Chapter 2

LITERATURE SURVEY
Chapter 2: LITERATURE SURVEY

In recent years, the technology of wire electrical discharge machining (WEDM) has improved significantly to meet the requirements in various manufacturing fields, especially in the precision tool and die industry.

The main goal of WEDM manufacturers and users is to achieve a better stability of the process and higher productivity. As newer, more exotic materials are developed, and more complex shapes are presented, conventional machining operations reach their limitations; hence the increased use of WEDM in manufacturing continues to grow at an accelerated rate. Wire electrical discharge machining manufacturers and user emphasize on achievement of higher machining productivity with a desired accuracy and surface finish. However, due to a large number of variables even a highly skilled operator with a state-of the art WEDM is rarely able to achieve the optimal performance.

This chapter is dedicated towards reviewing the literature focused in view of the topic under study. The chapter is broadly classified into following subgroups viz. literature related to influence of process parameters, review of various thermal models for EDM, review of technical papers focused on machining of few materials including carbides using EDM/WEDM and last but not the least a brief review based on carbides.

2.1 Influence of Process parameters

The optimum utilization of the capacity of WEDM process requires proper selection of machining parameters. This part of literature review aims to investigate the effect of various process parameters on desirable output. WEDM is complex in nature and is controlled by large number of parameter as shown in Figure 2.1.

i. Influence of Pulse Parameters

In most of the commonly used wire-cut EDM, the pulse on time is the switch-on period of electrical charge to the capacitor bank and the peak current actually the charging current. Before, the capacitor has been charged to the peak voltage, a driving pulse with the preset on and off- time, switches on and off the transistors rapidly.
Therefore, the gap voltage proceeds towards the full value step by step. The pulse on
time, peak current and the capacitance determine the number of steps to reach the
peak value. If the on time and peak current are sufficient and the capacitance is small
enough, the gap voltage can take only one step to jump to the peak value.

**Figure 2.1 Factors Influencing the Wire EDM process [36]**

**ii. Effect of Frequency**

The total period of charging process is controlled by the four pulse parameters,
namely, pulse on time, pulse off time (pulse frequency), capacitance and peak current.
The actual average sparking frequency can be determined by the preset values of
pulse on time, frequency, peak current, capacitance, and servo reference voltage.
When other parameters are kept at constant values, lower servo voltage generates
higher sparking rate (multi sparking) and short circuit frequencies, and vice versa. Commonly used pulsing circuit is represented in Figure 2.2.

![Commonly used pulsing circuit in WEDM][68]

Figure 2.2 Commonly used pulsing circuit in WEDM [68]

![Effect of Current and Frequency on Surface Roughness and MRR][36]

Figure 2.3 Effect of Current and Frequency on Surface Roughness and MRR [36]

![Surface Finish as related to Frequency and Current][36]

Figure 2.4 Surface Finish as related to Frequency and Current [36]
As illustrated in Figure 2.3, increased discharge frequency can improve the surface finish within limits, by doubling the amperage and frequency; the metal removal rate will double without changing the finish [36]. At high frequencies, the amperage is reduced due to inductance, thereby reducing the MRR. The economics involved therefore sets practical limit on surface finish. The relationship between current, frequency on surface finish is shown in Figure 2.4.

iii. Influence of Wire Positioning

Trezise [101] concluded that the fundamental limit on machining accuracy is due to the dimensional consistency of the wire, and the positional accuracy of worktable. However, other factors conspire to prevent this theoretical precision from being achieved. Most of the uncertainties arise because the working region is an unsupported section of the wire, remote from the guides. It is necessary to hold the wire in a designated position against the object because the wire repeats complex oscillations due to electrical discharge between wire and the work piece. It may also be noted that the unsupported length of wire changes with thickness of the job jeopardizing the wire vibration frequency. The computer controlled positioning system constantly maintains the gap between the wire and the work piece. Disturbances from the external and internal sources generate vibrations in the wire, which ultimately influence the repetitive sparking process in spite of the controlled positioning system. This deviation of the electrode from its mean position therefore has considerable influence on the occurrence of the next discharge. It also influences the breakdown voltage of the discharge and the discharge energy since the gap is changing continuously during the vibration.

It was reported by Masuzawa [62] that the amplitude of the vibrations can easily reach 10 μm or more, and cannot be neglected. Most commercial machines are specially designed for rigidity to minimize the tool deflection, even though it is not possible to completely eliminate the influences, which tend to displace the wire from its mean position.

Rajagopal and Noble [80], Trezise [101] described these disturbances as a form of minute electrostatic, electro dynamic and hydraulic forces, which of course are functions of machining parameters. Dekeyser and Snoeyes [17] reported that these disturbances could result in geometrical inaccuracies and wire breakage.
iv. Effect of Wire Tension

Within considerable range, an increase in wire tension significantly increases the cutting speed and accuracy. The higher tension decreases the wire vibration amplitude and hence decreases the cut width so that the speed is higher for the same discharge energy. However, if the applied tension exceeds the tensile strength of the wire, it leads to wire breakage (Figure 2.5). Moreover excessive amplitude of equivalent to the spark gap length might cause short-circuit.

