark simulation four different levels of R_w are taken into consideration i.e. 0.15, 0.20, 0.25 and 0.30. In case of multi-sparks simulation three different levels of R_w are taken for the simulation purpose i.e. 0.15, 0.20 and 0.25.

3.1.5 Domain Discretization

As mentioned earlier, the size of work piece is different in both the cases of single and multiple overlapped crater study. But domain discretization for the one single spark is same in each case. So domain discretization for one spark is explained here in this section. Heat distribution is assumed to be having Gaussian distribution on the work piece surface. In the present work, spark radius is taken to be 100 μm and the region under spark on the top face has been discretized into 20 different segments. These segments have the radii ranging from 5 μm to 100 μm with the increment of 5 μm in radii (i.e. 5, 10... 100) as shown in figure 3.2.

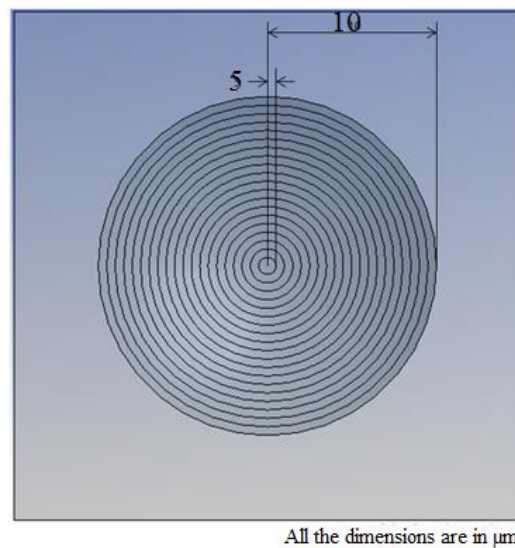


Figure 3.2: Work domains

3.1.6 Heat flux

In many of the research works hemi-spherical disk type heat source is used. But it does not match with the actual conditions. A more realistic approach of using Gaussian distribution (figure 3.3) is shown in Kansal et al. [2008]. So in the present work same methodology to calculate the heat flux equation is explained here.

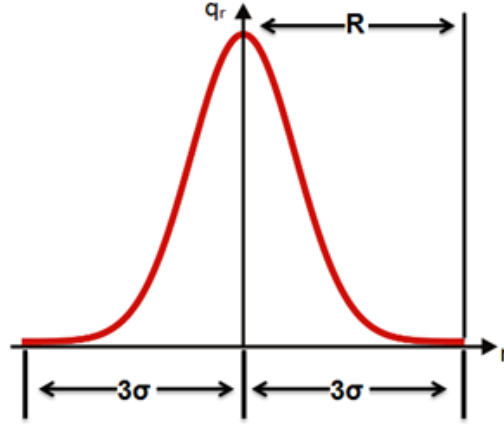


Figure 3.3: Gaussian distribution curve.

Probability density function (*pdf*) of Gaussian distribution for a random variable r is given in equation as below:

$$q(r) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{r^2}{2\sigma^2}} \quad (3.2)[\text{Kansal et al., 2010}]$$

Where, $\frac{1}{\sqrt{2\pi}\sigma}$ is peak value of distribution and σ is standard deviation.

Mathematically, Gaussian curve doesn't become zero until infinity and 99.75% of the data population lies in $\pm 3\sigma$ limits for this distribution as shown in figure 3.3.

Now $R = 3\sigma$ Substituting the value of σ in equation in 3.2.

$$q(r) = \frac{3}{\sqrt{2\pi}R} e^{-4.5 \frac{r^2}{R^2}} \quad (3.3) [\text{Kansal et al., 2010}]$$

In present work $q(r)$ is the intensity of heat flux on to work piece denoted by $Q_w(r)$ and is a function of r .

At $r = 0$, $q(r)=Q_o$; (Q_o is maximum intensity of heat at spark center).

So

$$Q_w(r) = Q_o e^{-4.5 \frac{r^2}{R^2}} \quad (3.4) \text{ [Kansal et al., 2010]}$$

Thus energy incident on work piece is

$$\begin{aligned} \oint Q_w(r) dA &= \int_0^R Q_w(r) 2\pi r dr \\ &= \int_0^R Q_o e^{-4.5 \frac{r^2}{R^2}} (r) 2\pi r dr \\ &= 0.2191\pi Q_o R^2 \end{aligned}$$

Considering the conservation of energy, rate of energy incident on work piece is equal to rate of energy supplied so

$$0.2191\pi Q_o R^2 = R_w V_b I K_n \quad (3.5) \text{ [Kansal et al., 2010]}$$

Where, R_w is fraction of heat going to work piece,

V_b is breakdown voltage (72% of supplied voltage)

I is the current in ampere and

K_n is a parameter to take into account the presence of powder mixed on Spark frequency and breakdown voltage. The value of K_n depends upon powder particle size, concentration and type of powder.

Modifying equation

$$Q_o = \frac{4.57 R_w V_b I K_n}{\pi R^2} \quad (3.6) \text{ [Kansal et al., 2010]}$$

Substituting into equation,

$$Q_w(r) = \frac{4.57 R_w V_b I K_n}{\pi R^2} e^{-4.5 \frac{r^2}{R^2}} \quad (3.7) \text{ [Kansal et al. 2010]}$$

3.1.7 Heat flux discretization and boundary conditions

Heat flux discretization

Equation 3.7 shows that heat flux is continuous function of r (radial distance along spark radius) so it needs to discretize for modeling purpose without much compromising with the accuracy. There are three possible ways of discretizing a continuous function as shown in figure 3.4.

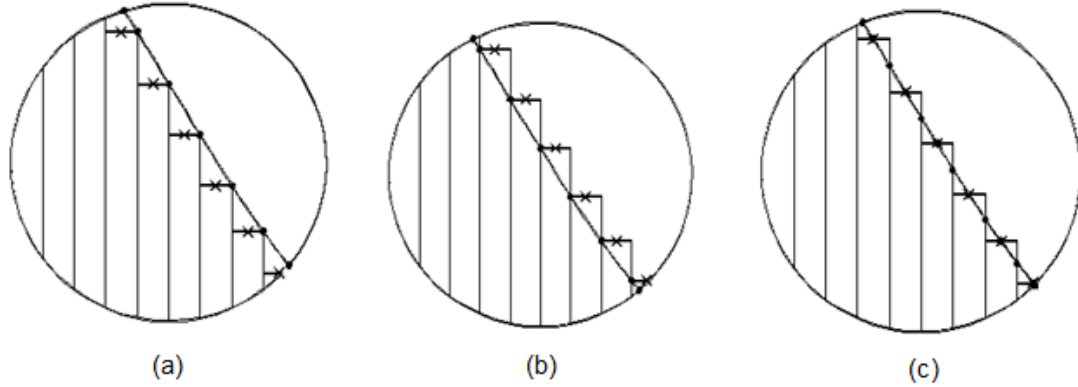


Figure 3.4: Different methods of discretization of a continuous function: (a) Conforming, (b) External, (c) Central method

Conforming method shown in Figure 3.4(a) predicts function values less than the actual continuous function values. Due to under prediction, it is not well suitable for the present work. External method shown in Figure 3.4(b) over predicts function values than the actual continuous function values. Mean value method shown in Figure 3.4(c) is the better method to discretize the heat flux as it averages the other two approaches. In this method discretization is much closer to the continuous function, because it is carried out on the midpoint. So in present work mean value discretization has been used.

Boundary conditions

Boundary conditions for both single and multi-spark simulation are almost similar. The shape of heat source with Gaussian distribution is considered and it is symmetric about centroid axis of spark region as shown in figure 3.5. Heat flux is the maximum at center and goes on decreasing in radial direction in 20 discrete steps as discussed in section 3.1.5 from the center of the spark.

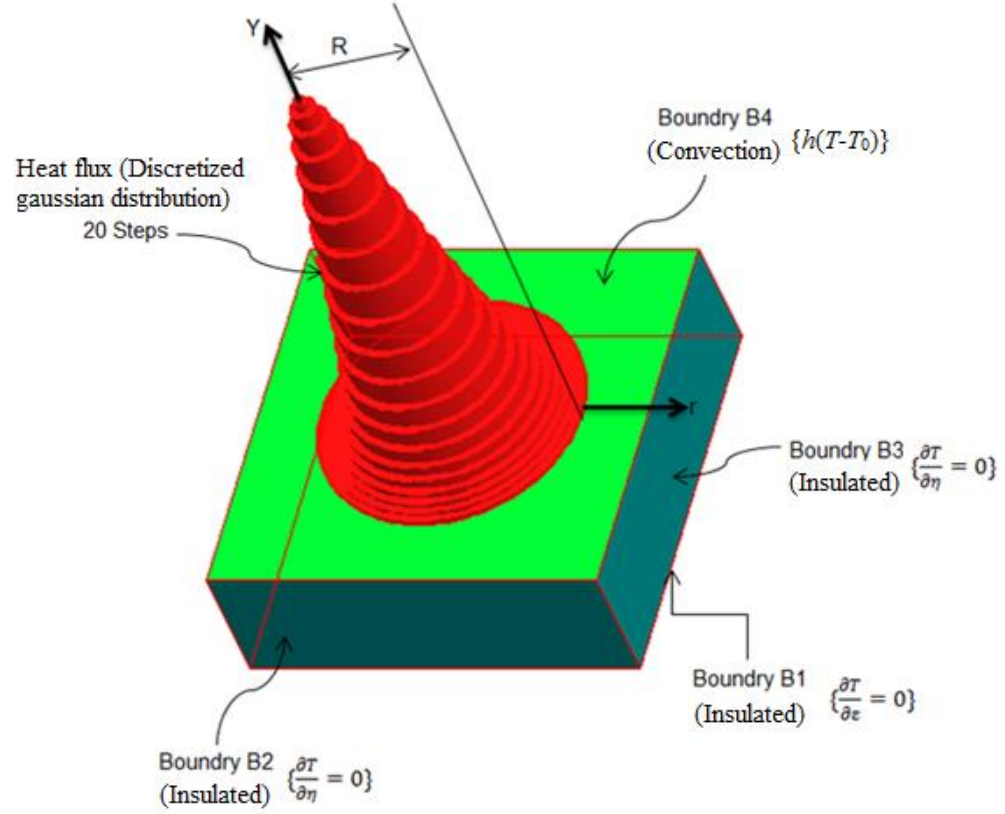


Figure 3.5: Boundary conditions for single spark model

Figure 3.5 shows a 3-D view of distribution of heat flux of spark radius of 100 μm . The radii of sub regions ranging from 5 μm to 100 μm with an increment of 5 μm are shown. So the total area under the spark region has been divided into 20 sub areas. These sub-areas have heat flux values depending upon its average distance from centroid of spark region. These values show Gaussian distribution as shown in figure 3.5. This discretized Gaussian distribution of heat flux is incident on boundary B4 of the work piece, starting from centroid axis of the spark region (In both cases of single and multi-sparks study) and ends up to radius R . Beyond this region, B4 is exposed to convection heat transfer due to heat loss in powder mixed dielectric medium.

Mathematically, for boundary B4:

$$K \frac{\partial T}{\partial z} = Q_w(r) \quad (3.8)$$

$$Q_w(r) = \begin{cases} \frac{4.57R_wV_bIK_n}{\pi R^2} e^{-4.5 \frac{r^2}{R^2}}, & r \leq R \\ h(T - T_0), & r > R \end{cases} \quad (3.9)$$

Where, T - Temperature

T_0 - 22°C

$Q_w(r)$ - Intensity of Heat imparted to work piece

r - Radial distance from center of spark

K_n - Powder particle size and concentration factor

V_b - Breakdown Voltage

I - Current

R_w - Fraction of Heat going to work piece

R - Spark radius

All the other boundaries i.e. B1, B2 and B3 remain insulated as shown in figure 3.5.

Mathematically, for boundary B1, B2, B3:

$$\frac{\partial T}{\partial \eta} = 0 \quad (3.10)$$

3.1.8 Spark radius

Size of plasma channel is not constant but grows with time. Theoretical and experimental efforts have been made by some researchers to predict the spark radius. In present work spark radius is varying from 5 μm to 100 μm and heat flux is given to these discretized areas in such a way that will leads to consideration of spark growth with the time. Figure 3.6 shows an analysis setting graph of simulation of PMEDM process. Simulation of growing spark is done by dividing pulse on time (T_{on}) into 20 different time steps. In a very first time step heat flux is given to only innermost region of the spark and it continues up to the end of T_{on} . Now when second time step starts, heat flux calculations

using equation 3.7 is also applied to next region to the innermost region and continues up to end of T_{on} . This is done for all 20 different time steps as shown in figure 3.6.

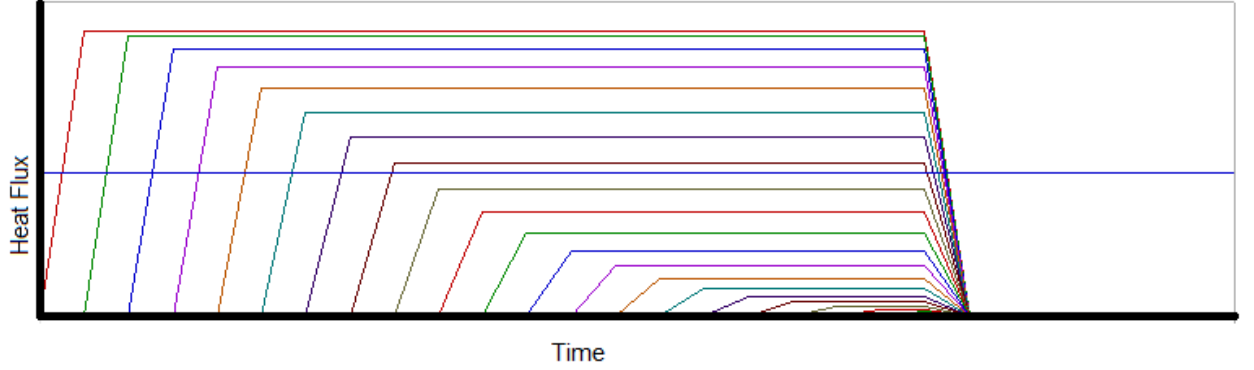


Figure 3.6: Schematic representation of heat flux input at each time steps

3.2 SIMULATION METHODOLOGY

FEM simulation package, ANSYS is used for the purpose of simulation of PMEDM process. Simulation methodology steps are explained for both single and multiple overlapped crater formation. Heat flux applied to the work surface followed by geometric modeling and meshing are explained thoroughly for both single and multiple overlapped craters along with convection loading.

3.2.1 SINGLE SPARK STUDY

In this study each step of simulation for single spark of the PMEDM process has been explained. Heat flux applied to the work surface along with meshing scheme applied to the single spark and geometric modeling are explained here.

Geometric modeling

A model has been created to simulate the single spark simulation of PMEDM process. It is formed in two parts. First part is a cuboid of dimensions 300x300x300 μm and second part is a part of sphere which is sliced from the first part as shown in figure 3.7. Both the parts of the model are symmetric about Y-axis. First part is made by simple extrude command and second is made by slicing the first using Revolve command. The size of hemi-spherical part is 100 μm in radial direction and 60

μm in depth direction. Now to apply different heat fluxes to different sub areas, 20 different surfaces are created on the top surface of the model as shown in the figure. Radii of these regions are 5 to 100 μm with an increment of 5 μm (i.e. 5, 10, 15, 20... 100).

Material assigned to both the parts of model is H13 hot die steel. Its properties are already discussed in section 3.1.3.

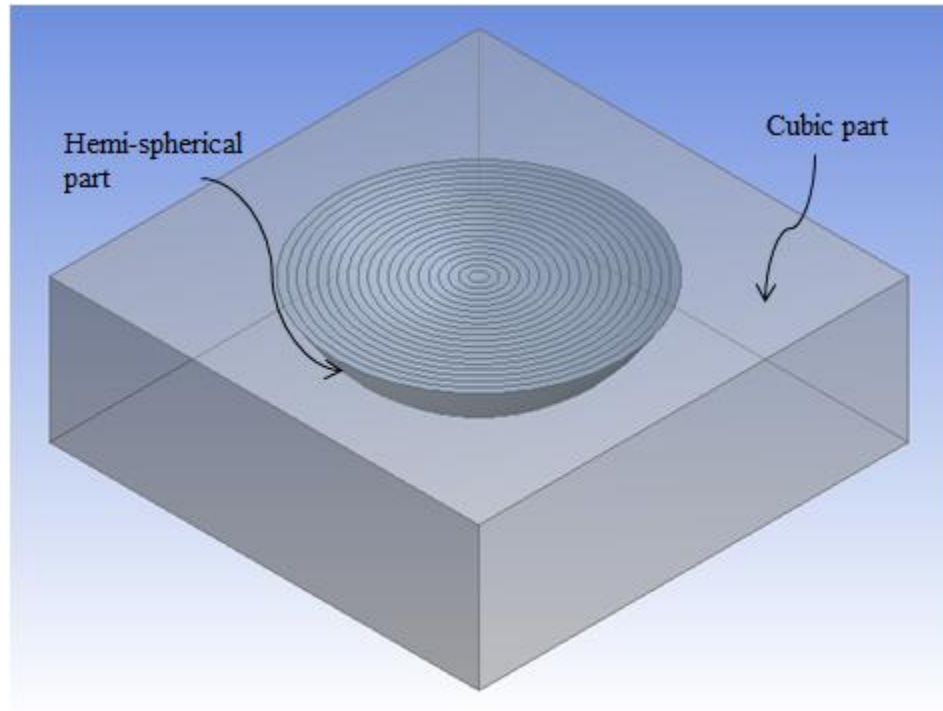


Figure 3.7: Geometric model

Meshing

Figure 3.8 shows a 3-D sectional view of body in meshing. It is clear from the figure 3.8 that hemi-spherical part of model is meshed very finely but outer part is meshed coarsely. Both the parts of model all meshed by using tetrahedral meshing scheme. But element size is different in both cases. Cubic part of model is meshed using default mesh size and hemi-spherical part is meshed by using 4 μm mesh size.

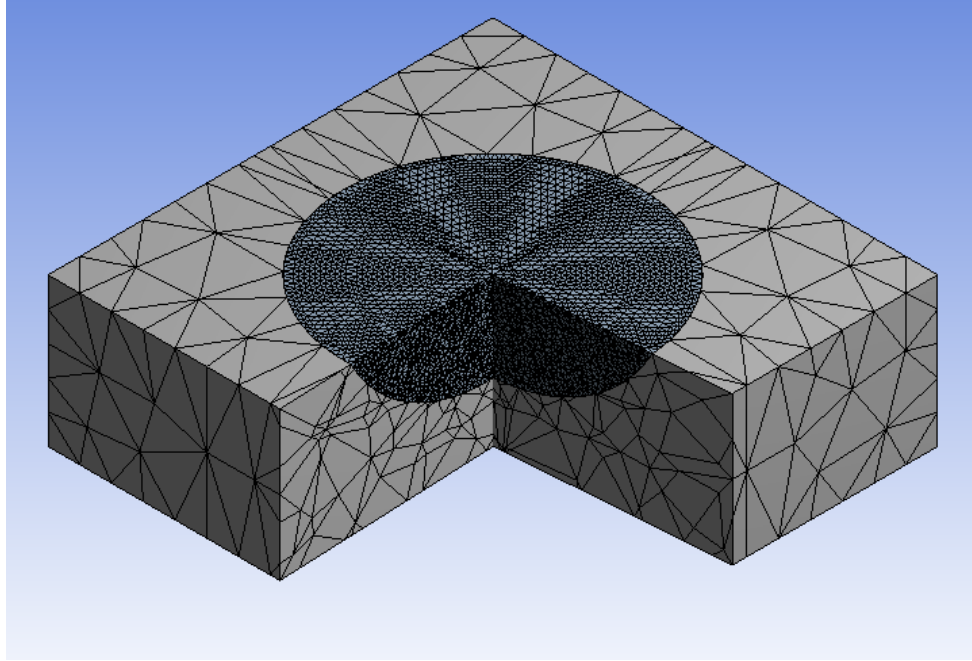


Figure 3.8: Meshing details

Table 3.3 gives the parameters used in simulations.

Table 3.3: Parameters used in simulation

Current (A)	3, 5, 7 and 9
Voltage (V)	38
K_n	2.4
R_w	0.15, 0.20, 0.25 and 0.30
Pulse On Time (μ s)	20, 50, 100
Spark radius (μ m)	100
Initial temperature ($^{\circ}$ C)	22
T_m ($^{\circ}$ C)	1454
T_{rc} ($^{\circ}$ C)	970
T_B ($^{\circ}$ C)	3054
Dielectric	Kerosene (convective heat transfer Coefficient 12000 W/m ² -K)

Heat fluxes applied on the work surface

Using parameter settings in table 3.4 and equation 3.7 heat flux values has been calculated for different sub regions using centralized discretization technique. These calculated heat fluxes have been used in transient thermal analysis as input to sub regions of spark as shown in figure 3.9. Q-t diagram of heat flux applied to work surface is shown in figure 3.6 to show the growing nature of spark with the time as discussed earlier in the section 3.1.8. This kind of heat input method corroborates a more realistic situation of growing spark, as may happen in a real situation. Kansal et al. [2010] and Bhattacharya et al. [2012] has not used such kind of heat flux input rather total heat flux (discretized) was given for the whole domain of spark at time $t=0$.

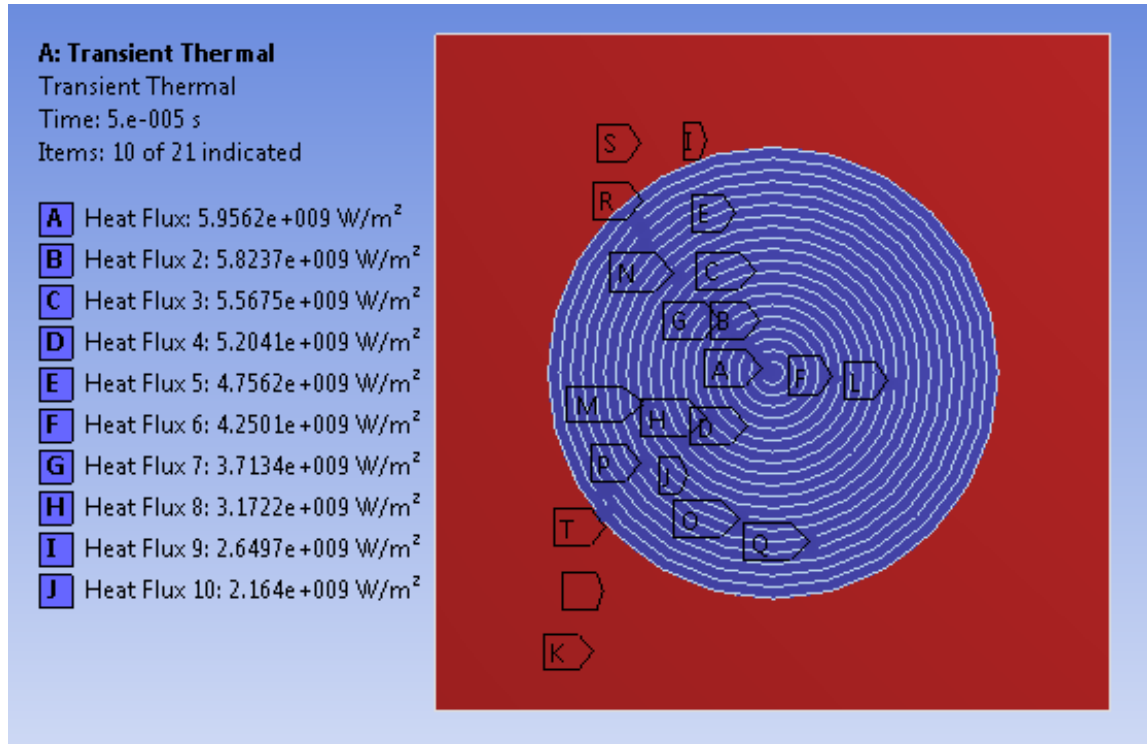


Figure 3.9: Different heat fluxes applied on different locations following Gaussian distribution.

Convection loading

In actual PMEDM process, region under spark is directly affected by heat flux of plasma channel. Beyond the spark region there is no heat flux active on the work surface. As the spark grow with the pulse on time (T_{on}) spark region expands and convection region contracts. So to simulate this, convection is applied to the contracting convection region with the growing spark

region. But it is found that there is not much difference if convection is simply applied to beyond the maximum spark region for all the period of time as discussed in results and discussion. So as shown in Figure 3.10 beyond the spark radius whole surface is exposed to a convection heat loss due to dielectric medium. Convection used in present work is $12000 \text{ W/m}^2\text{-}^\circ\text{C}$ (for kerosene).

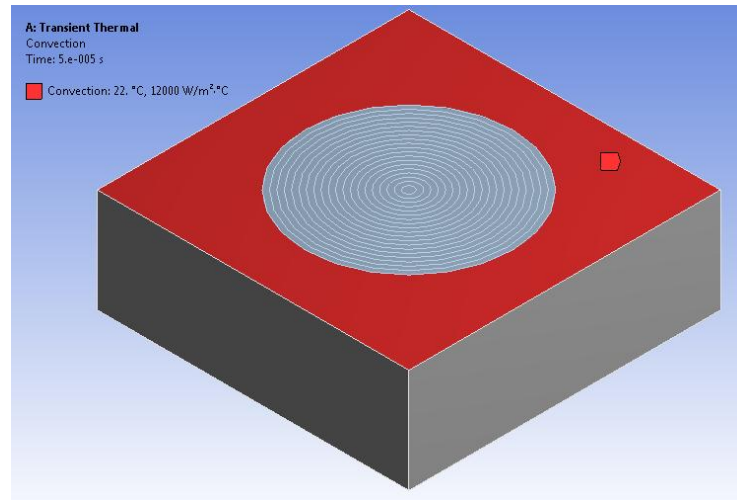


Figure 3.10: Convection applied on work piece beyond spark region

3.2.2 MULTIPLE OVERLAPPED CRATERS STUDY

In this section each step of simulation of multiple overlapped craters of PMEDM process has been explained. Heat flux applied on the work surface followed by random location generation, geometric modeling and meshing are explained along with convection heat loss to the work surface.

RANDOM LOCATION CREATION

Random location of five successive sparks has been created using a MATLAB code. These random locations are created within a particular region so that proper overlap can be found by only five random locations. So to get feasible overlap between five craters many times random location are generated. These random locations are created within a limit of circular region of radius $500 \mu\text{m}$ from the center of the work piece at the top surface of work piece. Some of the examples are as shown in figure 3.11(a, b, c, d). Out of which figure 3.11(a), figure 3.11(b) and

figure 3.11(d) are not feasible because there is no possibility of successive crater to be produce to such a close location as material will be removed after the creation of first crater. Some of the crater locations are also not feasible because location like in figure 3.11(d) is too far so there will be no overlapping between the successive craters. So location scheme shown in figure 3.11(c) is selected for the simulation of PMEDM process for multiple overlapped craters. The coordinate values (x, z) for each spark for selected locations are spark1 (19, 30), spark2 (104,-19), spark3 (221,-61), spark4 (-71,-124) and spark5 (75, -228).

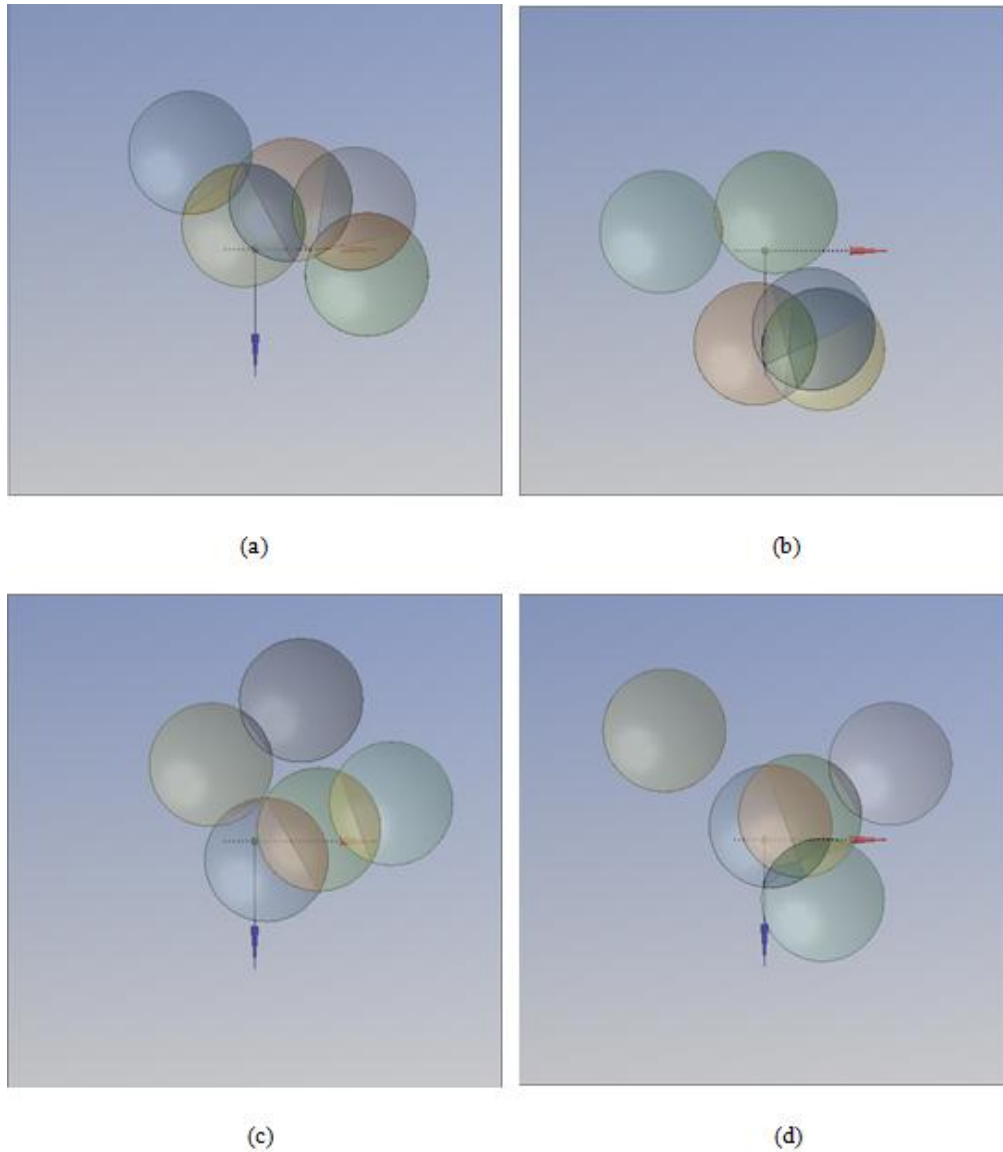


Figure 3.11: Random locations of craters

Geometric modeling

A model has been developed to simulate the multiple overlapped craters of PMEDM process. It is a cuboid of size 800x800x100 μm with five randomly located spark regions as discussed above. Model is first made by simple extrude command to make the cuboid. Now new planes are created at random locations on the top surface of cuboid formed. These planes are used to create slice of hemi-spherical part of spark as shown in figure 3.12(spark1, spark2, spark3, spark4 and spark5) using revolve command at each plane.

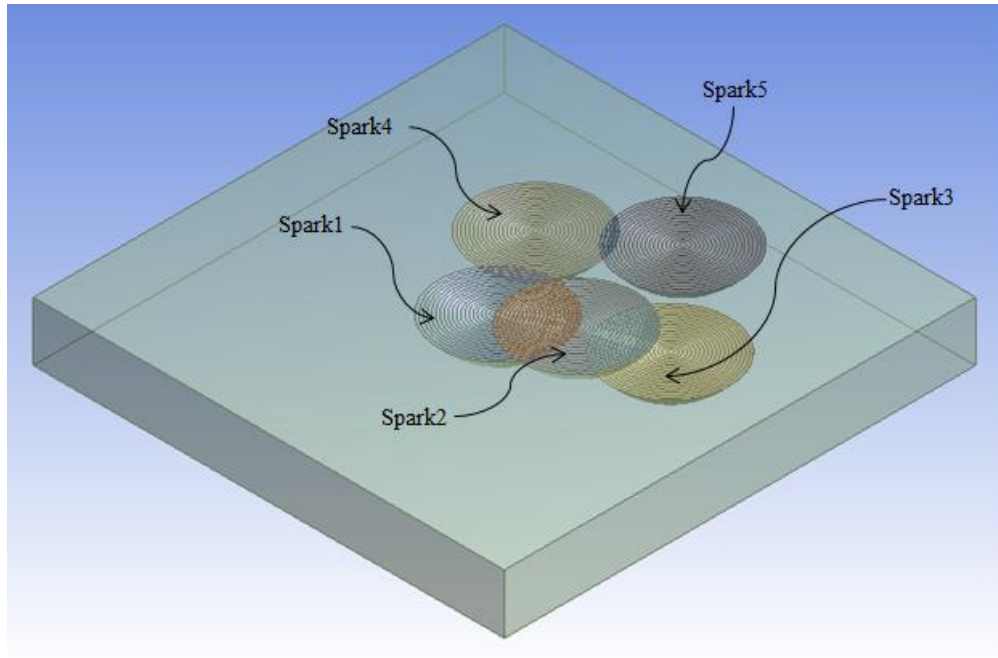


Figure 3.12: Geometric model for multi-spark simulation

Size of each hemi-spherical part is 100 μm in radius and 50 μm in depth. To apply different heat fluxes at different sub areas 20 different faces have been created for each spark on the top surface of the model by using split face command. Radii of these regions are ranges from 5 to 100 μm with an increment of 5 μm (i.e. 5, 10, 15, 20, 25, 30, 35, 40.....100 μm). Model is completed in 10 body parts as shown in figure 3.12 (cuboid, spark1, intersection of spark1 and spark2, spark2, intersection of spark2 and spark3, spark3, intersection of spark1 and spark4, spark4, intersection of spark4 and spark5, and in the last spark5). Material assigned to each part of model is H13 hot die steel with properties as listed in table 3.2.

Meshing

Model is meshed using tetrahedral meshing element. Each part under the spark region is meshed with finer element size of $4\text{ }\mu\text{m}$ and rest with default element size settings. Figure 3.13 shows meshing detail for multi-spark simulation.

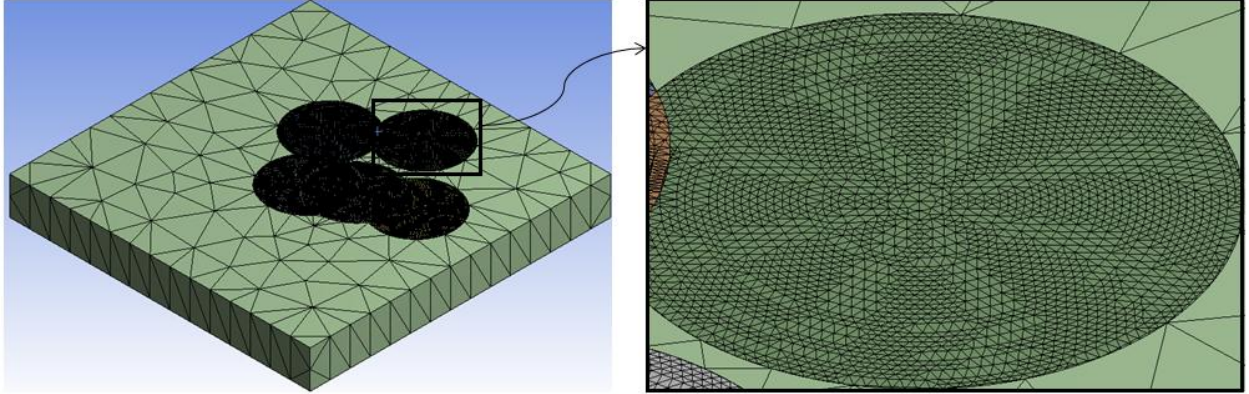


Figure 3.13: Meshing detail for multi-spark simulation

Table 3.4 gives the parameters used in simulations.

Table 3.4: Parameters used in simulation

Current, I (A)	3, 5 and 7
Voltage, V_b (V)	38
K_n	2.4
R_w	0.15, 0.20 and 0.25
Pulse On Time, T_{on} (μs)	50, 100
Spark radius, r (μm)	100
Initial temperature	22
Melting temperature, T_m ($^{\circ}\text{C}$)	1454
Re-crystallization temperature T_{rc} ($^{\circ}\text{C}$)	970
Boiling temperature T_B ($^{\circ}\text{C}$)	3054
Dielectric	Kerosene (convective heat transfer Coefficient $12000\text{ W/m}^2\text{-K}$)

Heat fluxes applied on the work surface

In actual PMEDM process, a series of rapid, repetitive and randomly distributed discrete electric sparks occur one after another. So to simulate this, random locations are already created and now sparks have to apply one after another to replicate the actual process. To do this heat flux values have to be applied to the regions under spark1 as discussed in previous section 3.2.1. Figure 3.14 shows a zoomed view of heat flux distribution scheme for spark1 during simulation of multiple overlapped craters of PMEDM process.

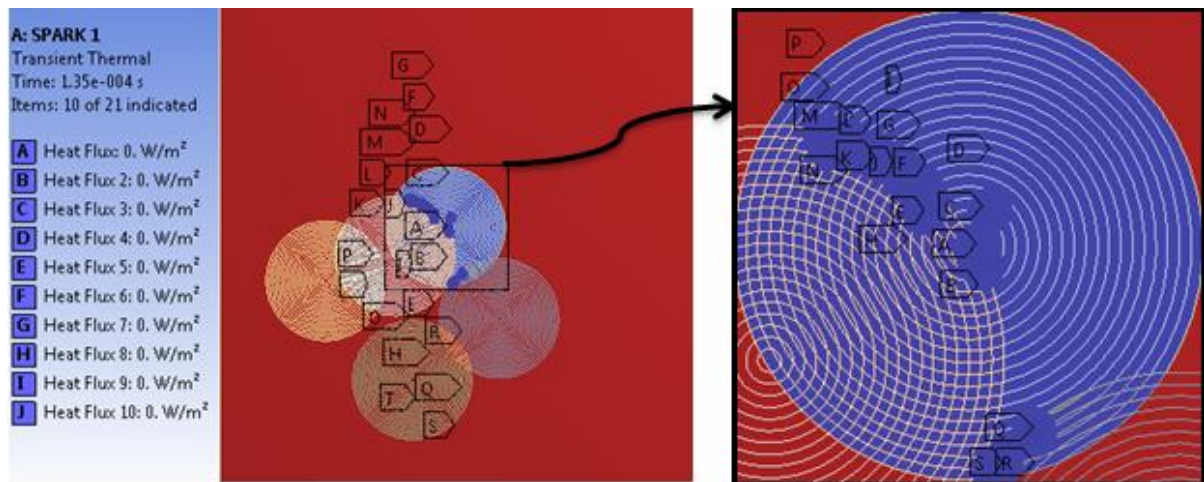


Figure 3.14: Different heat fluxes applied on different locations following Gaussian distribution for Spark 1.

Now in the end of spark1 when the material is removed by suppress spark1 region. A crater is formed and heat flux values calculated for 20 sub regions as discussed earlier has to apply on spark region2. Figure 3.15 shows a zoomed view of heat flux distribution scheme for spark2 during simulation of multiple overlapped craters of PMEDM process.

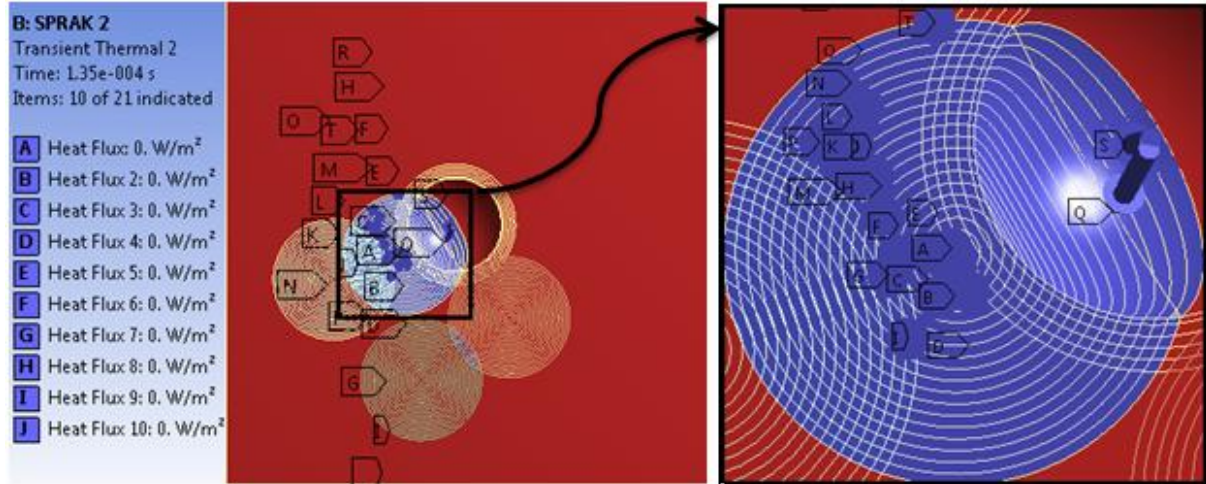


Figure 3.15: Different heat fluxes applied on different locations following Gaussian distribution for Spark 2.

Similarly after the simulation of spark2, region under the influence of spark2 has to suppress to apply the third spark i.e. spark3. Figure 3.16 shows a zoomed view of heat flux distribution scheme for spark3 during simulation of multiple overlapped craters of PMEDM process.

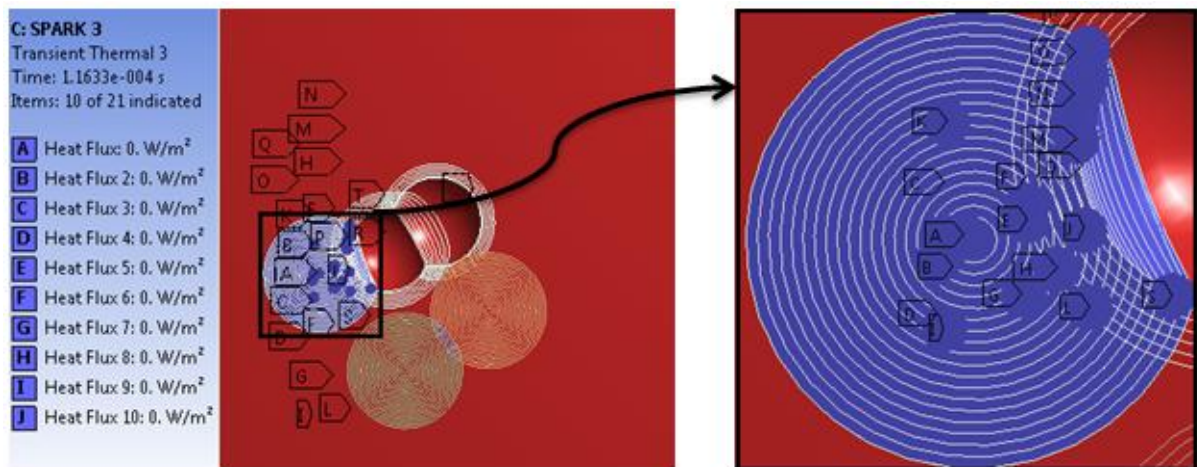


Figure 3.16: Different heat fluxes applied on different locations following Gaussian distribution for Spark 3.