![Graph showing the relationship between wire tension and cutting speed.](image)

Figure 2.5 Change in Cutting Speed with Wire Tension [36]

Jeenes et.al [42] found relation between the wire vibrations and occurrence of short circuits, resulting in lower cutting speeds and an increased possibility of wire rupture. The reasons shown above suggest the necessity for controlling the machine parameters in order to minimize the effects of the disturbances.

v. Effect of Wire Material Composition

A desirable wire material for WEDM electrode should possess following properties:

- Adequate tensile strength with high fracture toughness
- High electrical conductivity [% IACS - International Annealed Copper Standard, a unit of electrical conductivity for metals and alloys relative to a standard annealed copper conductor; an IACS value of 100% refers to a conductivity of $5.80 \times 10^7$ siemens per meter (58.0 MS/m)].
• Good flushing ability
• Low melting point and Low energy requirement to melt and vaporize [36].

Sho et al. [93] reported that the machining rates increase with increase in Zn content in the wire. Higher the Zn content allows lower servo voltage (mean machining voltage), thereby making short circuiting difficult. The machining is known to increase with the increase in Zinc content. This is because of cooling due to zinc evaporation and also because the ZnO coating on the surface helps to prevent short circuits.

Copper or brass core wires, coated with a Zinc or ZnO layer of 20-30μm thickness, when used increase the cutting speed. The evaporation of the zinc coating produces a ‘heat-sink’ effect in the wire and thus cooling the core material [91]. This ‘heat-sink’ effect on the wire results in the improvement of the efficiency of the WEDM process by reducing the wire temperature, and therefore allowing a more thermal flow, leading to an increase of the cutting speed by up to 50% [15], whilst due to evaporation of coating, the gap increases leading to better dielectric flushing, and debris removal. It also stabilizes the plasma column of spark. Research has also been conducted to improve the technology of the tool by overcoming the thermal effects to prevent the wire from breaking during the process. Different wire composition would determine their final performance.

vi. Effect of Work Piece Material

Researchers [36, 54, 82] have also communicated that specific physical, metallurgical, and electrical properties of the work piece material also influence the process. These properties include how well the metal is polished, its magnetic condition, and how the metal was removed from the heat treatment process when it was produced. One must also consider the phenomenon of expansion and contraction according to the temperature of the material. For material processed by EDM or WEDM, the initial surface condition affects the results.

A low melting point in the material increases the MRR and improper heat treatment of the metal results in distortion, breakage of the die and punches while machined by WEDM. As for example, Kim and Jeong [52] carried out WEDM tests on various cemented carbides with different percentage of cobalt present in WC [GT 10 (6% Co),
GT 20 (12% Co), GT 30 (15% Co)] and found out that the percentage of cobalt has an influence on the speed of erosion. A high Co-content worsens the final surface quality as a greater quantity of solidified metal deposits on the eroded surface.

vii. Effect of the Thickness of the Work Piece

In the WEDM process, cutting speed decreases as the thickness of the work piece increases. Normally, WEDM uses a transistor controlled capacitor circuit in which the cutting speed is controlled by a capacitor value. When using a fixed capacitor to machine a thicker work piece, the cutting speed is decreased.

Hatchek [36] reported that the thicker the work piece, the faster is the cut, all other factors being equal. In any EDM operation, every pulse does not produce a spark. However, the longer length of wire electrode in a thicker work piece provides more opportunities for the spark to occur. This makes the process more efficient for a thicker work piece.

viii. Influence of Dielectric

The dielectric fluid and the flushing thereof perform following functions [36]:

- To insulate the gap before a large amount of energy is accumulated and to concentrate the discharge energy to a small area (insulator).
- To recover a desired gap condition after the discharge by cooling the gap and deionizing (cooling).
- To flush away the debris of the work piece removed by spark (flushing medium).

ix. Flushing Pressure

The commonly used flushing methods are immersion flushing, spray or jet flushing. Figure 2.6, shows the curve of influence of flushing pressure on machining speed and surface roughness. The cutting performances during roughing cuts have been improved since the removed particles in the machining gap are evacuated more efficiently (the pressure must be reduced during finishing in order to avoid geometrical part errors). It can be seen that when flushing pressure is less than certain pressure value, it is impossible to do any machining. Along with increased flushing pressure the machining speed also increases, but when it is over 1 kg/cm$^2$
(98066.5Pa), the increased trend slows down while the surface roughness improves gradually with increased flushing pressure; due to effective removal of debris. When flushing pressure is less than 0.3kg/cm$^2$ (29420Pa), high temperature is easily registered along electric discharge area.

Figure 2.6 Influence of flushing pressure on surface roughness, machining speed [36]

x. Heat affected zone

Figure 2.7 Effect of variation in pulse width [68]
Figure 2.7, represents the effect of variation in pulse, which is resulting in various machining processes. The variation in pulse time results into wide spectrum of machining processes right from glazing to heat treatment. Table 2.1 represents the working domain of specific energy, power density and interaction time for various processes. Figure 2.8 represents the effect of variation in pulse heat energy resulting in variation of temperature at various points. Heat is applied at point ‘A’ on the surface, for any processing operation, the temperature at ‘A’ will rise faster than the point ‘B’ which is below the surface and receives heat through conduction only. The temperature at point ‘B’ will lag behind that of ‘A’.