After the simulation of spark3, region under the influence of spark3 has to suppress to apply the third spark i.e. spark4. Figure 3.17 shows a zoomed view of heat flux distribution scheme for

spark3 during simulation of multiple overlapped craters of PMEDM process. Convection currents are also applied on the cavity formed by the removed crater1, crater2 and crater3.

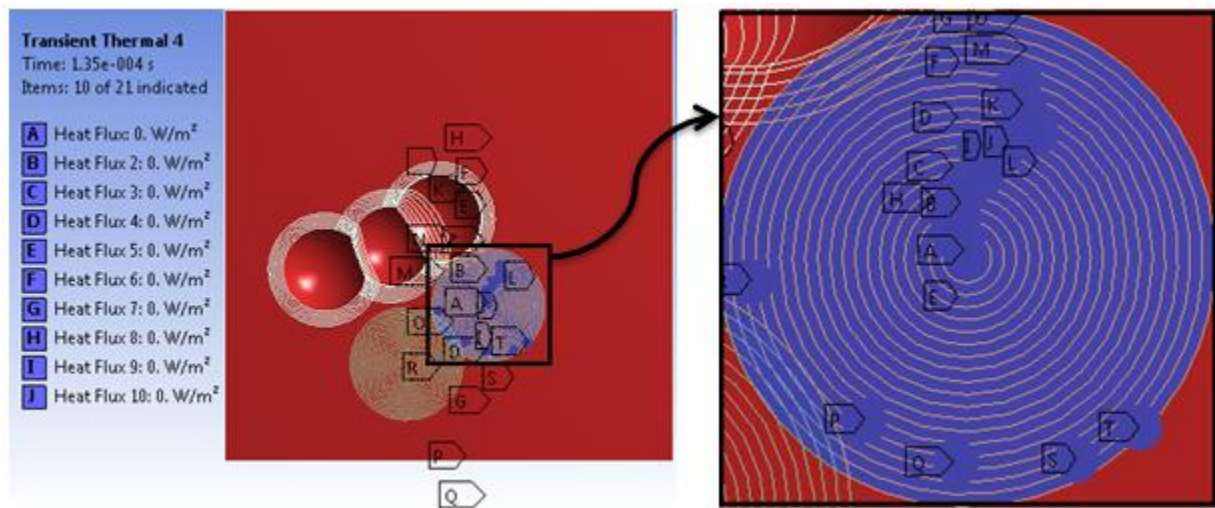


Figure 3.17: Different heat fluxes applied on different locations following Gaussian distribution for Spark 4.

Now in the last when all the previous four craters are formed spark 5 have to be charged with the heat loads in the same manner for each step by step loading in all the 20 discretized reigns as shown in figure 3.18.

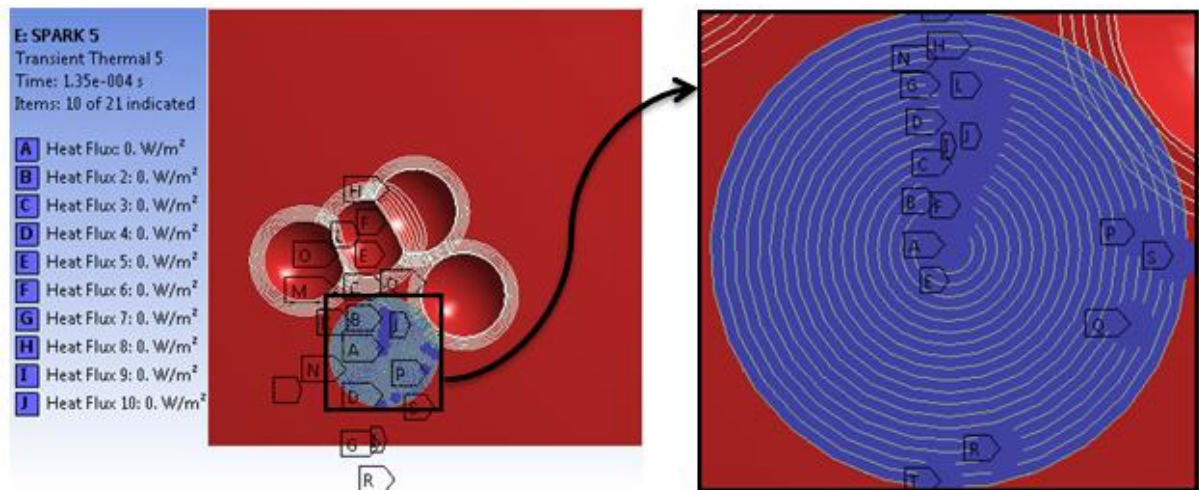


Figure 3.18: Different heat fluxes applied on different locations following Gaussian distribution for Spark 5.

Convection loading

In actual PMEDM process region under spark is directly affected by the heat flux of spark channel. Beyond the spark radius there is no heat flux active on the work surface. So as the spark is grows, convection region contracts. This is because when heat flux is provided to the inner most region at the time of first step, convection would be present on all the remaining regions and this process would go on as the spark grows. Means convection loading has to be applied to remaining region which does not have heat flux input at that time step. But it is found that there is no effect of considering the convection in this manner or simply applying the convection currents beyond the spark region. So as shown in Figure 3.19 beyond the spark radius whole surface is exposed to a convection heat loss due to dielectric medium. Convection used in present work is $12000\text{W/m}^2\text{-}^\circ\text{C}$ (for kerosene).

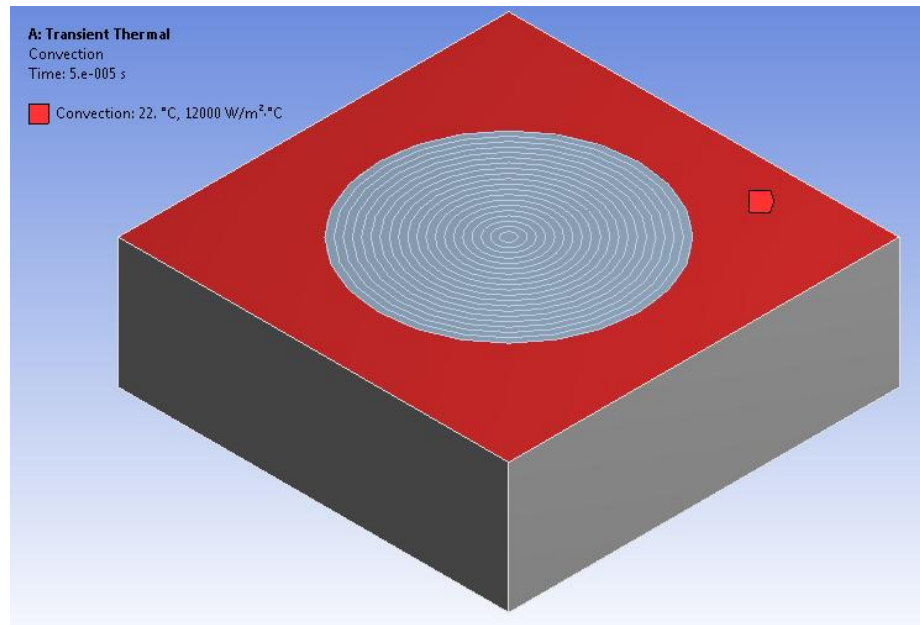


Figure 3.19: Convection applied on work piece beyond spark region

CHAPTER 4

SIMULATION RESULTS

Following the methodology as depicted in Chapter 3, the simulation of PMEDM process for single and multi-spark simulations are completed at different process conditions. Values of process parameters used for single spark analysis is given in Table 3.3 and for multiple spark analysis given in Table 3.4 After simulation, the following outputs are extracted and analyzed further.

- i) Temperature distribution along radial and depth direction (for single spark and multi-spark simulation)
- ii) Variation of peak temperature with different parameters (for single spark simulation)
- iii) Different temperature zones (for single spark simulation)
- iv) Volume of crater formed (for both single and multi-spark simulation)
- v) Comparison volume removal due to melting and vaporization. (for single spark simulation)

4.1 Single spark

Single spark of PMEDM process originates for a particular instant of time and leave a cavity on the work piece. But there is no stress before the occurrence of that spark. Different results after the simulation of single spark with no initial stress are discussed in the coming sections.

4.1.1 Temperature distribution

In present work considering the thermal aspects of PMEDM process, heat source is discretized in 20 different sub-regions using Gaussian distribution. To apply the heat on the work surface region under spark channel, spark region was discretized into 20 different sub areas. Heat flux was applied on these discretized areas for the different pulse on time, with corresponding heat flux intensity using Gaussian distribution. Due to heat fluxes applied on the spark region non uniform temperature distribution is generated into the domain. To observe temperature distribution in radial as well as in depth direction temperature plots have been made. Temperature distribution given by transient thermal analysis is exported (in excel file) to plot in radial as well as depth direction. Information in this file is related to each node of the model

mesh. It extracts complete information regarding each node i.e. node number, nodal coordinates and temperature generated at each node. A program was developed in Visual C++ 6.0 to sort this excel file containing non uniform distribution and finally make a list of sorted nodes in radial direction and depth direction along with its corresponding temperature. Figure 4.1 shows the complete algorithm for this purpose.

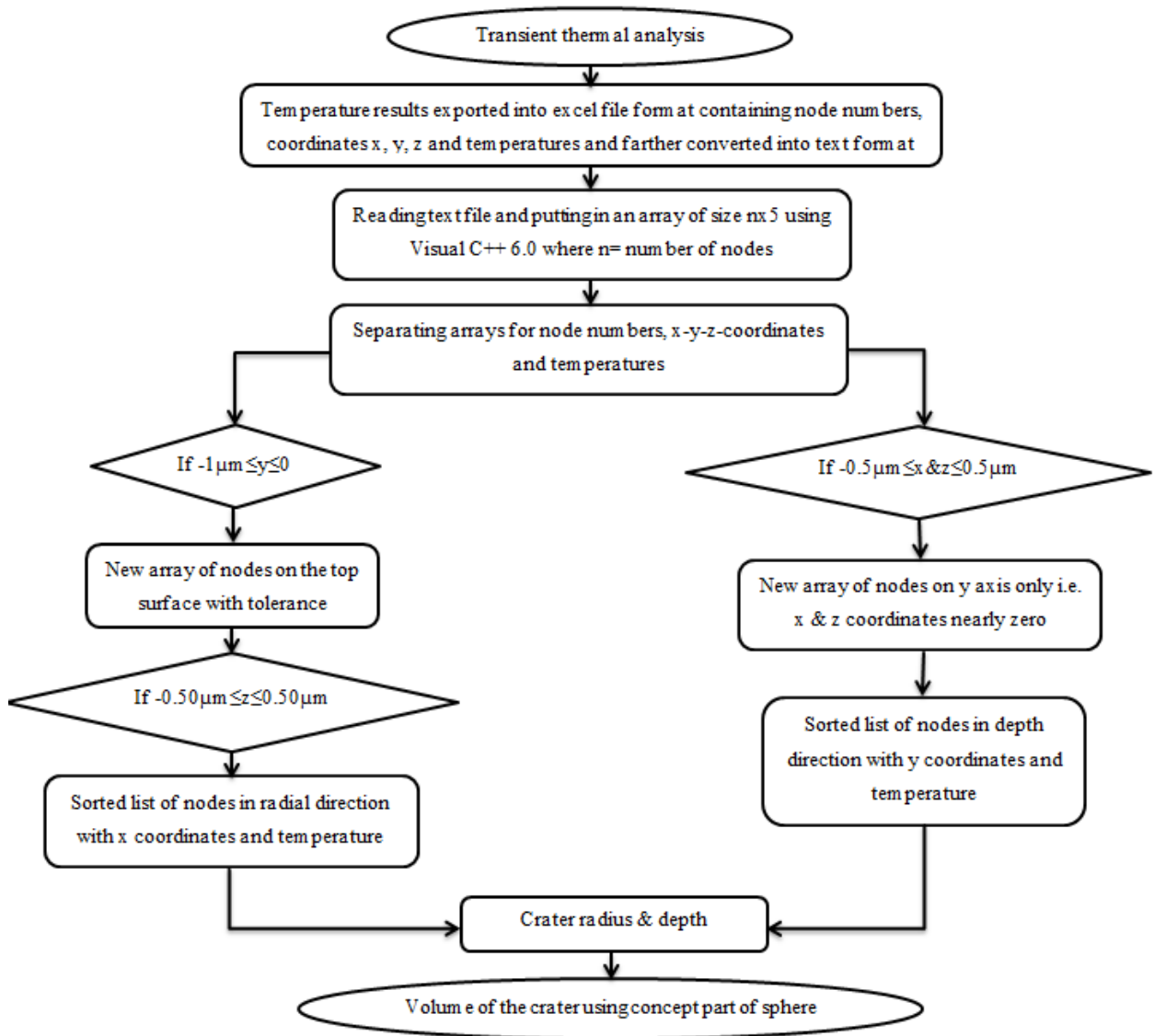


Figure 4.1 : Algorithm to illustrate the extraction of nodal coordinates and temperatures above melting temperature to evaluate volume removal of crater for single spark simulation

Temperature distribution along the radial direction

To study the effect of different parameters on the work piece four levels of current i.e. 3, 5, 7 and 9 A have been taken and four levels of R_w i.e. 0.15, 0.20, 0.25 and 0.30 have been taken. As shown in figure 4.2 temperature distributions has been predicted using surface plots for the pulse on time $20 \mu s$ using powder concentration factor $K_n = 2.4$, discharge Voltage $V_b = 38$ V, for different values of R_w and I . From the figure 4.2 it is clearly visible that temperature distribution follows Gaussian distribution as it is supposed to. Temperature at the center of spark is the maximum and starts decreasing while moving away from center of spark. It is noticed that temperature rises by increasing current and R_w factor. In the figure 4.2 temperature distribution is predicted up to spark radius (R) in radial direction. It is inferred from the surface plots that significant temperature drop is there for different R_w factor near to center of spark and it starts decreasing while moving away from spark center.

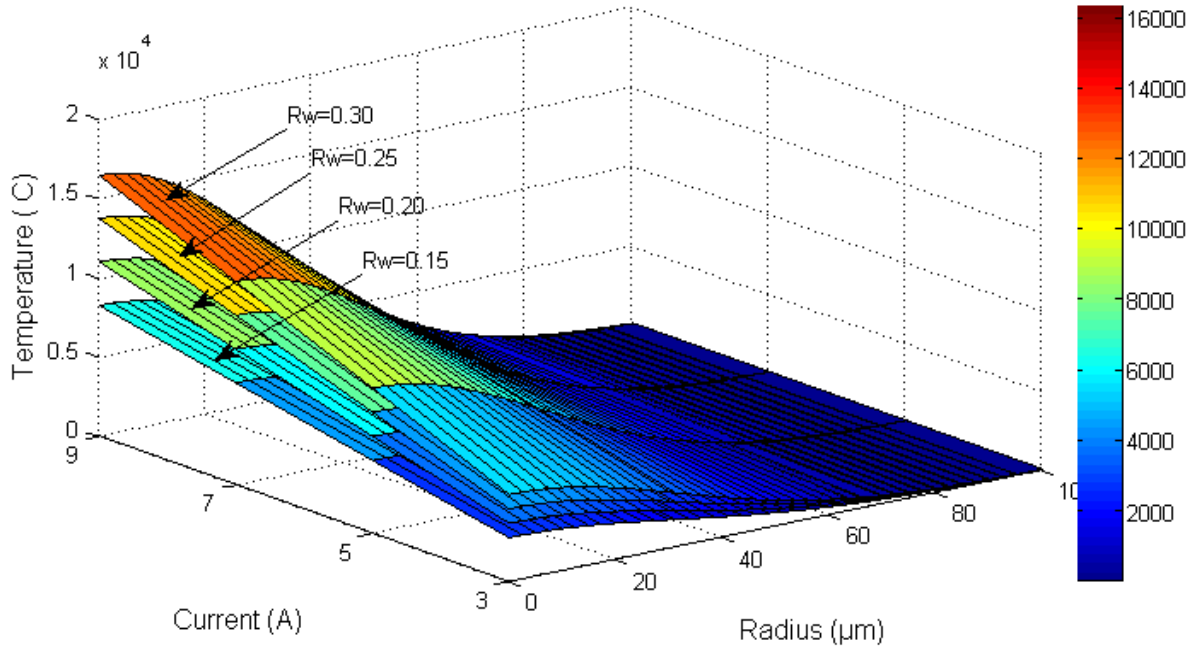


Figure 4.2 : Temperature distribution in radial direction generated during simulation using $K_n = 2.4$, $V_b = 38$ Volts, $T_{on} = 20 \mu s$ for different R_w at different I

To represent results of temperature distribution in the form of 3D colored contour plots images have been taken for each individual simulation and few of them as sample representation are

shown in figure 4.3 (a) to (d). In these particular cases constant $T_{on} = 20 \mu s$, $R_w = 0.30$, $K_n = 2.4$ $V_b = 38V$ is taken as input parameter. Four different levels of current, $I = 3, 5, 7$ and $9A$ has been used for four different simulations. Red region in the contour plots represent material above vaporizing temperature of H13 ($3045^\circ C$) and yellow region in the contour plots represent material above melting temperature of H13 ($1454^\circ C$). From the figure 4.3 (a) to (d) it is clearly visible that red plus yellow region is the predicted volume to be removed while actual machining and increases significantly with increase in current. It is also noticed that diameter of crater is much larger than the depth.

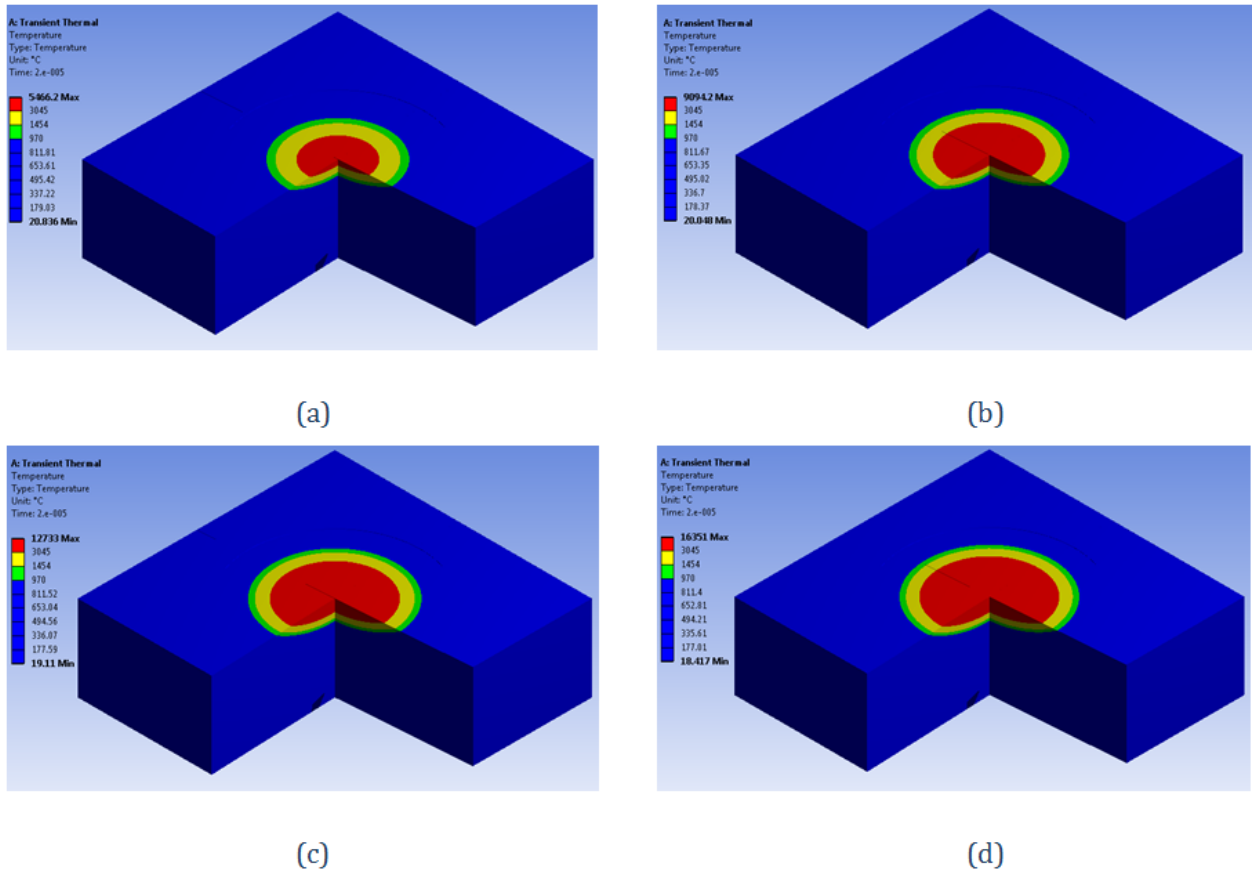


Figure 4.3 : Temperature distribution with $K_n = 2.4$, $V_b = 38V$, $T_{on} 20\mu s$ for different R_w at different current settings (a) 3A, (b) 5A (c) 7A and (d) 9A

Figure 4.4 shows temperature distribution for the pulse on time $50\mu s$ using powder concentration factor $K_n = 2.4$, discharge Voltage $V_b = 38 V$, for different values of R_w and I . From the Figure 4.4 it is clearly visible that temperature distribution follows Gaussian distribution as it is supposed

to. Temperature at the center of spark is the maximum and starts decreasing while moving away from center of spark. It is noticed that temperature rises by increasing current and R_w factor. In the Figure 4.4 temperature distribution is predicted up to spark radius (R) in radial direction. It is inferred from the plots that significant temperature drop is there for different R_w factor near to center of spark and it starts decreasing while moving away from spark center.

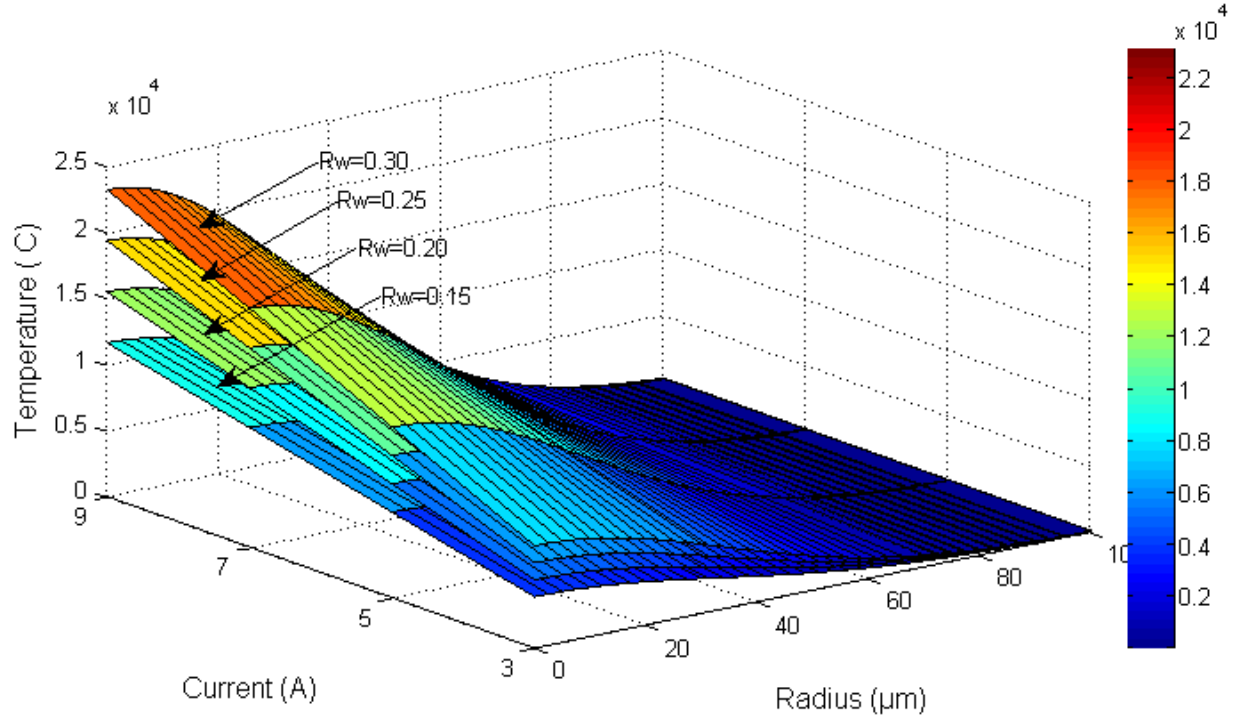


Figure 4.4 : Temperature distribution in radial direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{V}$, $T_{on} = 50\mu\text{s}$ for different R_w at different I

As discussed earlier for $T_{on} = 20\mu\text{s}$, to represent results of temperature distribution in the form of 3-D colored contour plots images for $T_{on} = 50\mu\text{s}$ are shown in Figure 4.5 (a) to (d). In these particular cases constant $T_{on} = 50\mu\text{s}$, $R_w = 0.30$, $K_n = 2.4$, $V_b = 38\text{V}$ is taken as input parameter. Four different levels of current, $I = 3, 5, 7$ and 9A has been used for four different simulations. Red region in the contour plots represent material above vaporizing temperature of H13 (3045°C) and yellow region in the contour plots represent material above melting temperature of H13 (1454°C). From the Figure 4.5 (a) to (d) it is clearly visible that red plus yellow region is the

predicted volume to be removed while actual machining and increases significantly with increase in current. It is also noticed that diameter of crater is much larger than the depth.

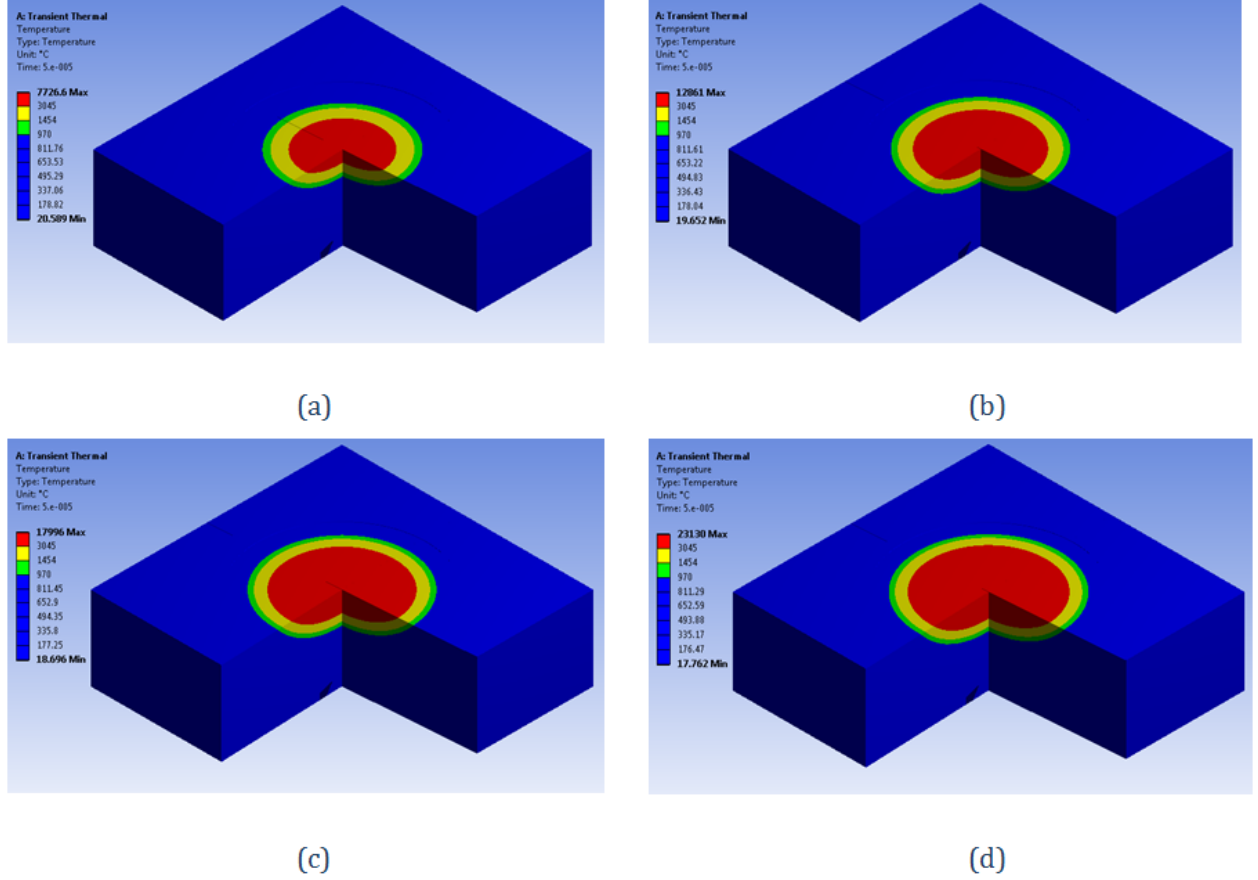


Figure 4.5 : Temperature distribution with $K_n = 2.4$, $V_b = 38V$, $T_{on} 50\mu s$ for different R_w at different current settings (a) 3A, (b) 5A, (c) 7A and (d) 9A

Figure 4.6 shows temperature distribution for the pulse on time $100\mu s$ using powder concentration factor $K_n = 2.4$, discharge Voltage $V_b = 38V$, for different values of R_w and I . From the Figure 4.6 it is clearly visible that temperature distribution follows Gaussian distribution as it is supposed to. Temperature at the center of spark is the maximum and starts decreasing while moving away from center of spark. It is noticed that temperature rises by increasing current and R_w factor. In the Figure 4.6 temperature distribution is predicted up to spark radius (R) in radial

direction. It is inferred from the plots that significant temperature drop is there for different R_w factor near to center of spark and it starts decreasing while moving away from spark center.

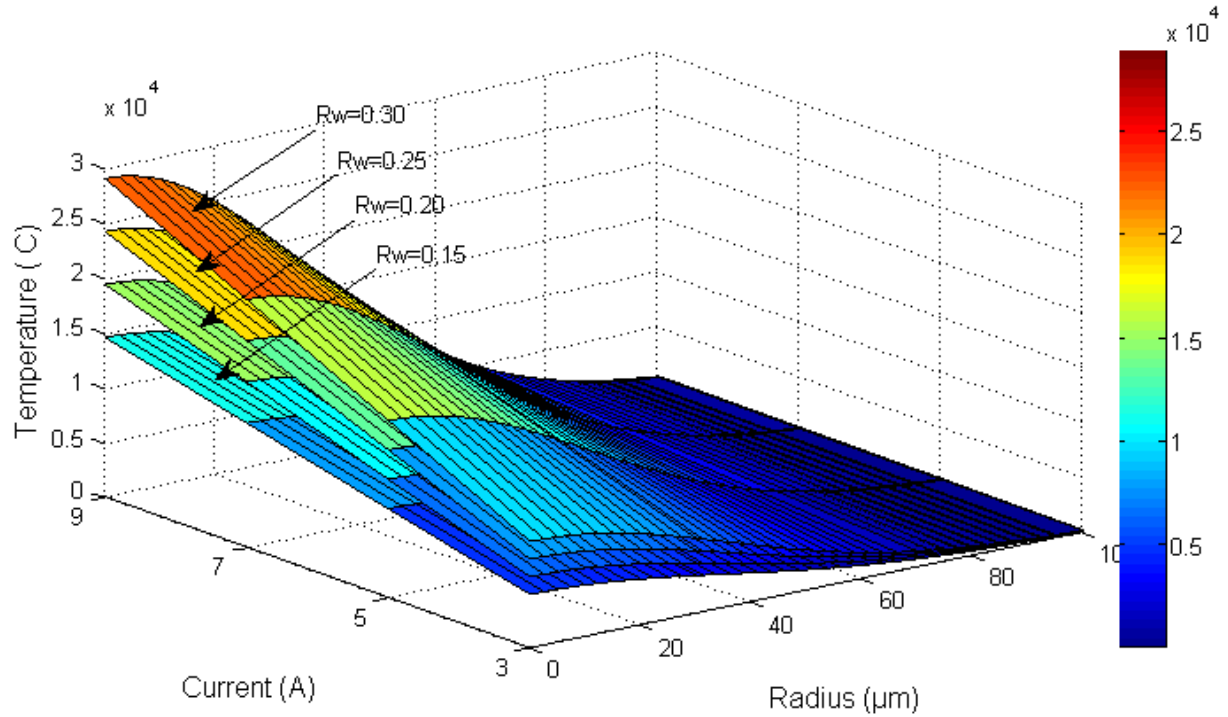
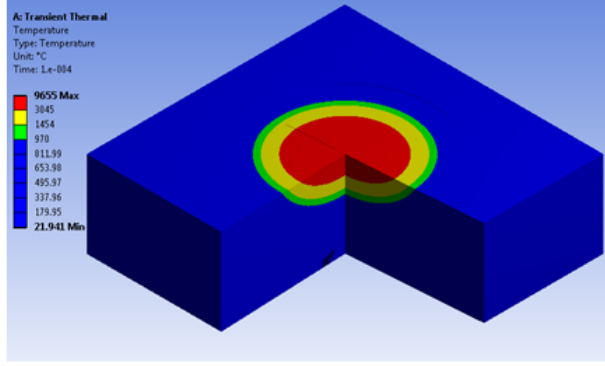
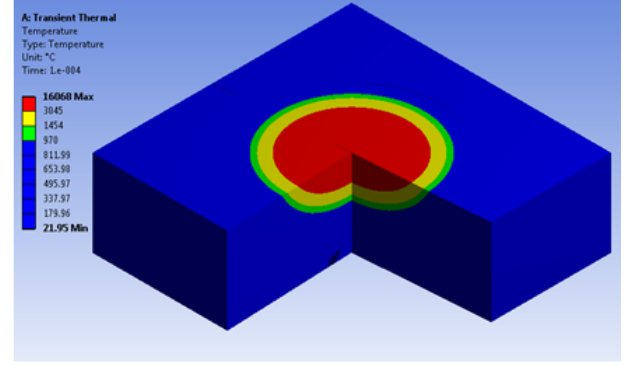


Figure 4.6 : Temperature distribution in radial direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{V}$, $T_{\text{on}} = 100\mu\text{s}$ for different R_w at different I

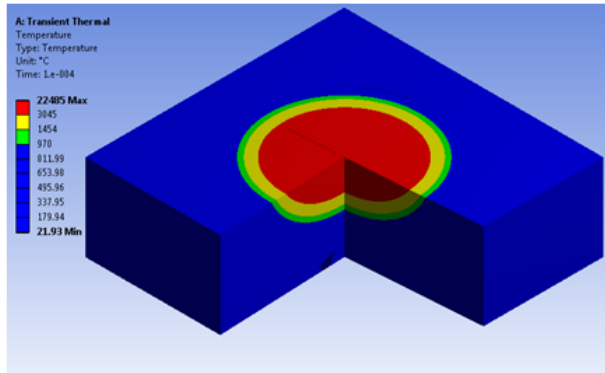
As discussed earlier, 3-D colored contour plots images for $T_{\text{on}} = 100\mu\text{s}$ are shown in Figure 4.7 (a) to (d). In these particular cases constant $T_{\text{on}} = 100\mu\text{s}$, $R_w = 0.25$, $K_n = 2.4$, $V_b = 38\text{V}$ is taken as input parameter. Four different levels of current, $I = 3, 5, 7$ and 9A has been used for four different simulations. Red region in the contour plots represent material above vaporizing temperature of H13 (3045°C) and yellow region in the contour plots represent material above melting temperature of H13 (1454°C). From the Figure 4.7 (a) to (d) it is clearly visible that red plus yellow region is the predicted volume to be removed while actual machining and increases significantly with increase in current. It is also noticed that diameter of crater is much larger than the depth.



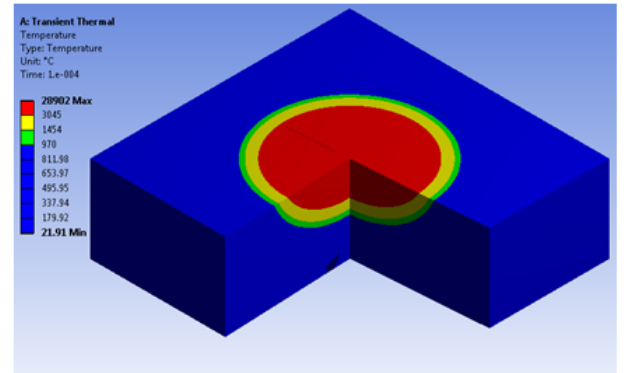
(a)



(b)



(c)



(d)

Figure 4.7 : Temperature distribution with $K_n = 2.4$, $V_b = 38V$, $T_{on} 100\mu s$ for different R_w at different current settings (a) 3A, (b) 5A, (c) 7A and (d) 9A

Temperature distribution in depth direction

To observe temperature distribution into work material in depth direction simulation results have been plotted as shown in Figure 4.8. Input parameters for these particular cases are pulse on time $20\mu s$, $R_w=0.15, 0.20, 0.25$ and 0.30 , $K_n= 2.4$, $V_b=38V$ and current = 3, 5, 7 and 9A.

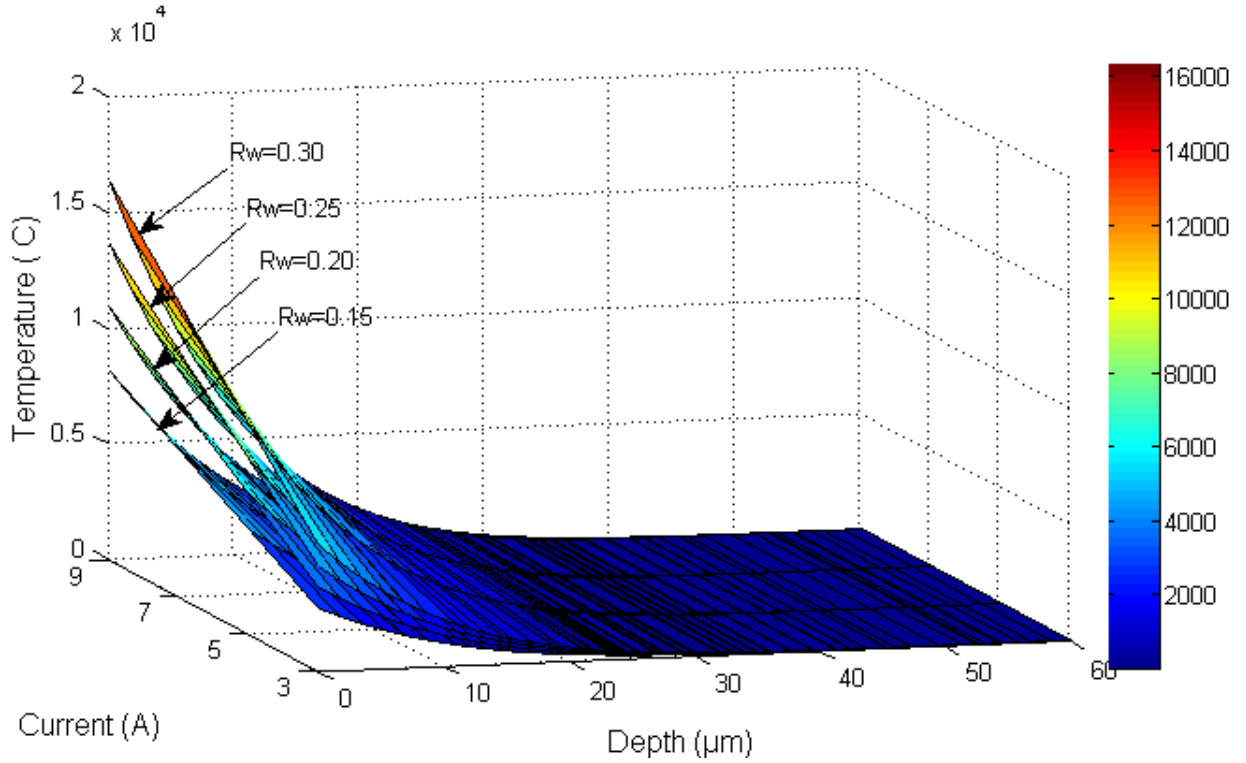


Figure 4.8 : Temperature distribution in depth direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{V}$, $T_{on} = 20\mu\text{s}$ for different R_w at different I

Comparing figure 4.2 and 4.8 it is observed that rate of decreasing temperature is large in depth direction compared to the radial direction. From above discussion it is clear that depth of the crater is predicted to be less compared to radius of crater. It is also inferred that peak temperature increases with increase in current and R_w .

Similarly to observe temperature distribution into work material in depth direction simulation for $T_{on} = 50\mu\text{s}$ results have been plotted as shown in Figure 4.9. Input parameters for these particular cases are pulse on time $50\mu\text{s}$, $R_w = 0.15, 0.20, 0.25$ and 0.30 , $K_n = 2.4$, $V_b = 38\text{V}$ and current = 3, 5, 7 and 9A.