Table 2.1 Working Domain for material Processing [68]

<table>
<thead>
<tr>
<th>Processing</th>
<th>Specific Energy (J/cm²)</th>
<th>Energy Density (W/cm²)</th>
<th>Interaction time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing</td>
<td>1 - 10</td>
<td>10⁶ - 10⁷</td>
<td>10⁻⁶ - 10⁻⁴</td>
</tr>
<tr>
<td>Shock Hardening</td>
<td>10 - 10²</td>
<td>10⁵ - 10⁶</td>
<td>10⁻⁸ - 10⁻⁶</td>
</tr>
<tr>
<td>Machining</td>
<td>10⁴ - 10⁴</td>
<td>10⁵ - 10⁶</td>
<td>10⁻⁵ - 10⁻³</td>
</tr>
<tr>
<td>Welding</td>
<td>10³ - 10⁴</td>
<td>10⁶ - 10⁶</td>
<td>10⁻² - 10⁻¹</td>
</tr>
<tr>
<td>Transformation</td>
<td>10⁴ - 10⁵</td>
<td>10⁴ - 10⁵</td>
<td>10⁻⁴ - 10⁻³</td>
</tr>
</tbody>
</table>

In conventional thermal processing, because of low energy rate input, though the temperature of ‘B’ will lag behind ‘A’, yet it will follow a very closer path. So the desired change is observed at ‘A’ and the undesired one at ‘B’. This undesired change
may be referred as thermal damage, distortion, or inaccuracy etc. as defined in different processing operations. Hence, higher energy level is applied for a shortened time. The net result is raising the temperature at 'A' faster as compared to the previous case and the rate of temperature rise at 'B' will not be that fast as compared to 'A' (because of conduction); there exist a wide gap in between the $T_A$ and $T_B$ curve. Hence, at this point one can observe vaporization at point 'A' and thermal distortion at point 'B'. This condition again varies when one applies higher energy rate input for a very short time which creates vaporization at 'A' but no change at point 'B' as it is below the recrystalisation temperature during the pulse interval.

In any thermal process like WEDM, higher density is applied in pulsations that brings in desired change, with higher accuracy and without any disturbing characters (changes) as associated with conventional thermal processes. The Wire EDM process is predominantly a thermal process and therefore some annealing of the work piece can be expected in a zone just below the machined surface. In addition some of the work piece material melted by the discharge is expelled into the bulk of the work piece, resulting in an exceedingly hard surface. The depth of the annealed layer is proportional to the amount of power used in the cutting operation. It will range from 5μm for finish cutting, to approximately 20μm for high metal removal rates. The amount of annealing is usually about 2 points of hardness below the parent metal for finish cutting. This happens when the finishing operation done by WEDM is after heat treatment; otherwise the reverse is observed while machining a material in annealed condition. In the rough cuts, the annealing effect is approximately 5 points below the parent metal. Figure 2.9 relationship of the heat-affected zone to the cutting conditions.

![Figure 2.9 EDM Heat affected zone](116)
Since the annealing effect is most common when unstable machining conditions exist, it can be reduced by choosing conditions that produce better stability [68] for example, by choosing electrodes that produce more stable machining at lower rates. Using a finish cut operation in order to remove the annealed material left by the previous high-speed rough cut.

xi. Surface Integrity [116]

Surface integrity involves all aspects of the surface and near surface regions, which may ultimately affect the functional behavior of the WEDM processed parts. Such aspects as micro-geometry, hardness and microstructure are involved, in addition to residual stresses. The surface texture, which governs principally the surface roughness, is essentially a measure of surface topography. The surface metallurgy is the study of the layer produced in machining. The surface finish obtained by WEDM is quite different from the one, obtained through conventional finishing process. Surface recorders show approximately same general roughness pattern. However, the geometry is considerably different as peaks and craters replace the lines and valleys of conventionally machined profiles.

The surface appearances of WEDM and conventionally ground samples are given in Figure 2.10. It can be seen that on the surface of a WEDM specimen, there are many very small spherical bumps and hollows; which in turn contain numerous micro craters. Between the bumps and hollows a smooth transition exists, while the conventionally machined surface displays regular tool cutting marks. Hence, the surface cut by the WEDM is less sensitive to stress concentration than a conventionally machined surface. WEDM results a multidirectional or no lay finish (non-directional) on the surface instead of the directional pattern of a conventionally machined surface.

Crater volume or metal removal per discharge is directly related to the surface roughness produced. When it is multiplied by the effective discharge frequency, it yields the metal removal rate. Fusion and plastic deformation are always associated with the craters. This is attributed to the molten liquid solidifying epitaxially, when quenched by the dielectric. The high thermal contraction produces high stresses, which in turn causes severe slip, twining and cleavage, depending on the crystal structure of work piece. In practice, the thermal effect is located in the volume of
metal, limited by the crater produced. The transmission of heat to the lower layers of metal is insignificant because the duration of pulse is not continuous. In fact, nearly all the calorific energy of the discharge is dissipated in the volume of the metal affected directly by the discharge. The transmission of calorific energy to lower layers in practice is negligible. Heating of the work piece or the temperature of the machined layer can be minimized by choosing the proper electrical parameters and by working under normal conditions [78, 108].