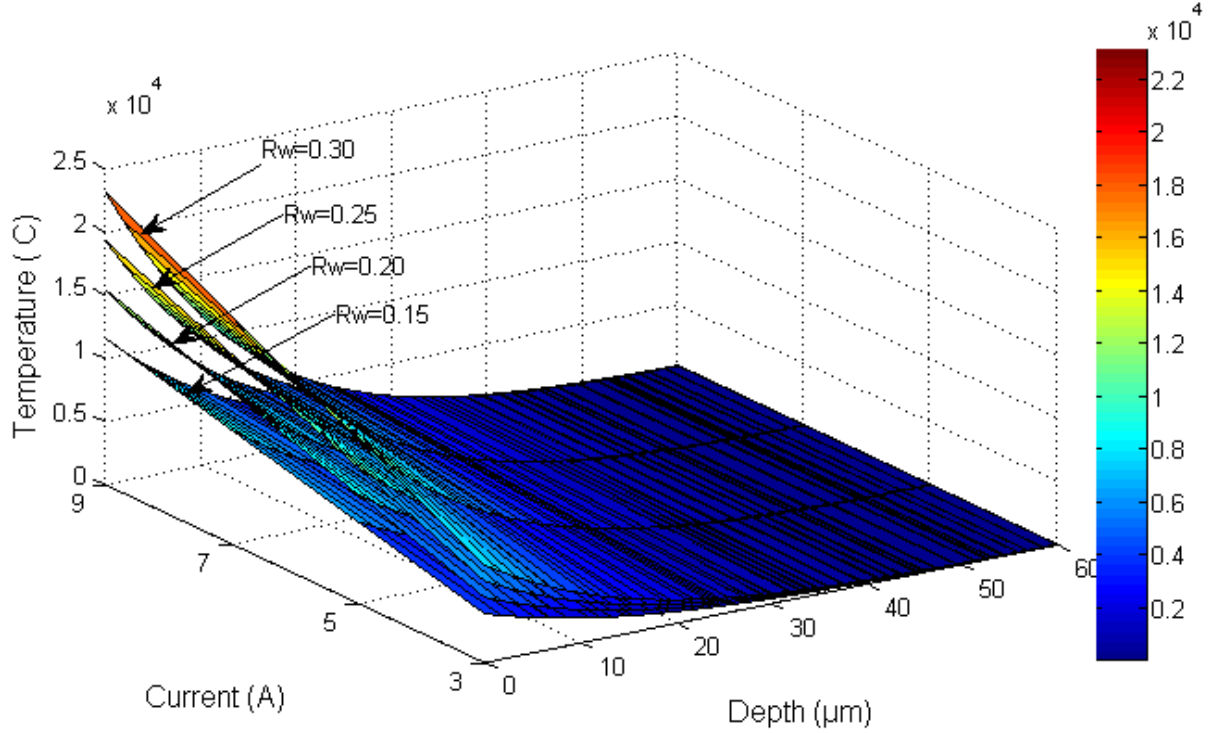


Figure 4.9 : Temperature distribution in depth direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{V}$, $T_{on} = 50\mu\text{s}$ for different R_w at different I .

Comparing Figure 4.4 and 4.9 it is observed that rate of decreasing temperature is large in depth direction compared to the radial direction. From above discussion it is clear that depth of the crater is predicted to be less compared to radius of crater. It is also inferred that peak temperature increases with increase in current and R_w .

To observe temperature distribution into work material in depth direction for $T_{on} = 100\mu\text{s}$ simulation results have been plotted as shown in Figure 4.10. Input parameters for these particular cases are pulse on time $100\mu\text{s}$, $R_w=0.15, 0.20, 0.25$ and 0.30 , $K_n= 2.4$, $V_b=38\text{V}$ and current = 3, 5, 7 and 9A.

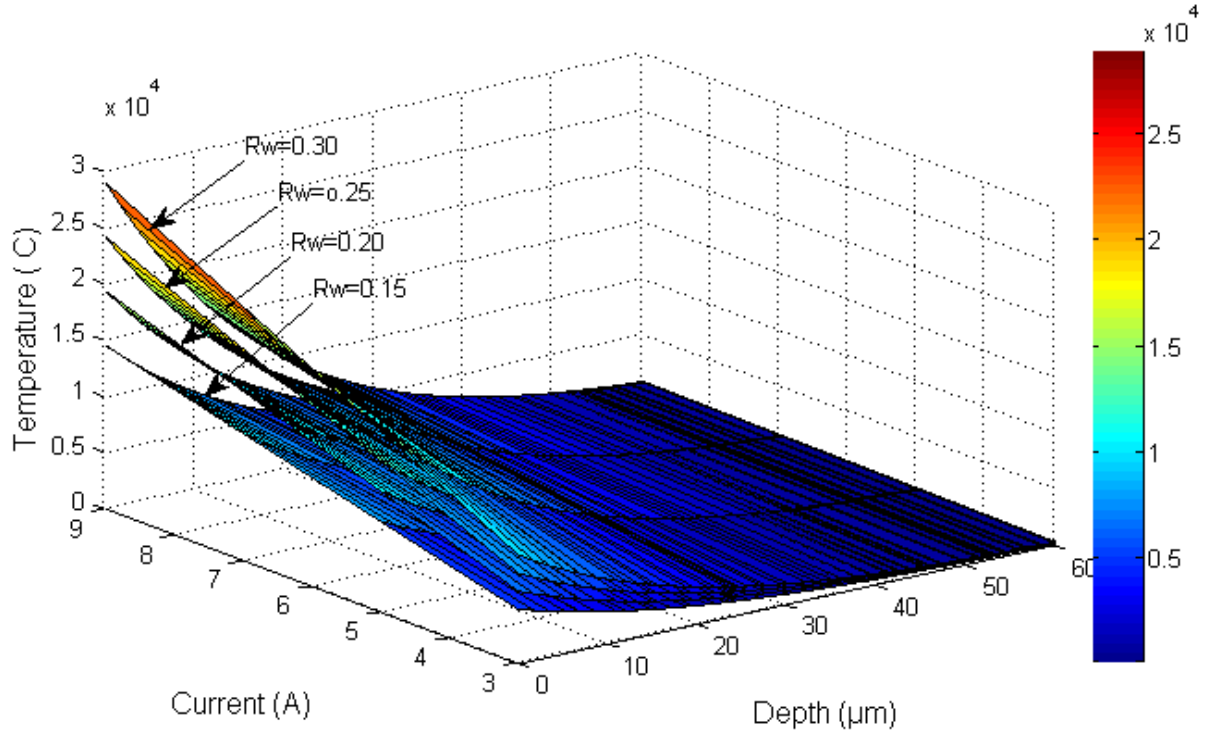


Figure 4.10 : Temperature distribution in depth direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{V}$, $T_{on} = 100\mu\text{s}$ for different R_w at different I .

Comparing Figure 4.6 and 4.10 it is observed that rate of decreasing temperature is large in depth direction as compared to the radial direction. From above discussion it is clear that depth of the crater is predicted to be less as compared to radius of crater. It is also inferred that peak temperature increases with increase in current and R_w .

4.1.2 Peak Temperature variation

To observe peak temperature variation more clearly, plots have been plotted with different R_w and currents as shown in figure 4.11, 4.12 and 4.13 for different pulse on times i.e. 20, 50 and $100\mu\text{s}$ seconds respectively. Figure 4.11 shows peak temperature plots for $T_{on} 20\mu\text{s}$. There is a significant increase in peak temperature developed with increase in current and R_w . But increase in temperature due to increase in Current is more significant as compared to R_w as shown in figure 4.11(a) and (b).

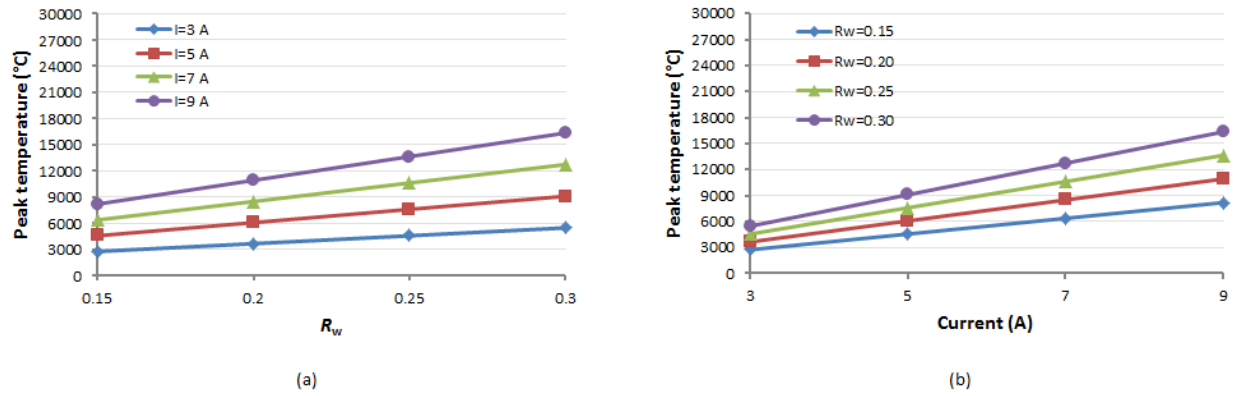


Figure 4.11 : Peak temperature variation using $T_{on} 20\mu s$ for different I at different R_w (a) and for different R_w at different current settings (b)

Now to observe peak temperature variation for $T_{on} 50\mu s$ simulation results have been plotted in figure 4.12 for different values of R_w and I . It is observed that slope of figure 4.12(b) is more as compared to figure 4.12(a). So Current is more sensitive than R_w . Comparing figure 4.11 and 4.12 it is confirmed that peak temperature increases considerably with the pulse on time.

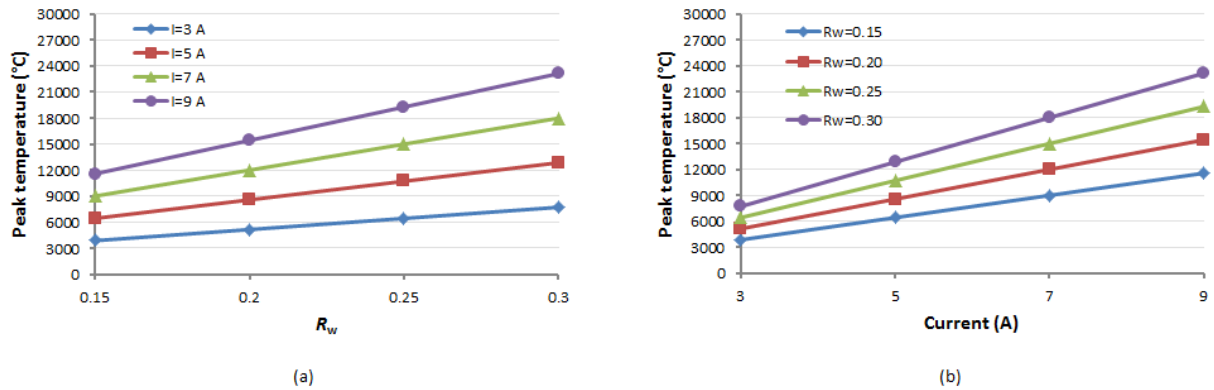


Figure 4.12: Peak temperature variation using $T_{on} = 50\mu s$ for different I at different R_w (a) and for different R_w at different current settings (b)

Simulation results of peak temperature variation for pulse on time $100\mu s$ are also plotted in figure 4.13. Similarly on comparing figure 4.13(a) and (b) it is confirmed that current has more influence on peak temperature as compared to R_w . If we compare figure 4.11, 4.12, 4.13 (a) and (b) it is clear that slope

of Figure (b) is more than Figure (a) for $T_{on} = 20, 50$ and $100\mu s$ respectively. So increasing the current is more effective than R_w for each case.

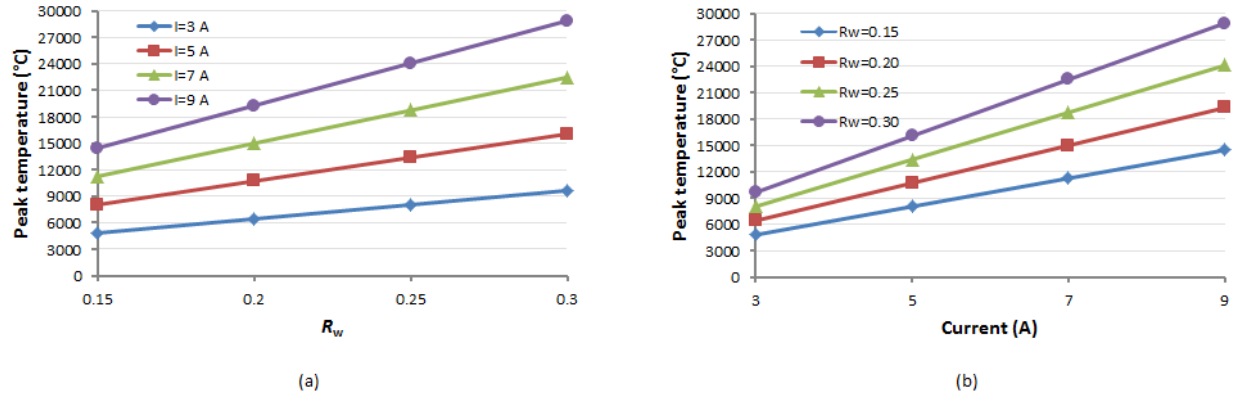


Figure 4.13: Peak temperature variation using $T_{on} = 100\mu s$ for different I at different R_w (a) and for different R_w at different current settings (b)

Comparing figure 4.11, 4.12 and 4.13 it is observed that with the increase of pulse on time there is a significant increase in the peak temperature. Peak temperature for pulse on time $20\mu s$ is $16351^\circ C$ but it is for $50\mu s$ is $23130^\circ C$ and it increases to $28902^\circ C$ for pulse on time $100\mu s$.

4.1.3 Different Temperature Zones of heated work piece

During PMEDM process machining of the material occurs due to melting as well as evaporation. So it is important to study the material above melting temperature of H13 that is $1454^\circ C$. The region under spark has been divided in four different temperature zones:

1. Unaffected zone (below $970^\circ C$)
2. Recrystallizing / Heat affected zone ($970^\circ C$ to $1454^\circ C$)
3. Melting zone (between $1454^\circ C$ to $3045^\circ C$)
4. Evaporation zone (above $3045^\circ C$)

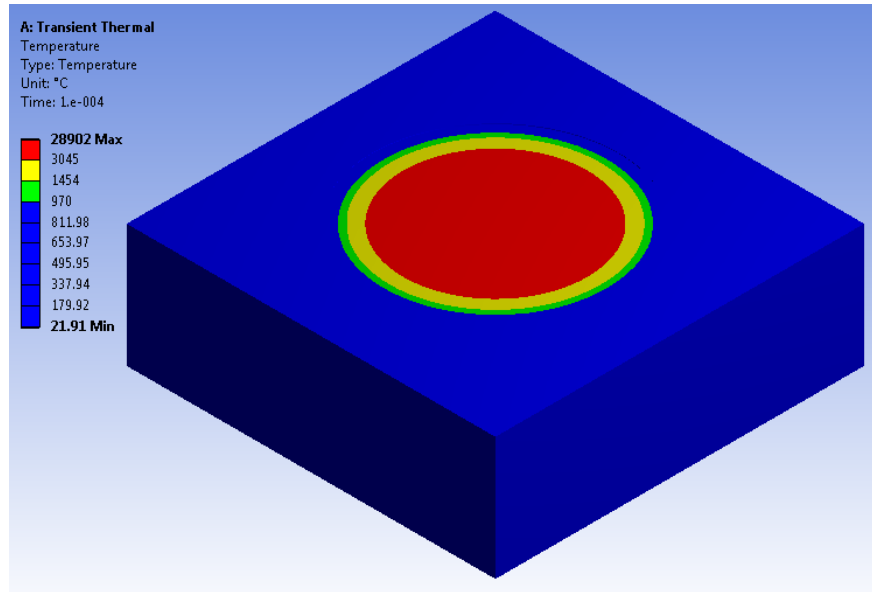


Figure 4.14: Different temperature zones

Figure 4.14 shows heated work material at different temperature zones with constant input parameters pulse on $100\mu\text{s}$, $K_n = 2.4$, $V_b = 38\text{V}$, $R_w = 0.30$ and $I = 9\text{A}$. Figure 4.14 gives information of different temperature zones generated during simulation using discharge $I = 9\text{A}$ and $R_w = 0.30$. It is observed that evaporation zone is quit larger than melting zone in this simulation. Figure 4.14 indicate that red region is evaporation region, yellow region is melting region, green region is recrystallized region/ heat affected region and blue one is unaffected region.

4.1.4 Volume removed

Based on the results given by the transient thermal analysis in temperature distribution form crater volume to be removed has been predicted. For this purpose temperature distribution results has been exported into the excel file and sorted there. Radius of the crater is noted down by sorting the nodes on the top surface of the work piece and making $z \approx \text{zero}$. Coordinate where the temperature falls below the 1454°C (melting temperature of H13) is the radius of the crater. Similarly depth of the crater has been estimated while moving in depth direction and making x and z both nearly zero. So assuming the crater is a part of a sphere and using radius and depth of the crater calculation is done for volume removed by a single spark as follows:

$$V_c = \frac{\pi}{6}(3a^2 + h_c^2) \quad (4.1)$$

Where a = crater radius, V_c = crater volume and h_c = crater depth.

Images for the volume removed in the 3-D contour form are captured for each simulation. As shown in Figure 4.21 (a) crater surface and its shape to be produced is predicted and in Figure 4.21 (b) removed volume in the form of crater is shown separated from the work material in two different views as shown. Input parameters used in simulation shown in Figure 4.1 are pulse on 100 μ s, K_n 2.4, V_b 38 V, current 9 A and R_w 0.30. Crater radius in this simulation is 85 μ m, depth 49.5 μ m and volume removed is 624965 μ m³

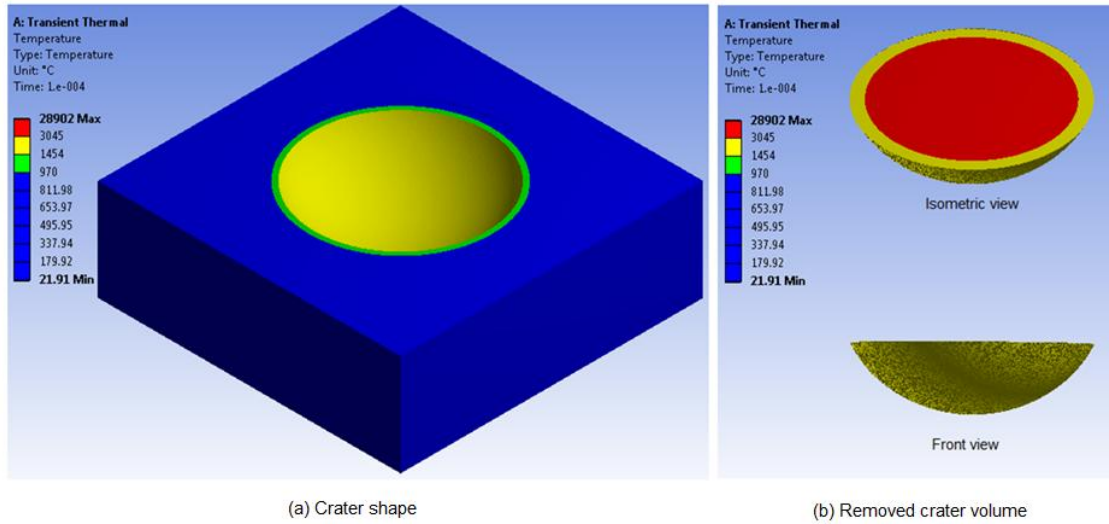


Figure 4.15 : Predicted crater shape and removed volume (both isometric and front views) during simulation using $T_{on}=100\mu$ s $K_n=2.4$, $I=9$ Amp, $V_b=38$ V and $R_w=0.30$

Results for volume removed calculated using equation (4.1) for different simulations have been plotted in Figure 4.22, 23, 24 for different pulse on time 20, 50 and 100 respectively. Figure 4.22, 23, 24 (a) gives the volume removed for different current at different R_w factor. Figure 4.22, 23, 24 (b) gives the volume removed for different R_w at different current settings. Input parameters for simulations presented in Figure 4.22, 23, 24 are pulse on 20, 50, 100 μ s, K_n 2.4, V_d 38 V, current 3, 5, 7, 9 A and R_w 0.15, 0.20, 0.25, 0.30. It is visible from the Figure 4.21, 22, 23 that volume removed increases with increase in current and R_w factor which resulted in high

material removal rate (MRR) and lower surface finish. It is also seen that changing the current is more effective than changing the value of the factor R_w .

Figure 4.22 (a) and (b) shows variation of total volume removes in cubic micron for single spark with different values of current and R_w . For figure 4.22 (a) R_w is plotted along abscissa and total volume along ordinate for different current. Figure 4.22 (b) shows current on abscissa and total volume on ordinate for different R_w . It can be inferred that current has more influence on total volume from both the figures, because figure 4.22(a) has larger gaps in plots and figure 4.22(b) has larger slop.

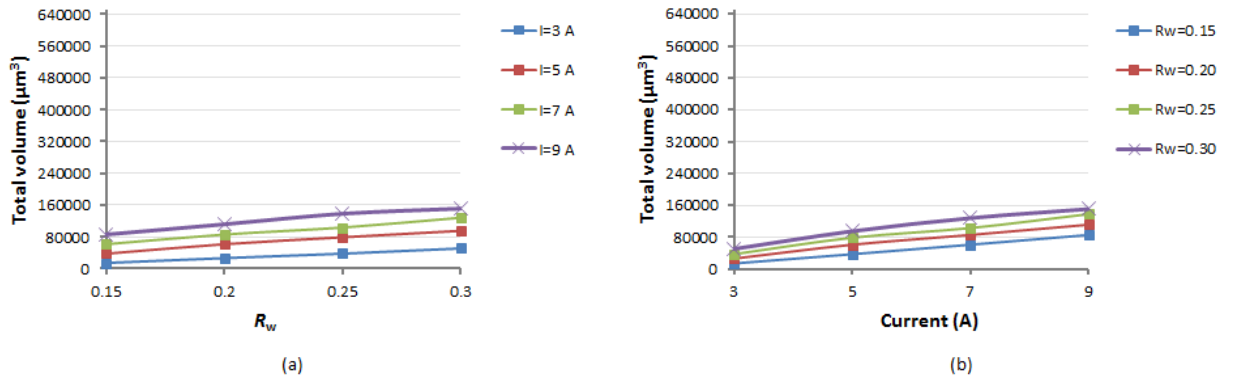


Figure 4.16: Total volume removed during $T_{\text{on}}=20\mu\text{s}$ for different I at different R_w (a) and for different R_w at different current settings (b)

To observe the total volume removed for single spark for pulse on time 50 plots are plotted as shown in figure 4.23 in the same way as discussed earlier for pulse on 20. Comparing figure 4.22 and 4.23 it is cleared that increase in pulse on time increases the total volume removed and also increases the rate of increase of total volume with the current and R_w .

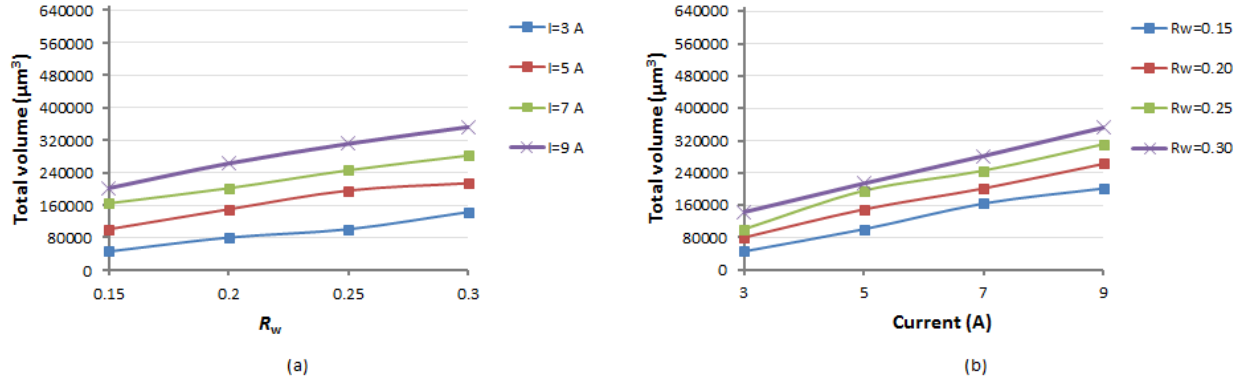


Figure 4.17: Total volume removed during $T_{on}=50\mu s$ for different I at different R_w (a) and for different R_w at different current setting (b)

Again to predict the variation of total volume removes in single spark for pulse on time 100 plots are drawn for different values of current and R_w as show in figure 4.24. Figure 4.24 predicts that there is large volume removed in single spark for pulse on time 100 as compared to 50 and 20 and larger slope also indicates that there is a large variation of total volume with the R_w and current as compared to pulse on time 50 and 20.

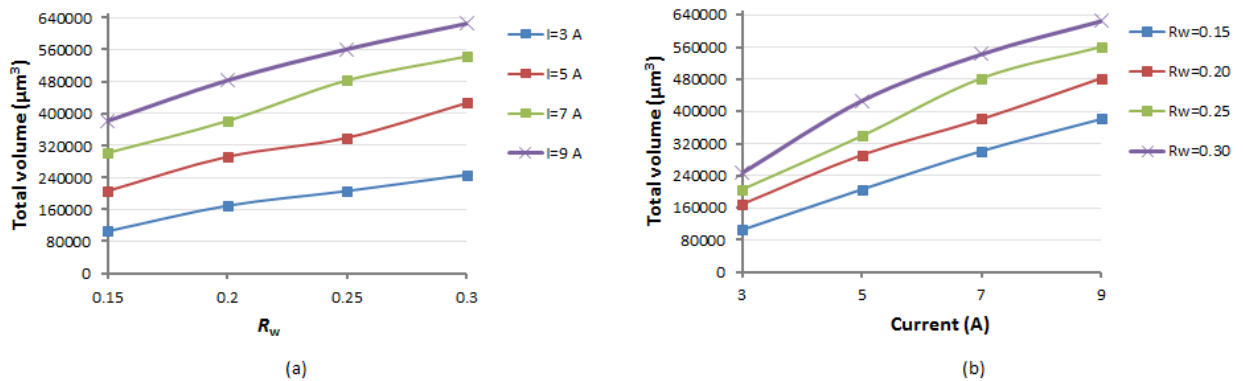


Figure 4.18: Total volume removed during $T_{on}=100\mu s$ for different I at different R_w (a) and for different R_w at different current setting (b)

4.1.5 Comparison of different volumes

To compare the volumes removed due to evaporation, melting and total volume for different currents and R_w , different plots are made for $T_{on}=20\mu s$ as shown in figure 4.25. Figure 4.25(a)

shows the comparison of volume removed at different current i.e. 3, 5, 7 and 9 A for R_w 0.10. Similarly figure 4.25 (b), (c) and (d) show comparison of different volumes for different currents at R_w 0.15, 0.20 and 0.25 respectively. It is predicted from the figure that as R_w increases there is larger increase in the volume removed due to melting as compared to volume removed due to evaporation. As a result for R_w 0.30 and current nearly 8A there is a larger removal of material due to vaporizing as compared to melting as shown in figure 2.25(d).

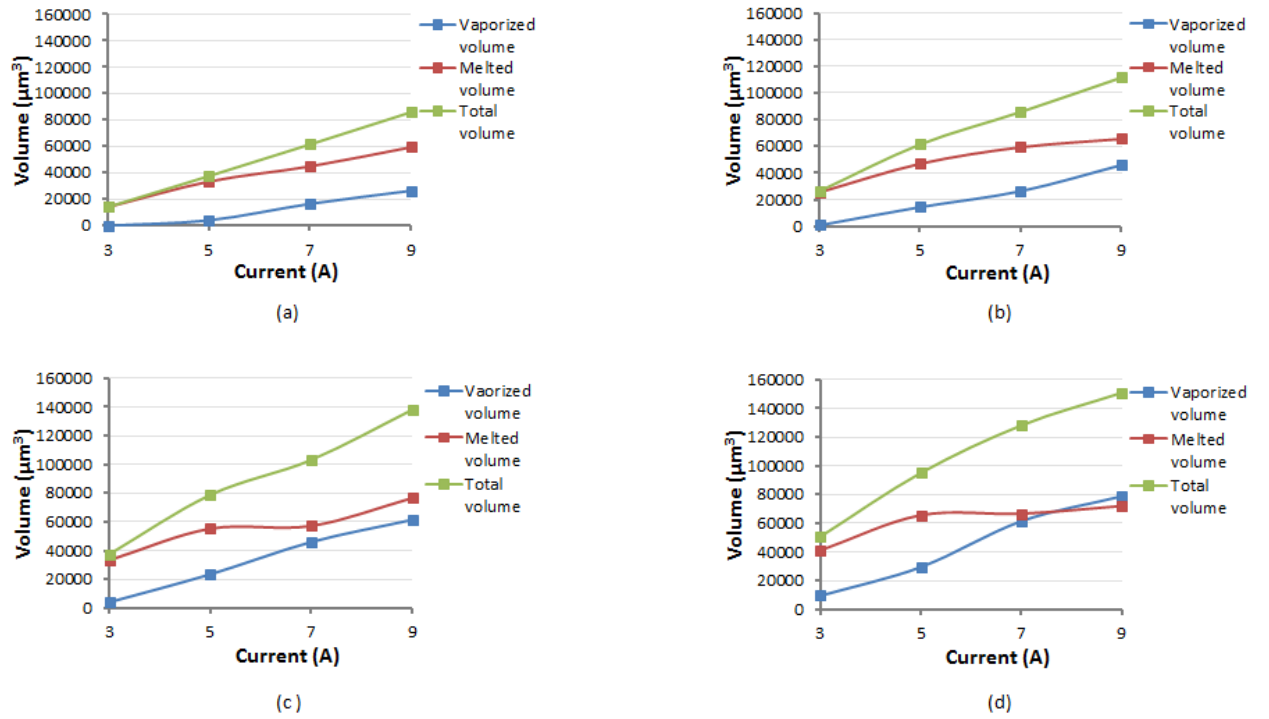


Figure 4.19: Variation of volume removed due to vaporization, melting and total for different current settings for $T_{on}=20\mu\text{s}$ at different R_w (a) 0.15, (b) 0.20, (c) 0.25 and (d) 0.30 respectively

To analyze the volume removal for T_{on} 50 μs simulations are done to calculate different volumes removed during spark generation. Figure 2.26(a), (b), (c) and (d) show the different volumes removed due to spark generation at different values of R_w i.e. 0.15, 0.20, 0.25 and 0.30 and different values of current i.e. 3, 5, 7 and 9A. It is predicted from the figures that larger the value of R_w and current, larger is the total volume removed. By comparing figure 4.25 and 4.26 it is clear that larger value of T_{on} results into larger total volume removed and earlier vaporized

volume line crosses line due to melting volume of work piece. It is predicted from the figure that these lines cross each other at $R_w=0.25$ and $I=7A$.

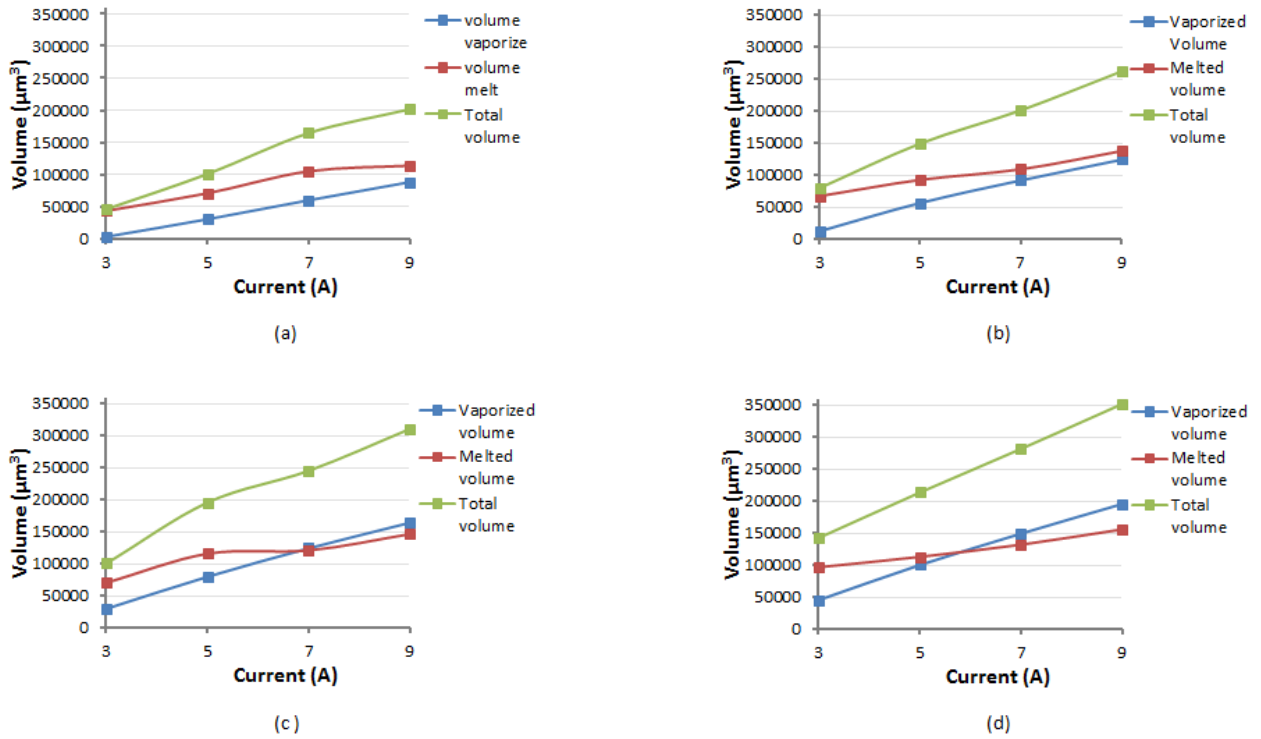


Figure 4.20: Variation of volume removed due to vaporization, melting and total for different current settings for $T_{on}=50\mu s$ at different R_w (a) 0.15, (b) 0.20, (c) 0.25 and (d) 0.30 respectively

Figure 4.27 shows the variation of volume removed due to vaporization, melting and total volume removed for different currents i.e. 3, 5, 7 and 9 A for pulse on time 100 at different R_w i.e. 0.15, 0.20, 0.25 and 0.30. Comparing the figure 4.25, 4.26 and 4.27, it is predicted that with the increase of pulse on time there is a quicker increase of volume removed due to vaporizing at lesser values of current and R_w . Figure 4.27(b) shows that vaporizing volume is more as compared to volume removed due to melting at R_w 0.20 above current 7A.

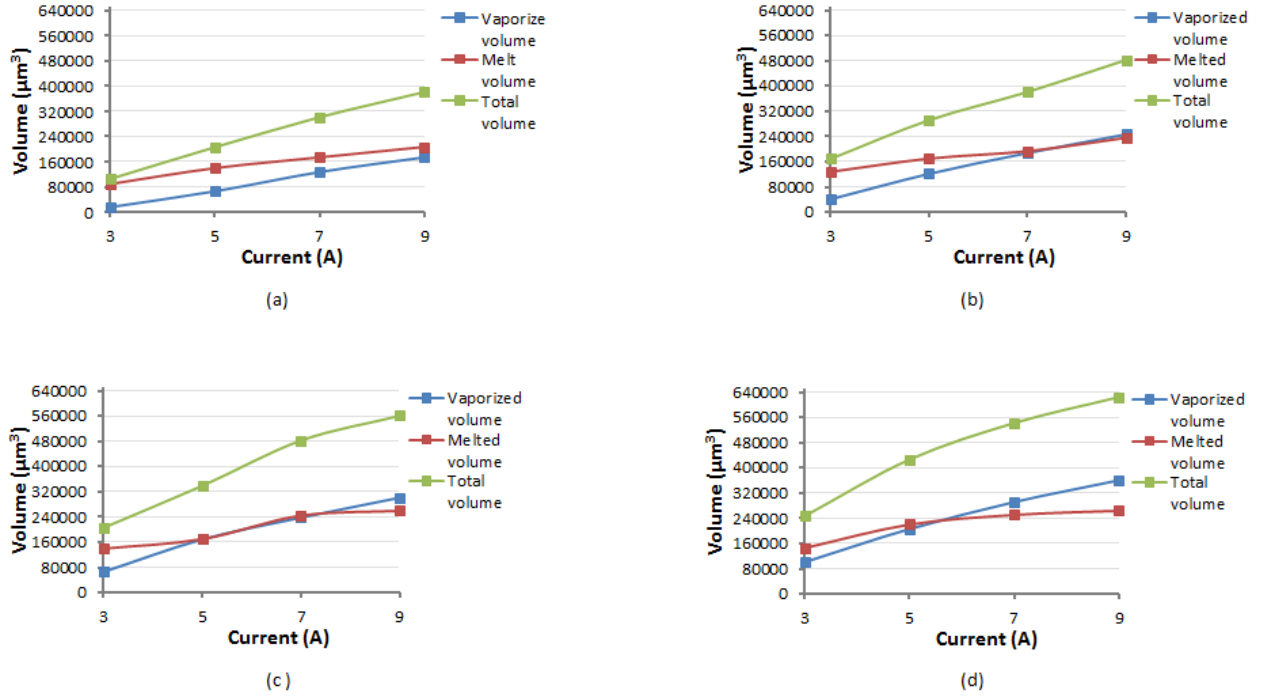


Figure 4.21: Variation of volume removed due to vaporization, melting and total for different current settings for $T_{on}=100\mu\text{s}$ at different R_w (a) 0.15, (b) 0.20, (c) 0.25 and (d) 0.30 respectively

4.2 Multiple overlapped craters

Multiple overlapped craters due to occurrence of discrete randomly generated electric spark one after the other is a more realistic way of simulating the PMEDM process. In this simulation, it is observed that there are pre-stresses in the work piece for all the sparks after the first spark. Methodology used to simulate multiple overlapped craters is already discussed in section 3.2.2.

4.2.1 Temperature distribution

In present work considering the random generation of electric sparks five random locations are created as discussed in section. To simulate it one after the other, region under each spark is discretized in 20 different sub-region areas. As discussed earlier for single spark to consider the thermal aspects of PMEDM process, heat source is also discretized in 20 different sub-regions using Gaussian distribution. These heat flux values were applied to regions under sparks one after the other. Due to heat fluxes applied on the spark region for first spark non-uniform temperature distribution is generated into the domain. To observe temperature distribution in radial as well as in depth direction temperature plots have been made. Temperature distribution

given by transient thermal analysis is exported (in excel file) to plot in radial as well as depth direction. Information in this file is related to each node of the model mesh. It extracts complete information regarding each node i.e. node number, nodal coordinates and temperature generated at each node. A new program was developed in Visual C++ 6.0 to sort this excel file as discussed earlier for single spark. But this new program requires coordinates of center of the spark generated which can be manually put into the console window while running the program. Figure shows complete algorithm for this purpose.

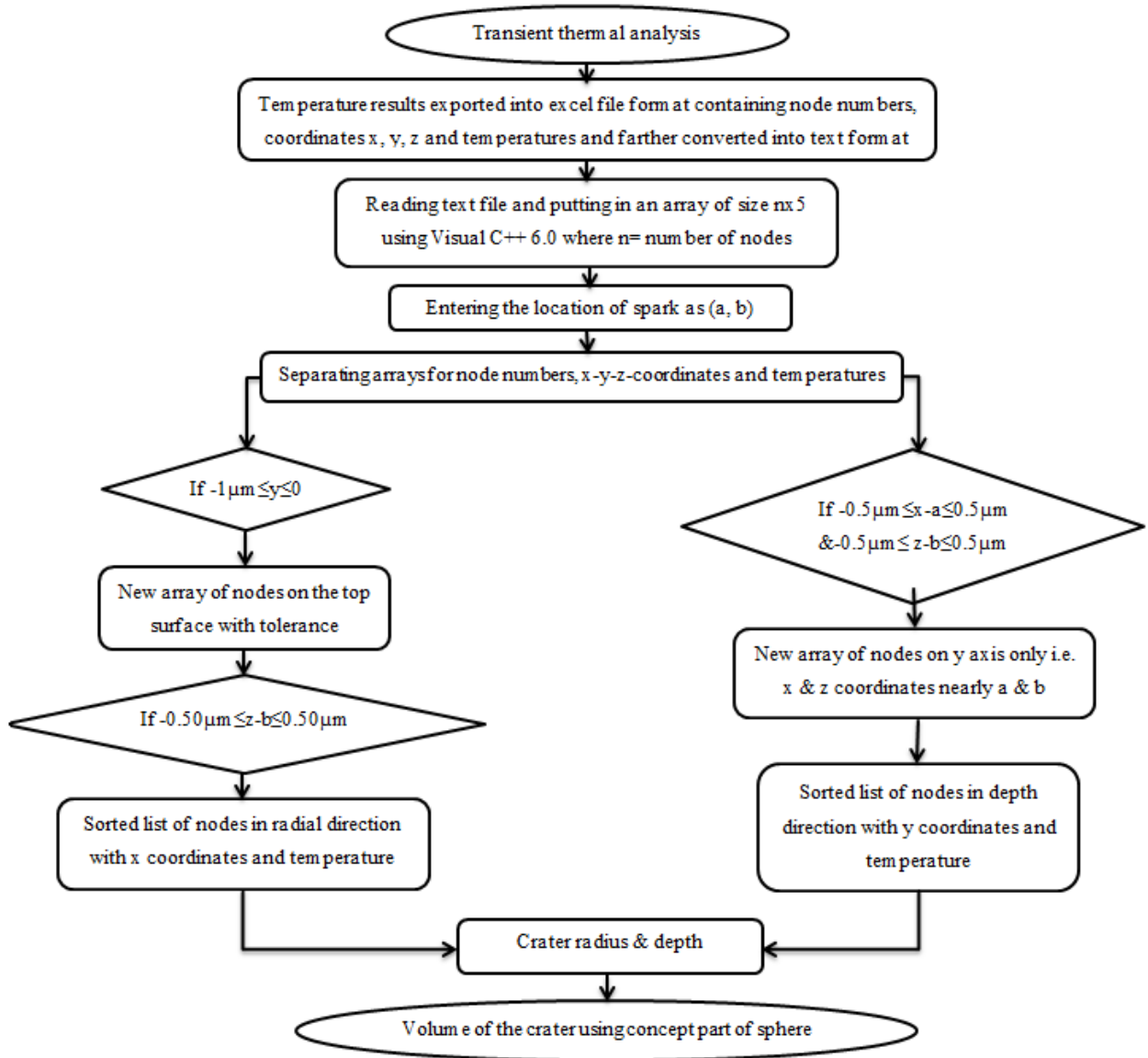


Figure 4.22: Algorithm to illustrate the extraction of nodal coordinates and temperatures above melting temperature to evaluate volume removal of crater for multi-spark simulation

Temperature distribution along the radial direction

To study the effect of different parameters on the work piece three levels of current i.e. (3, 5 and 7A) and three levels of R_w (i.e. 0.15, 0.20 and 0.25) has been taken for each spark as shown in figure 4.23. Figure 4.23(a), (b), (c), (d) and (e) show surface plots for spark1, spark2, spark3, spark4 and spark5 respectively for the pulse on time $50\mu\text{s}$ using powder concentration factor $K_n = 2.4$, discharge Voltage $V_b = 38\text{ V}$, for different values of R_w and I .