The WEDM affected surface layers on the whole, may be classified into three zones (from the surface to the inside) viz., they are the white layer, the rehardened layer and the over-tempered layer. Up to now it has not been possible with any of the reagents employed in metallography to etch the white layer from its surface. Only with the help of radio graphical methods is it possible to detect the structure in this layer. Normally, the white layer consists of annealed martensite, secondary austenite and some carbides characteristic of the steel. The white layer results from a spark erosion process are similar to the white layer formed by any other machining process. Higher percentage of austenite leads to increase in corrosion resistance of the white layer.

![Figure 2.10 SEM surface appearance of WEDM (left) and the ground samples (right) of hardened die steels, X500 [82]](image)

The micro hardness is significantly different throughout the depth of the whole WEDM affected layer. The impact fatigue life of the hardened steels is longer for parts processed on WEDM than parts processed by conventional machine. There are very little chances that fatigue cracks will begin. The wear resistance of WEDM
affected surfaces is more and the bending strength is slightly less. It was also noticed that residual tensile stresses exists in the surface layers of the hardened steels machined by the process. As the depth of spark affected layer from the surface increases the residual stress decreases. Formation of micro cracks in white layer normally depends on the high carbon content in electrolytic solution and excessive electric parameters [108].

Earlier research has been done [83, 84] to improve the surface finish in this process. In a relaxation type of generator circuit, DC leakage current under the deionized water causes electrolytic affection and may decrease the hardness on the machined work piece surface due to the electrolytic corrosion. To overcome this decrease in hardness, a transformed coupling circuit has been developed as an adapter for the relaxation type of generator and found micro fine finishing of the machined surface. WEDM doesn’t have large tool electrode area; hence the effect of the capacitor, formed between the wire electrode and the workpiece is negligible. In addition the discharge gap pollution is low when compared to die sinking EDM. These two conditions offer distinct advantages for micro finishing by wire EDM. To obtain the micro finished surface it is very important to prevent the continuous arc discharge. However because the wire is moving continuously, the possibility of arcing is very less [84].

2.2 Literature on Thermal Modeling

As one of the motives of current study is to develop a thermal model the necessity to get an insight into various important aspects such as, types of thermal models, transient temperature and heat flow in semi infinite solid etc. was felt necessary and is communicated herewith.

Types of thermal models

The models are broadly divided into three sections, namely [5]:

a. Plasma Channel Model
b. Anode Erosion Model
c. Cathode Erosion Model

All models are mainly based on the electro-thermal mechanism where the material erosion at the anode and cathode occurs as a result of an extremely high temperature, due to the high intensity of current flowing through the plasma channel. A number of
approaches have been adopted to predict the temperature distribution in the electrode and hence estimate the unit material removal of electrical discharges.

Some models employed numerical methods to predict the temperature distribution within an electrode based on a steady state heat diffusion model and employed a Gaussian heat input and convective cooling as boundary conditions. On the other hand, the temperature distributions within an electrode based on a transient heat diffusion model with an instantaneous heat source were predicted using numerical methods by others. Figure 2.11 represents the breakdown mechanism in EDM.

![Breakdown Mechanism](image)

Each model has different characteristics since the development process varies according to the hypothesis put forward in each research. Consequently, the resulting material removal predicted differs between the models. It is important to elucidate these differences and identify the model which may provide the closest approximation of material removal in relation to the actual process. This knowledge will provide a significant contribution to the selection of the machining process parameters and facilitate requirements of the machining process. In addition, the approximation results can be extended to estimate material removal rate (MRR), tool wear ratio (TWR) of the process, allowing improvements to process planning.

### 2.2.1 Basic Fourier Law of heat conduction

The rate of heat transfer through a material is proportional to the negative gradient in temperature and at right angles to the area through which the heat is flowing.
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\[ Q = -k \frac{\partial T(X,t)}{\partial X} \]  

(2.1)

where, \( Q \) - heat flux in x direction (W/m^2), \( k \)-Thermal Conductivity of Solid (W/m K)

2.2.2 Transient Temperature and Heat Flow in a semi-infinite solid

Ozisik [5] has proposed various important factors regarding the transient temperature and heat flow in semi infinite solid. He has further proposed a basic thermal model for conduction which, is discussed in this section. The concept of a one-dimensional semi-infinite solid refers, mathematically, to a region that has a single boundary surface and extends to infinity in one direction. However, in practice it implies a plate that is sufficiently so thick that any temperature disturbances applied to one of its surfaces, has negligible effect for all practical purposes on the other surface, during the period of observation of temperature transitions.

Sudden change in the surface temperature –

Consider a semi-infinite solid that is initially at a uniform \( T_i \) and confined to a domain \( x \geq 0 \). There is no internal heat generation. Mathematical formulation of 1D heat conduction is given by –

\[ \frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T(X,t)}{\partial t} \]  

(2.2)

Subject to boundary conditions –

\[ T = T_0, \text{ at } x = 0, \ t > 0 \]

\[ T \to T_i, \text{ as } x \to \infty, \ t > 0 \]

And initial condition –

\[ T = T_i, \text{ for } t = 0, \ x \geq 0 \]

The transient heat conduction problem has been solved for the above conditions and the dimensionless temperature \( \theta(x,t) = \frac{T-T_0}{T_i-T_0} \) is expressed in the terms of dimensionless parameter \( \xi \)

\[ \xi = \frac{x}{2\sqrt{\alpha t}} \]  

(2.3)
with the following expression \( \theta(x,t) = \text{erf} \left( \frac{x}{2\sqrt{\alpha t}} \right) \); Figure 2.12 shows the plot of the dimensionless temperature \( \theta(x,t) \) as the function of the parameter, \( \frac{x}{2\sqrt{\alpha t}} \).

![Figure 2.12 Plot of dimensionless temperature [5]](image)

For a given value of \( x \), the graph represents the variation in temperature with time at that particular location \( x \). Conversely, for a given value of \( t \), the graph represents the variation of temperature with position within the solid at a particular time \( t \).

The heat flux at any point is obtained from the following definition,

\[
q(x,t) = -k \frac{\partial T}{\partial x}
\]

Then the heat flux at the boundary surface \( x = 0 \), becomes

\[
q_t = k \frac{(T_0 - T_i)}{\sqrt{\pi \alpha t}} \quad \text{W/m}^2
\]

Suddenly imposed surface heat flux,

\[
\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T(X,t)}{\partial t}
\]

Subject to boundary conditions,

\[
-k \frac{\partial T}{\partial x} = q_0, \quad \text{at} \quad x = 0, \quad t > 0
\]
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\( T \rightarrow T_i, \text{ as } x \rightarrow \infty, \ t > 0 \)

And initial condition,

\( T = T_i, \text{ for } t = 0, \ x \geq 0 \)

This transient heat conduction problem is solved and temperature distribution within the solid is determined as a function of position and time as –

\[
T(x,t) = T_i + \frac{2q_0}{k} \sqrt{\frac{\alpha t}{\pi}} \left[ \frac{1}{\sqrt{\pi}} e^{-\xi^2} + \text{erf} (\xi) - \xi \right] \tag{2.4}
\]

It’s noted that the temperature continues to change with time as long as heat flux \( q_0 \) is maintained at the boundary surface. The quantity of material removed due to single spark can be determined by considering diameter of crater and the depth to which melting temperature has been reached. Due to circular symmetry, the temperature at any point depends on \( r \) and \( z \). Figure 2.13 represents the idealized heat source used in EDM. The equation of heat conduction is –

\[
\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \tag{2.5}
\]

Figure 2.13 Description of idealized heat source using EDM [5]

The initial and boundary conditions are –

\( t \leq 0, \ \theta(r,z,t) = 0 \)

\( t > 0, \ r > a, \ \frac{\partial \theta}{\partial z} = 0 \)

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\[ \frac{-k \partial \theta}{\partial z} = \frac{H}{\pi a^2 t_d} \]

0 < r < a,

Since, intuitively, it can be seen that the depth to which the melting temperature is reached is maximum at the centre, our interest lies in the solution at \( r = 0 \). The temperature at a point on the axis at the end of the discharge assuming that the temperature is reached at \( t = t_d \) as the heat input stops at this instant is given by:

\[ \theta(0, z, t) = \frac{1}{2} \frac{H}{\pi a^2 t_d} \int_0^\infty J_0(\xi a) J_1(\xi a) \left[ e^{\xi^2} \text{erfc} \left( \frac{z}{2\sqrt{\xi a d}} - \xi \sqrt{\xi a d} \right) \right] \frac{d\xi}{\xi} \]

where \( \xi \) is a dummy variable. If \( Z \) is the depth to which the melting temperature is reached, the equation obtained is

\[ \theta_n = \frac{2H}{\pi a^2 t_d} \left[ \text{erfc} \left( \frac{z}{2\sqrt{\xi a d}} \right) - \text{erfc} \left( \frac{Z + a^2}{2\sqrt{\xi a d}} \right) \right] \]

\[ \text{erfc}(\xi) = \frac{1}{\pi} e^{-\xi^2} - \xi \text{erfc}(\xi) \]

To take into account latent heat of vaporization of the molten material, the actual heat input rate can be found out by subtracting the heat used to melt the material from the total heat supplied by the spark. Thus, the rate of heat input is given by:

\[ \frac{H(\text{total}) - H(m)}{\rho a^2 Z} \frac{\text{cal}}{\text{cm}^2 \text{sec}} \]

where, \( H(\text{total}) = \) total amount of heat released,

\[ H(m) = \text{latent heat (cal/g)} \]

The diameter of the crater has been assumed to be equal to \( 2a \) i.e. the spark diameter, which, under idealized condition of uniform strength is given by

\[ 2a = KW^{\text{td}^n} \text{ cm} \]

where, \( W \) is the total pulse energy in joules and \( m, n, K \) are constants characterizing the properties of electrodes and dielectric medium. The melting temperature depth \( Z \) is related to crater volume as

\[ V_c = \frac{\pi}{6} h_c (3a + h_c^2) \text{ cm}^3 \]
where $h_c$ = crater depth. So it is clear that $Z$ gives an indication of the volume of the material removed by each spark.