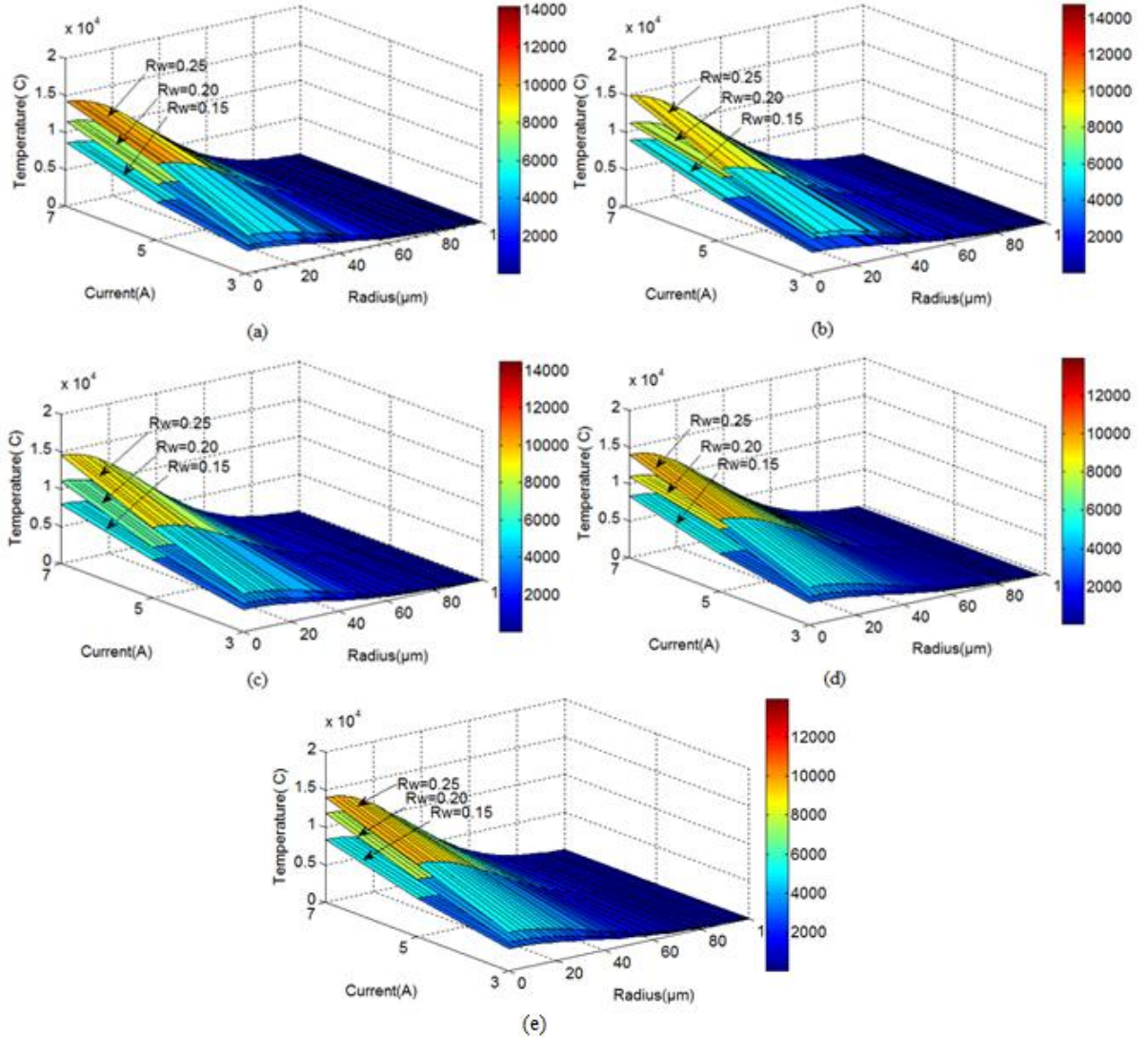


Figure 4.23: Temperature distribution in radial direction generated during simulation using $K_n = 2.4$, $V_b = 38\text{ V}$, $T_{on} = 50\mu\text{s}$ for different R_w at different I for spark(a) 1, (b) 2, (c) 3, (d) 4 and (e) 5

Similarly to study the effect of different parameters on the work piece simulations are being performed for pulse on time $100 \mu\text{s}$. Figure 4.24 (a), (b), (c), (d) and (e) shows surface plots for spark1, spark2, spark3, spark4 and spark5 respectively for the pulse on time $100 \mu\text{s}$ using powder concentration factor $K_n = 2.4$, discharge Voltage $V_b = 38 \text{ V}$, for different values of R_w and I .

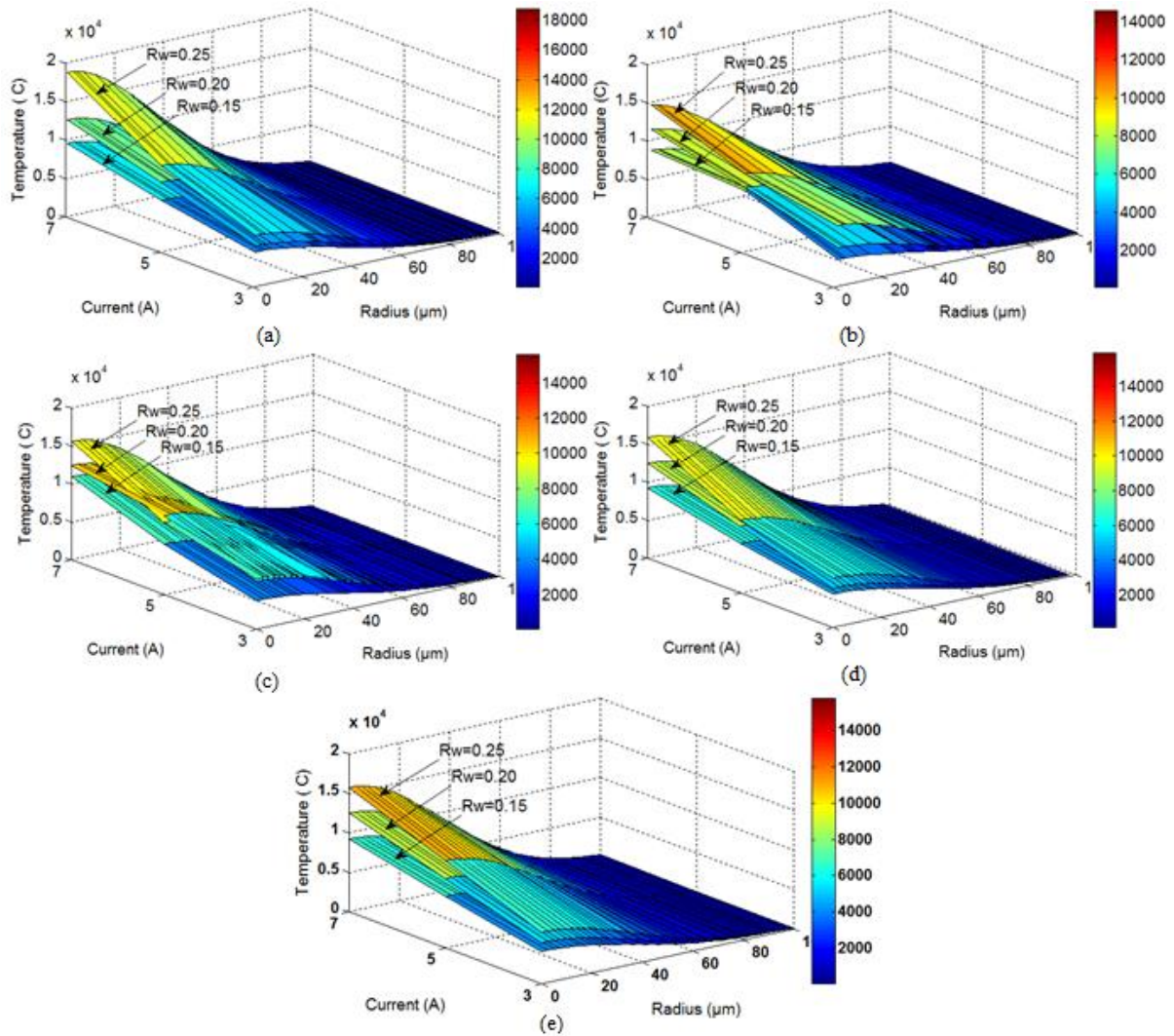


Figure 4.24: Temperature distribution in radial direction generated during simulation using K_n 2.4, V_b 38 V, T_{on} $100 \mu\text{s}$ for different R_w at different I for spark(a) 1, (b) 2, (c) 3, (d) 4 and (e) 5

From the figure 4.24 it is clearly visible that temperature distribution follows Gaussian distribution as it is supposed to. Temperature at the center of spark is the maximum and starts

decreasing while moving away from center of spark. It is noticed that temperature rises by increasing current and R_w factor. In the Figure 4.24 temperature distribution is predicted up to spark radius (R) in radial direction. It is inferred from the surface plots that significant temperature drop is there for different R_w factor near to center of spark and it starts decreasing while moving away from spark center. Comparing figure 4.23 and 4.24 peak temperature for pulse on time 100 μ s is considerably larger than pulse on time 50 μ s. It is also observed that influence of temperature distribution for pulse on time 100 μ s is larger for spark1, spark2 and spark3 as compared to pulse on time 50 μ s.

Temperature distribution along the depth direction

To observe temperature distribution into work material along depth direction simulation results have been plotted for each spark as shown in Figure 4.25. Input parameters for these particular cases are pulse on time 50 μ s, R_w (i.e. 0.15, 0.20, and 0.25), $K_n=2.4$, $V_b=38$ V and current (i.e. 3, 5, and 7 A). Figure 2.25 (a), (b), (c), (d) and (e) show temperature distributions for spark1, spark2, spark3, spark4 and spark5 respectively.

Comparing figure 4.23 and 4.25 it is observed that there is a sharp decrease in depth direction as compared to the radial direction as discussed earlier. So temperature sharply decreases below melting point within smaller depth. From above discussion it is clear that depth of the crater is predicted to be less as compared to radius of crater. It is also inferred figure 2.25 that peak temperature increases with increase in current and R_w .

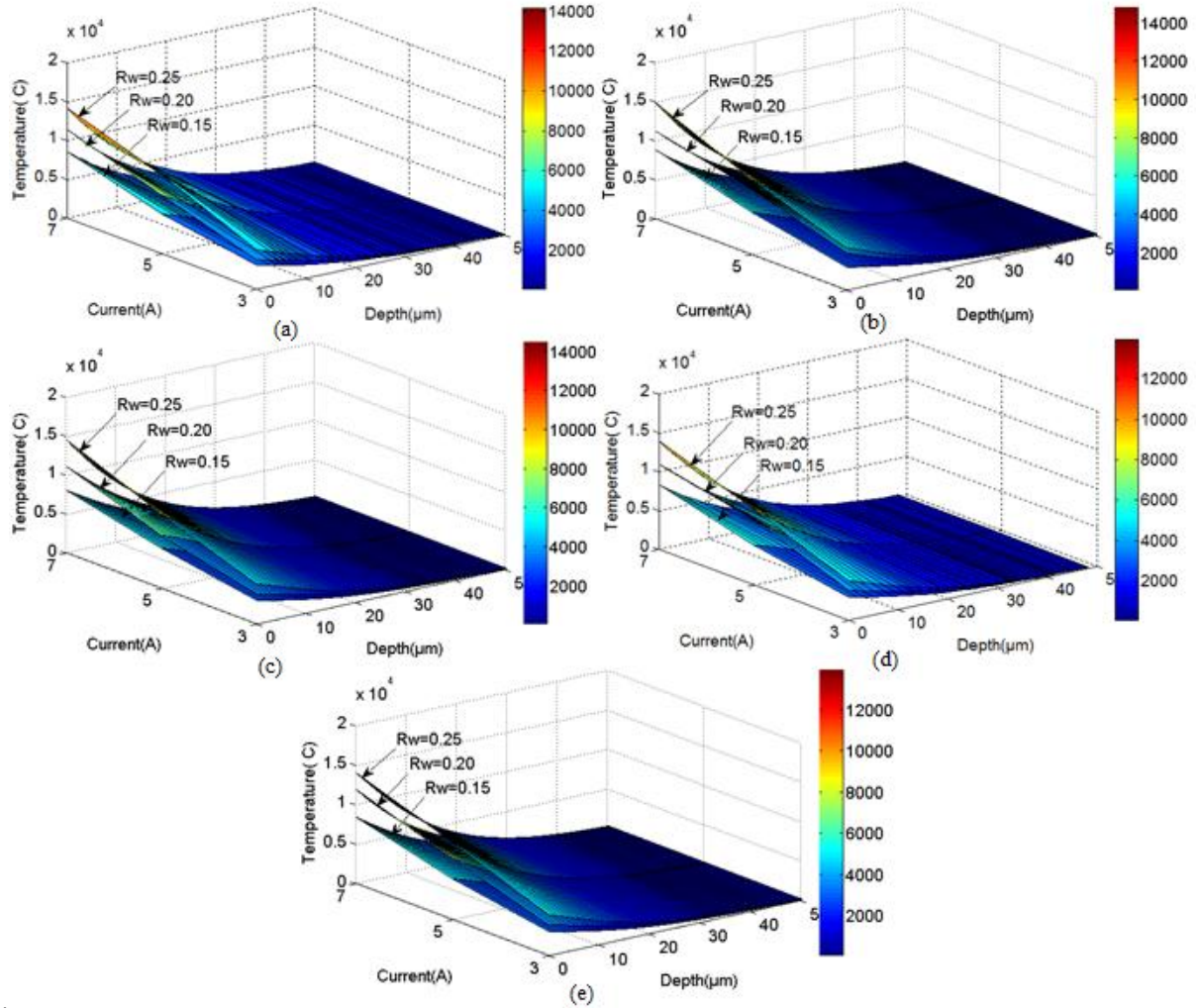


Figure 4.25: Temperature distribution in depth direction generated during simulation using K_n 2.4, V_b 38 V, T_{on} 50 μs for different R_w at different I for spark(a) 1, (b) 2, (c) 3, (d) 4 and (e) 5

To analyze the temperature distribution in depth direction for pulse on time 100 μs simulations have been done and plotted spark by spark as shown in figure 4.26. Figure 2.26 (a) to (e) show the temperature distributions along depth direction side for spark1 to spark5 respectively with input parameters T_{on} 100 μs , $R_w = 0.15, 0.20, 0.25$, K_n 2.4, V_b 38 V and current 3, 5, 7 A. By comparing figure 4.24 and 4.26 it is inferred that temperature fall sharply along depth direction as compared in radial direction. So depth of crater formed is less as compared to radius of crater. Comparing figure 4.25 and 4.26 it is predicted that increase in pulse on time increases the peak temperature during simulation. As the sparks were generated one after the other and geometry is

modifying at each step so there is a small difference in the surface plots for each spark as shown in figure 4.26 (a) to (d). This difference is observed due to overlap of sparks and pre stresses present in the body due to occurrence of previous spark.

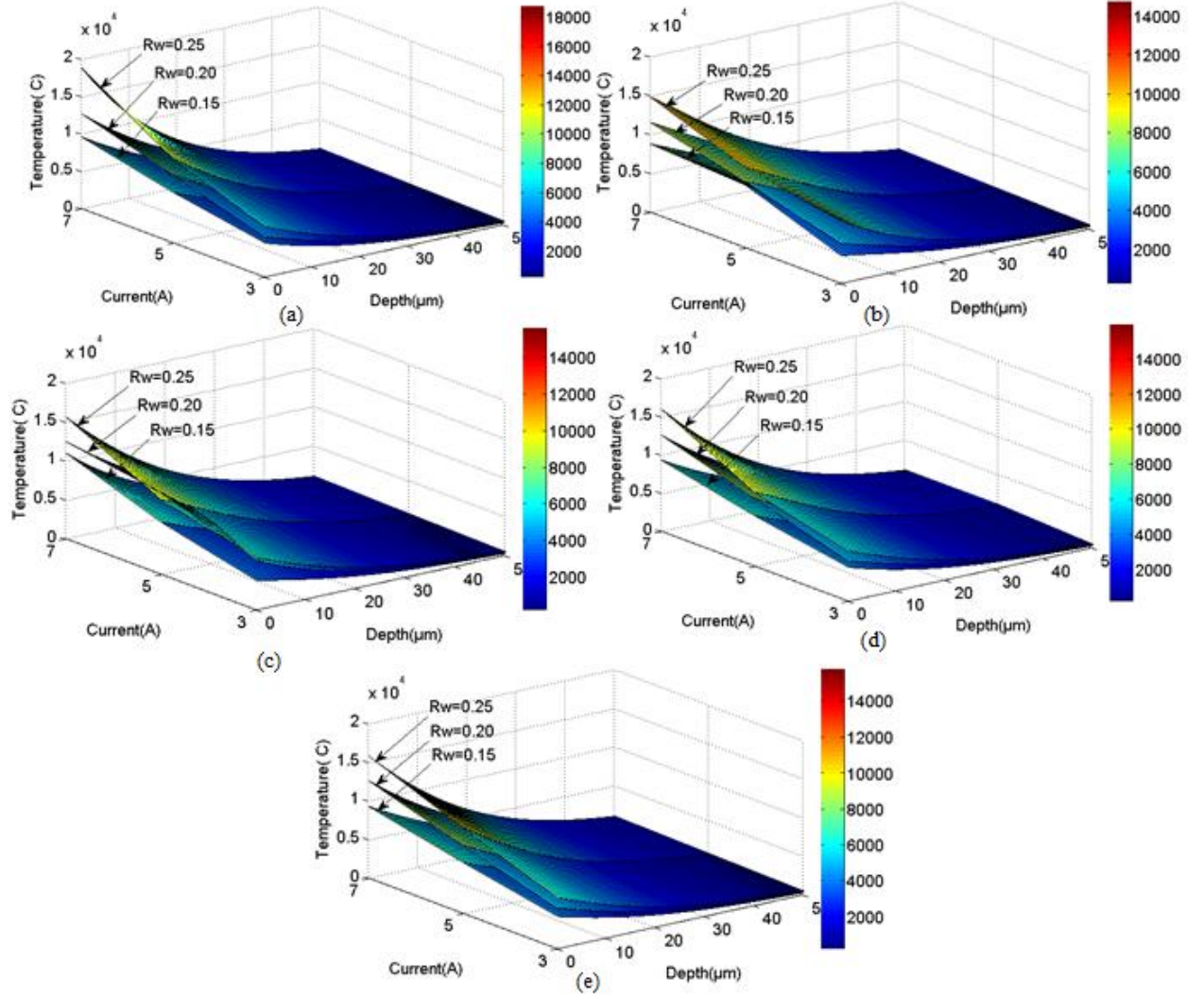


Figure 4.26: Temperature distribution in depth direction generated during simulation using K_n 2.4, V_b 38 V, T_{on} 100 μ s for different R_w at different I for spark(a) 1, (b) 2, (c) 3, (d) 4 and (e) 5.

4.2.2 Total volume

Depending upon the results in the previous sections for different values of current, R_w and T_{on} , different values of total volume removed due to each spark are plotted in this section. As discussed in section 4.1.4 crater is assumed to be a part of sphere. Equation 4.1 is used to

calculate the volume removed due to each crater. In case two sparks are overlapping common volume shared by each crater is subtracted from second crater to calculate the actual volume removed by second crater. Figure 4.27 shows total volume removed for each spark during $T_{on}=50\mu s$ for different R_w (i.e. 0.15, 0.20 and 0.25) at different I (a) 3, (b) 5 and (c) 7 A. It is predicted from figure 4.27(a) and (c) that with the increase of R_w there is increase in total volume removed.