Figure 2.14 shows the theoretical values of $Z$ for a given spark energy and a constant spark diameter for Cu, Al and Zn as the electrode materials. Figure 2.15 depicts the actual nature of variation of the crater volume with $t_d$ for different spark energies. One important feature which becomes evident from these results is that material removal is very low for a small discharge time and increases with $t_d$ to each other. Then, reaching a peak values, it suddenly drops to zero. Also it is has been strongly established that the material removed per discharge depends on the melting point of the material.

Further literature survey was also carried out for different Thermal models developed by various researchers to simulate actual EDM process by considering different assumptions.
Snoey’s Model (1971) [94]. Snoeys proposed a first ever widely acknowledged thermal model for EDM process and Figure 2.16 shows graphically representation of the model.

Features

1. Heat source is assumed to be of disk shape on the surface of electrode.
2. Cathode surface is assumed to be insulated at the outer area.
3. Radius at insulated surface is assumed 100 times, the radius of disk heat source.
4. Heat source assumed to be existent for the pulse-on-time with the gradually increasing and then decreasing heat source radius.

![Figure 2.16 Snoey's model](image)

Fraction of discharge energy transferred to cathode is assumed to be 50% ($F_c = 0.5$).

Based on the assumptions used, the temperature distribution at the cathode is given as equation (2.6).

$$T(r,z,t) = T_0 + \sum_{n=1}^{\infty} \frac{C_n}{2J_0} \left[ e^{i_n z} \left( \operatorname{erf} \left( \frac{i_n \sqrt{a t} + \frac{z}{2 \sqrt{a t}}} 2 \right) - 1 \right) + e^{-i_n z} \left( \operatorname{erf} \left( \frac{i_n \sqrt{a t} - \frac{z}{2 \sqrt{a t}}} 2 \right) - 1 \right) \right]$$

(2.6)

Where,

$$C_n = \frac{2q \gamma J_1 (i_n r_0)}{K_i i_n r_0 \gamma J_0 (i_n r_0)}$$
**Van Dijck’s Model** (1974) [104, 105], the model which accounts for the two-dimensional nature of the heat flow is solved for two cases, finite and infinite dimension in the $z$ direction. However, the latter case is similar to Snoeys’s model. The first case of a finite dimension in the $z$ direction is simplified than infinite case.

**Features**

1. The fraction of the energy transferred to the cathode is taken as 50% ($F_C = 0.5$).

2. The entire electrode and workpiece surfaces were assumed to be insulated outside the heat source.

3. The whole medium is assumed to be initially at ambient temperature.

4. A method to account the change in radius of heat source with time is proposed.

The schematic diagram of Van Dijck’s model is illustrated in the Figure 2.17.

![Van Dijck’s model](image)

Figure 2.17 Van Dijck’s model [104, 105]

The superposition principle and separation of variables were applied to the partial differential equation and the solution of the temperature distribution is given as:

$$T(r,z,t) = T_0 + \frac{q r_C}{K_l} \sum_{n=1}^{\infty} a_n J_0 (\lambda_n r) \left[ \sinh(\lambda_n z) \right]$$

$$+ \sum_{m=1}^{\infty} C_{mn} \sin(\mu_m z) e^{-\lambda_m^2 t}$$

$$= a \left( \lambda_n^2 + \mu_m^2 \right) t$$

(2.7)

For,

$$a_n = \frac{2 J_1(\lambda_n r_C)}{\cosh(\lambda_n l) \left[ \lambda_n r_0 J_1(\lambda_n r_0) \right]^2}$$

$$\mu_m = \left( \frac{\pi}{2l} \right) (2m-1)$$

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\[ C_{mn} = \frac{(-1)^m \lambda_m \cosh(\lambda_m l)}{l \left[ \lambda_m^2 + \mu_m^2 \right]} \]

**Beck’s Model** (1981) [7, 8], is also another disk heat source model. This mode is not developed specifically for the EDM process but resembles to the one. Figure 2.18 shows the schematic representation of the model.

Features

1. A disk shaped region over material surface is considered to be heated by heat flux.

2. The entire electrode surface is considered to be insulated; except over the circular region where the heat flux strikes the material surfaces.

As the model is not developed specifically for the EDM process, the heat flux did not take into account the fraction of energy transferred to the cathode.

![Figure 2.18 Beck’s model [7, 8]](image)

The temperature distribution is given by equation (2.8),

\[
T(r, z, t) = T_i + \frac{2 q r_c}{K_t} \left\{ \frac{r_c B(z, t)}{r_0^2} + \sum_{i=1}^{\infty} \frac{C_i(z, t) J_0(\lambda_i r) J_1(\lambda_i r_c)}{2 \left[ \lambda_i r_c J_0(\lambda_i r_c) \right]^2} \right\}
\]  

(2.8)

Where;

\[
B(z, t) = \sqrt{\frac{z}{at}} \text{erfc} \left( \frac{z}{2\sqrt{at}} \right) \quad C_i(z, t) = e^{-z \lambda_i} \left\{ I + \text{erf} \left[ \lambda_i \sqrt{\frac{z}{2at}} \right] \right\}
\]

**Jilani’s Model** (1983, 1986) [43, 44], and P.C. Pandey of University of Rurkee proposed a thermal model of EDM in 1983. Figure 2.19 shows the schematic representation of the model.
Features

1. This model assumes that the heat from the plasma channel is transferred to the workpiece or tool only by conduction.

2. The electrode is a semi-infinite body with radius $r_0$.

3. About 90% of the total energy liberated is conducted to the discharge gap and it was distributed equally between the anode and cathode ($F_c = 0.5$).

4. The plasma channel has been considered to be a disk heat source situated between two semi-infinite bodies (tool and workpiece).

5. The radius of heat flux is considered constant regardless of the discharge conditions.

6. The electrode surfaces are completely insulated except for the portion where the heat flux strikes the material surfaces.

The temperature distribution was derived using an infinite number of instantaneous point heat sources distributed round the circle, and it is given by equation (2.9).

$$T(r,z,t) = \frac{q r_c^2}{K_t} \sqrt{\frac{\alpha t}{\pi}} \int_0^t \left[ \frac{-r^2}{4 \alpha t + r_c^2} \right] \frac{1}{4 \alpha t + r_c^2} dt$$  (2.9)

In order to reach a reasonable degree of approximation, the model takes into account the effect of plasma channel growth through a constant surface temperature approach. Thus, the temperature at the center of the cathode spot was assumed to remain constant throughout the pulse on duration and equal to the boiling temperature of the cathode material. The boiling temperature of cathode material which is used to determine the crater radius is given as equation (2.10):
\[ T_b = \frac{q_{r_c}}{K_r \sqrt{\pi}} \tan^{-1} \left( \frac{4at}{\pi r_c^2} \right) \] (2.10)

**DiBitonto's Model** (1989) [19, 20], of Texas A&M University, America conducted a series of experiments in association with AGIE Corporation, a leading EDM manufacturer.

Figure 2.20 illustrates the spherical symmetry resulting from assumptions as well as the melt front radius (r-crater) of the material.

**Features**

1. Unlike all previous models, this model assumed a point heat source (PHSM) instead of a disk for conduction into its interior. This is because the plasma radius at the cathode was assumed to be much smaller than that at the anode.

2. The energy distributed to the cathode for erosion is assumed to be 18% \((F_c = 0.18)\).

![Figure 2.20 Dibitonto's model [19, 20]](image)

The temperature distribution was given by Carslaw and Jaeger in 1956 [10] as,

\[ T(r, z, t) = T_0 + \left( \frac{F_cUI}{2\pi K_r r} \right) \text{erfc} \left( \frac{r}{2\sqrt{at}} \right) \] (2.11)

This equation assumes constant current \(I\) during the pulse. At the melt radius \(R\),

\[ T_m = T_0 + \left( \frac{F_cUI}{2\pi K_r R} \right) \text{erfc} \left( \frac{R}{2\sqrt{at}} \right) \] (2.12)

Along the interface where the phase change takes place \((T = T_{melt})\) the equation (2.13) holds.
Chapter 2

\[ F_c UI = \pm \sigma \lambda f \frac{dV_c}{dt} \] (2.13)

where, \( \lambda_f \) = heat of fusion, \( V_c \) = molten cavity volume.

**K. Salonitis’s Model** (2006) [89].

Features: It is assumed that the distance from the workpiece surface at which the temperature exceeds the melting point coincides with the crater depth, neglecting the formation of a recast layer. It is a completely new and simple approach of thermal modeling where new concept of erosion front velocity is introduced and Figure 2.21 represents the schematic diagram for the model.

![Crater geometry](image)

Figure 2.21 Salonitis’s Model [89]

The crater is assumed to have circular paraboloid geometry and its diameter on the surface is determined from the empirical relations in equation (2.14).

\[ \frac{x^2 + y^2}{r_c^2} = \frac{(s - z)}{s} \]

\[ R_a = \frac{1}{4} \left[ \frac{r_c + r_s}{r_c} \right]^2 s \] (2.14)

where, \( R_a \) is average surface roughness.

Heat balance equation at the erosion front was given by equation (2.15).

\[ q_w = \rho L_v \frac{\partial s}{\partial t} - k \left( \frac{dt}{dz} \right)_{z=0} \] (2.15)

where,

\[ q_w = \frac{R_w p}{\pi r_s^2}, \quad p = I.U_a \]

and \( r_s = 2040 t_s^{0.43} t_s^{0.44} \) (2.16)
And the velocity on erosion front is stated as –

\[
\frac{\partial s}{\partial t} = \frac{q_W}{\rho \left( L_v + c_p (T_s - T_0) \right)}
\]

S.H. Yeo [118], of Nanyang Technical University, Singapore has recently done a work of comparing the first five models mentioned here above in light of experiments using WEDM on alloy steel (AISI-4140).

a) Temperature distribution

Yeo, plotted the temperature profiles for different models. It shows that the temperature profiles and isotherm surfaces are found to vary for each model. Snoeys's model has a bowl shape with a nearly flat bottom surface, while Van Dijck’s model provides similar characteristics with larger affected distance for the same temperatures. Beck’s model, has results similar to Snoeys’s model, Jilani’s model provides more crescent-like shape. On the other hand, DiBitonto’s model results in semi circular isotherm surfaces, as expected from using a point heat source model.

b) Crater geometry, erosion rate and MRR

Yeo carried out simulation for obtaining crater profiles. Snoeys’s model has a bowl shape crater with a nearly flat bottom surface. Similar shape is obtained by Beck’s model, but with approximately 20% larger size in terms of the crater diameter and depth. Jilani’s model has a crescent-like shape with parabolic edges until the center of the crater while Van Dijck’s model yields large crater diameter and depth with a nearly hemi-spherical shape. As for DiBitonto’s model, a perfect hemi-spherical crater shape is resulted. These shape variations are due to the use of a disk and point heat source approximation.