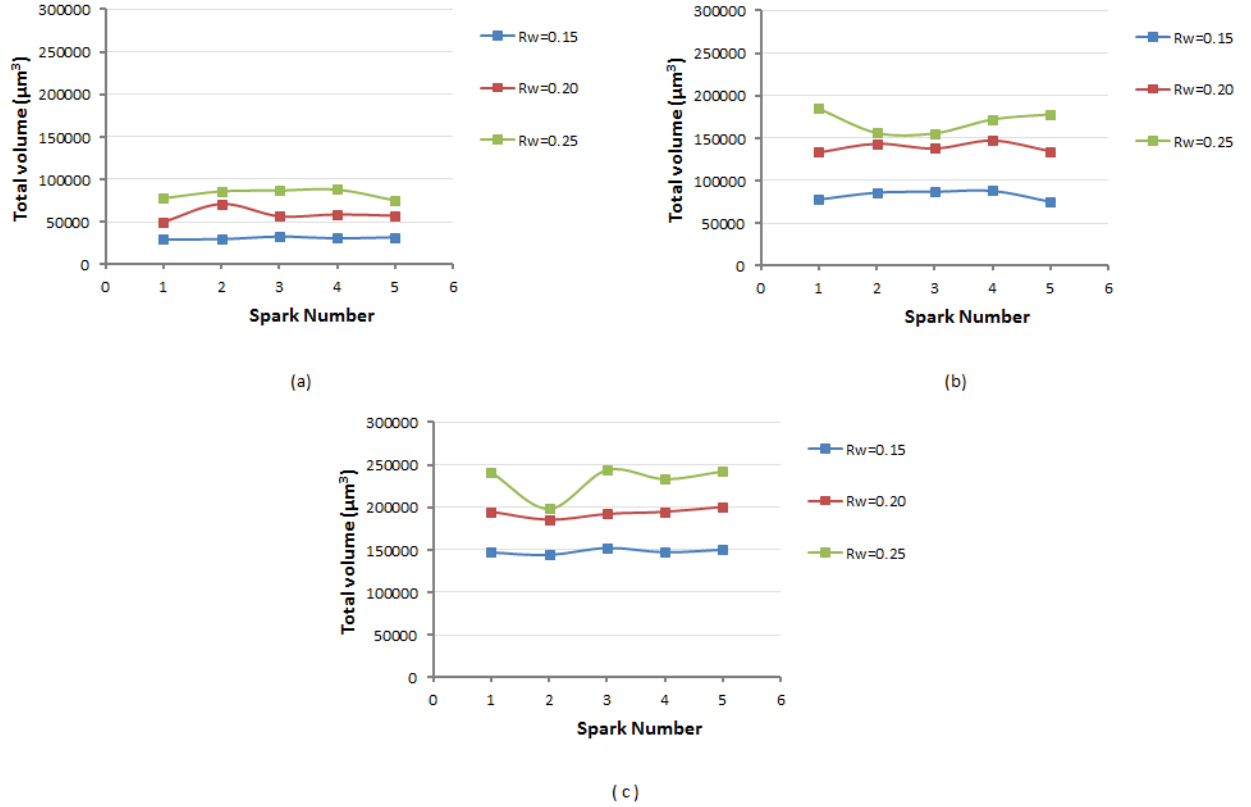
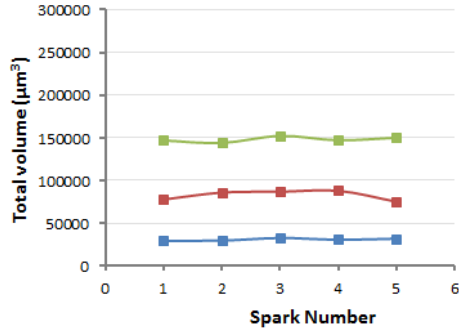
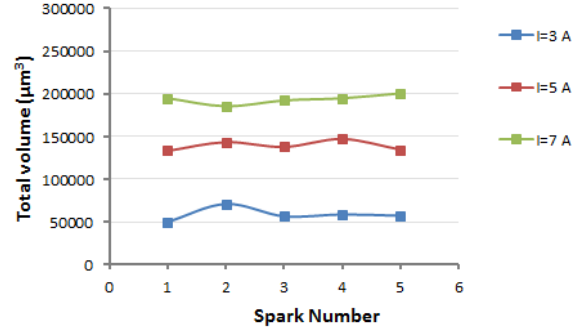


Figure 4.27: Total volume removed during $T_{on}=50 \mu s$ for different R_w at different I (a) 3, (b) 5 and (c) 7 A

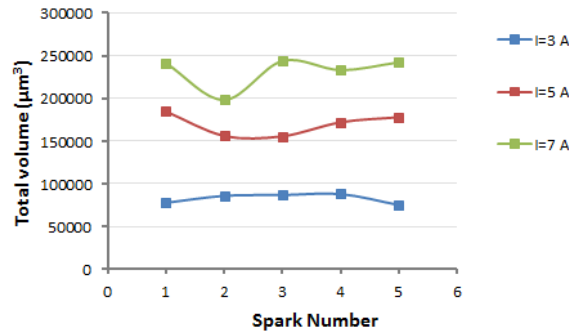
To observe the effect of current on total volume removed for each spark plots are drawn for pulse on time $50 \mu s$ and for different currents (i.e. 3, 5 and 7 A) at different R_w (i.e. 0.15, 0.20 and 0.25) as shown in figure 4.28. Comparing the figure 4.27 and figure 4.28 it is predicted that current has more influence on total volume removed as compared to R_w as discussed earlier for single spark.



(a)



(b)



(c)

Figure 4.28: Total volume removed during $T_{\text{on}}=50 \mu\text{s}$ for different I at different R_w (a) 0.15, (b) 0.20 and (c) 0.25

To predict the total volume removed during $T_{\text{on}}=50\mu\text{s}$ simulations are done for multiple overlapped crater for different I (i.e. 3, 5, and 7 A) at different R_w (i.e. 0.15, 0.20 and 0.25) and results are plotted as shown in figure 4.29. Figure 4.29 (a) shows total volume plots for $I=3$ A. Similarly figure 4.29 (b) and (c) show total volume removed during each spark for $I=5$ A and 7 A respectively. Comparing 4.27 and 4.29 it is predicted that increase in pulse on time increases total volume removed in each spark.

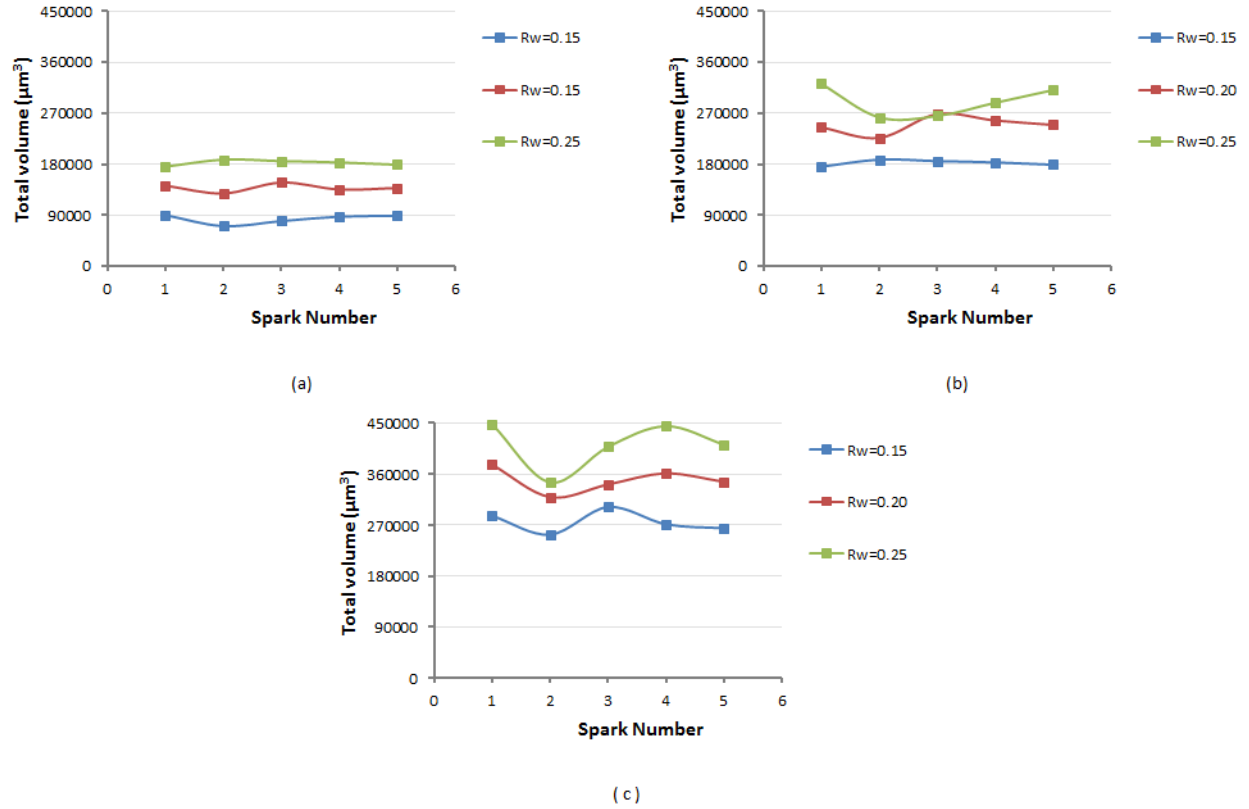


Figure 4.29: Total volume removed during $T_{\text{on}} = 100 \mu\text{s}$ for different R_w at different I (a) 3, (b) 5 and (c) 7 A

Figure 4.30 shows total volume removed due to each spark in case of multiple overlapped crater during $T_{\text{on}} = 100 \mu\text{s}$ for different I at different R_w . Comparing figure 4.30 with figure 4.29 and figure 4.28 show that volume removed is more influenced as compared to R_w and it also increase considerably with the increase of pulse on time respectively.

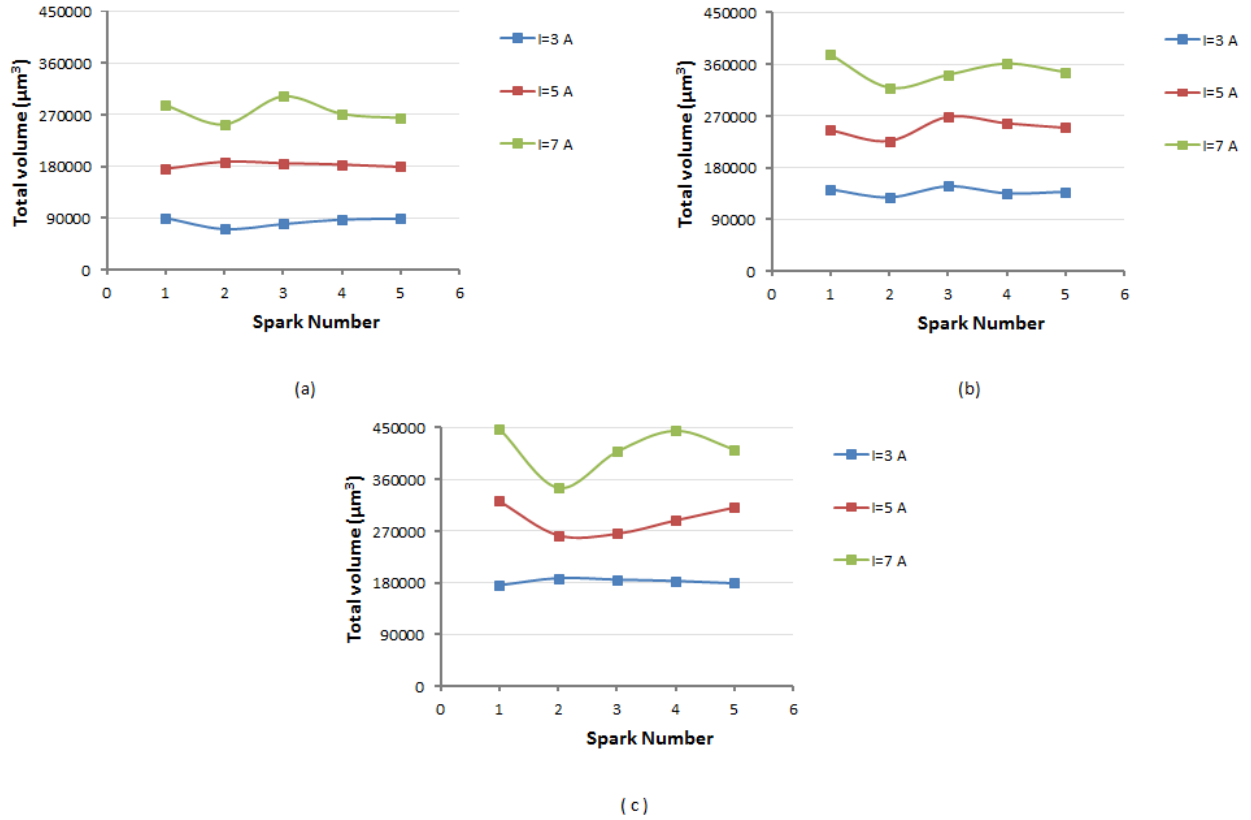


Figure 4.30: Total volume removed during $T_{\text{on}} = 100 \mu\text{s}$ for different I at different R_w (a) 0.15, (b) 0.20 and (c) 0.25

4.2.3 Comparison of different volumes

To compare the variation of volume removed due to evaporation, melting and total volume removed plots are drawn for different values of I , R_w and T_{on} . Figure 4.31(a) and (b) shows variation of different volumes for $T_{\text{on}} = 100 \mu\text{s}$ and $R_w = 0.25$ at current of 3 and 7 A respectively. It can be predicted from figure 4.31 that with the increase of current there is an increase in the amount of volume removed due to evaporation and at some value of current volume removed due to evaporation is equal to the volume removed due to melting of work material. Figure 4.31 also represent difference in the volumes of each spark at the same parameter conditions.

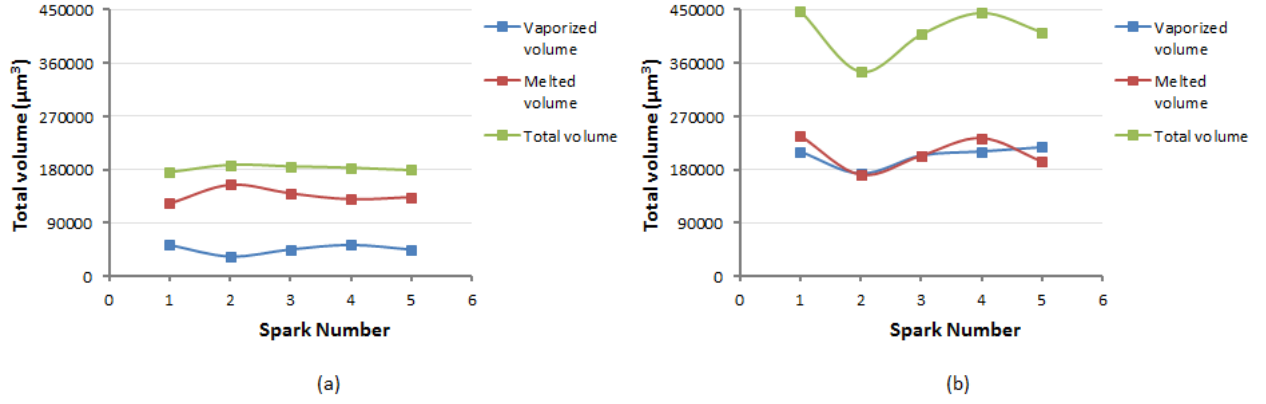


Figure 4.31: Variation of volume removed due to vaporization, melting and total for different sparks for $T_{on} = 100\mu s$ and $R_w = 0.25$ at different I (a) 3 and (d) 7 A.

Figure 4.32 represent comparison on volume removed due to evaporation, melting and total volume for pulse on time $100\mu s$ and current 7 A at different R_w (0.15 and 0.25). It is observed that as the value of R_w increases there is an increase in the value of volumes removed. As all the curves for vaporizing volume, melting volume and total volume are at similar distance in figure 4.32(a) but in figure 4.32(b) two curves are overlapping but in figure 3.31 it is not the same. So it is predicted from figure that current has more influence in volume removed as compared to R_w .

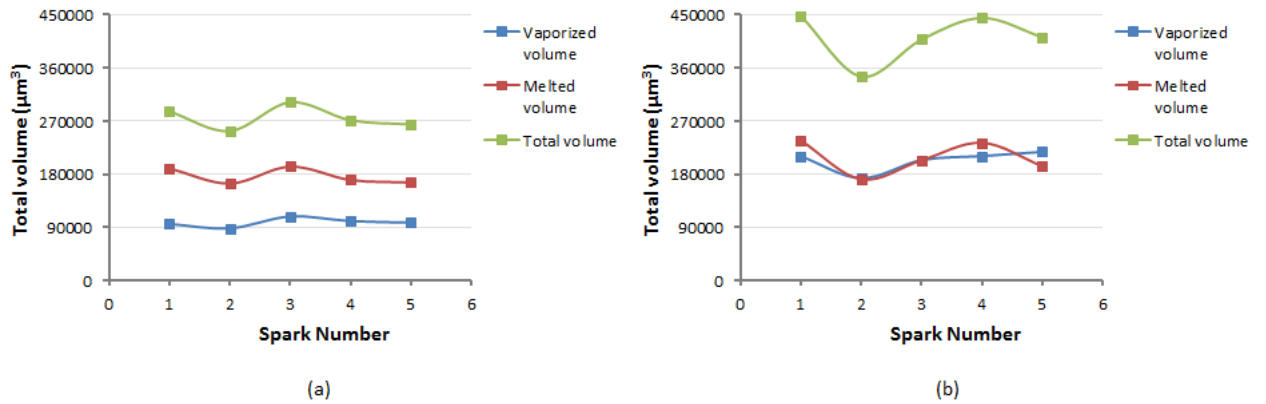


Figure 4.32: Variation of volume removed due to vaporization, melting and total for different sparks for $T_{on} = 100\mu s$ and $I = 7$ A at different R_w (a) 0.15 and (d) 0.25

Variation of volumes removed for each spark is predicted in figure 3.33. It is observed that increase in pulse on time increases the volume removed but it does not have much influence on relative amount of volume removed due to evaporation or volume removed due melting.

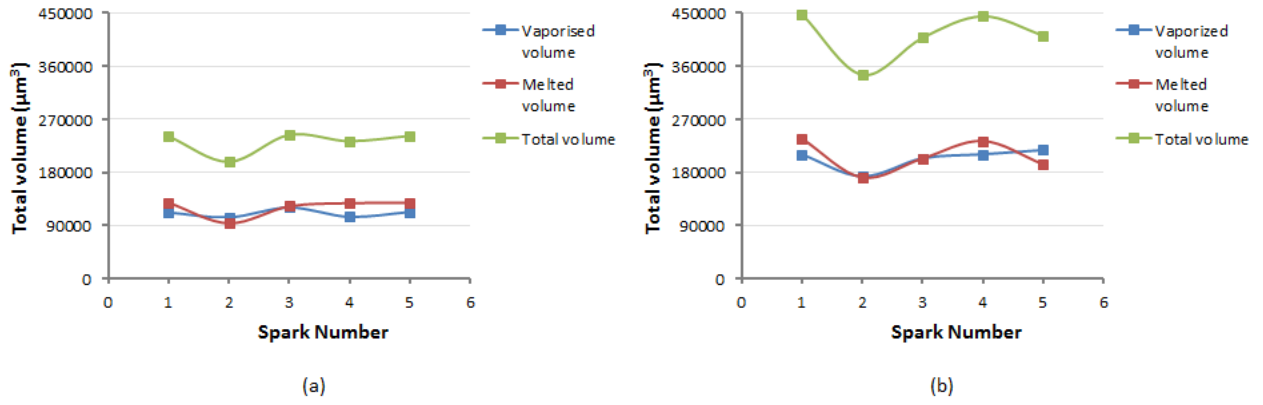


Figure 4.33: Variation of volume removed due to vaporization, melting and total for different sparks for $R_w = 0.25$ and $I = 7A$ at different T_{on} (a) 50 and (d) 100 μs

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

The present work is done to study the thermal aspects of Powder mixed EDM process. Transient thermal analysis module of finite element method has been used to simulate temperature distribution into work material due to incident heat flux on work piece for both single as well as random multiple crater cases. Gaussian distribution is used to apply heat flux on spark region. Different set of simulations are done by varying process parameters like discharge current, pulse on time and R_w (percentage of heat being transferred to work piece) at different levels as shown in Table 3.3 and Table 3.4 for single and multi-spark study respectively. Based on the results of the present work, following conclusions were drawn:

5.1.1 Temperature distribution

It is predicted that temperature of work material is maximum at center of the crater and it decreases towards the crater periphery. Temperature sharply decreases in depth direction as compared to radial direction so depth of crater is much lesser as compared to radius of crater. Discharge current, pulse on time and R_w are directly proportional to temperature and temperature increases with increase in all of these parameters. It is found that I and T_{on} are more influencing parameters as compared to R_w . Generating random crater locations, temperature and volume removal is simulated. It is also found that overlapping of craters influences the temperature distribution. Larger is the overlap larger will be the influence on distribution of temperature.

5.1.2 Peak temperature

It is observed that peak temperature of temperature distribution varies with the discharge current, R_w and pulse on time. Peak current increases with the increase of current, R_w and T_{on} . It is found that it is more influenced by current as compared to R_w .

5.1.3 Temperature zones

Behavior of work material has been studied at different temperature zones i.e. unaffected zone, heat affected zone, melting zone and evaporation zone. It is clarified that at high discharge current

evaporation proportionate to melting is quite large which will increase material removal rate. After the whole simulation results it is predicted that as values of parameters like I , R_w and T_{on} increases there is increase in the evaporating zone of the crater and decrease in the melting zone of the crater. In case of multi spark crater study zone are influenced by percentage of overlap of the crater.

5.1.4 Volume removed

Volume removed by single as well as multiple overlapped crater increases with increase in discharge current, R_w and pulse on time resulting increased MRR. Diameter and depth of the crater produced during pulse on time 100 μs is significantly larger than produced during pulse on time 50 μs . Due to large size of craters formed on the surface, surface finish will be less for high pulse on timings. It is observed that total volume removed is more influenced by discharge current as compared to R_w in each case of pulse on time for single as well as multiple overlapped craters.

5.1.5 Comparing different volumes

Comparison of volume removed due to melting and evaporation shows that for lower current more material is removed by melting as compared to vaporization. Amount of material removed by vaporization increases with increase in current and fraction of heat to work piece. Under some parametric combination, material removal due to vaporization becomes higher than the volume removal by melting.

5.2 FUTURE SCOPE

- 1) Fraction of heat entering into tool can be estimated and analysis of temperature distribution in tool and volume removal from tool can be studied.
- 2) Change in shape of tool during machining has great effect on the profile accuracy of the machined surface. Change in tool shape due to material removal may be studied by suitably modelling the tool wear.
- 3) Fatigue analysis of the work material during PMEDM process can be done to estimate the life of the machined surface.

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