A disk heat source has a circular heat flux, creating a large ratio of crater diameter to depth. In contrast, a point heat source transfers the heat uniformly in the radial direction, resulting in a hemi-spherical shape. The overall ratio of experimental to theoretical MRR calculated by him shows an exceptionally large variation for Van Dijck’s model where the MRR approximation is significantly above the experimental data. Snoeys’s model yields very close results with Beck’s model. Jilani’s model showed a closer approximation whereas DiBitonto’s model has a relatively better agreement with the experimental results as compared to all other models.
Chapter 2

Model comparison

The key summary of the five models is given in the Table 2.1. The models by Snoeys, Van Dijck, Beck, and Jilani are developed using a disk heat source while DiBitonto’s model is developed using a point heat source approximation. Unlike the other models where the thermo physical properties of the material are considered to be constant, DiBitonto’s model uses average thermo physical properties value over the whole temperature range from solid phase to liquid. In either case, the values do not change in the analyses. The fraction of discharge energy for DiBitonto’s cathode erosion is assumed to be 18% rather than 50% as in the other models. In the models by Snoeys, Van Dijck, and Jilani, the effect of melting heat is considered in model formulation.

c) Improvements Proposed By Yeo

Based on the comparative analysis, DiBitonto’s model is able to predict the dimensional geometry and erosion rate of the process with a good accuracy. The other models tend to overestimate the temperature distribution of the workpiece, resulting in larger crater geometry and erosion rate. This is thought to be due to the use of different fractions of energy in which DiBitonto’s model assumed $F_c = 0.18$, while the other models assumed that half of the discharge energy ($F_c = 0.5$) is consumed during material removal. In addition, errors might also be introduced in the approximation of the heat flux radius, which has a high influence on the numerical results for the first four models. To verify the effects of energy fraction and approximation of heat flux radius on the estimation of temperature distribution, the ratio of theoretical to experimental data was recalculated using the disk heat source models with a cathode energy fraction of 18% and heat flux radius approximation using the following equation (Patel et al., 1989 [75]).

$$r_c = 0.778r_d^{3/4}$$

(2.17)

This evidence clearly shows that the disk heat source model can be improved further if appropriate approximations are taken for the heat flux and energy fraction; the possible way can be development of a reliable plasma channel model. Based on the presented results, DiBitonto’s model is observed to be the most appropriate model to provide the initial approximation. The simplicity of its equation provides a fast processing time with adequate accuracy.
Table 2.2 Comparison of various thermal models [118]

<table>
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</thead>
<tbody>
<tr>
<td>Upper part of electrode is adiabatic</td>
<td>Upper part of electrode is adiabatic</td>
<td>Surfaces beyond the disk region are insulated</td>
<td>Constant thermophysical properties of the material over the whole temperature range</td>
<td>Uniform heat flux with constant radius</td>
<td>Heat flux from a point heat source. Effective (avg.) thermophysical properties of the material over the whole temperature range from solid to liquid melt</td>
</tr>
<tr>
<td>Constant thermophysical properties of the material over the whole temperature range</td>
<td>Constant thermophysical properties of the material over the whole temperature range</td>
<td>Erosion takes place in molten area of an electrode</td>
<td>Erosion takes place in molten area of an electrode</td>
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<td>Erosion takes place in molten area of an electrode</td>
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<tr>
<td>Main feature</td>
<td>two-dimensional heat flow</td>
<td>Two-dimensional heat flow</td>
<td>Two-dimensional heat flow</td>
<td>Two-dimensional heat flow</td>
<td>One-dimensional heat flow</td>
</tr>
<tr>
<td>Semi-infinite cylinder with circular heat source</td>
<td>Semi-infinite cylinder with circular heat source on surface</td>
<td>Semi-infinite cylinder heated over a disk-shaped region</td>
<td>Semi-infinite body with a disk heat source on the surface</td>
<td>Point heat source</td>
<td></td>
</tr>
<tr>
<td>Fraction of DE</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>18%</td>
</tr>
<tr>
<td>Radius of heat flux</td>
<td>Constant</td>
<td>Constant</td>
<td>Constant</td>
<td>Expanding with time</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Limitations</td>
<td>Approximation of heat flux radius is not readily available</td>
<td>Approximation of heat flux radius is not readily available</td>
<td>Approximation of heat flux radius is not readily available</td>
<td>Approximation of heat flux radius is not readily available</td>
<td>Large heat flux radius compared to crater radius in small pulse on time</td>
</tr>
<tr>
<td>Guideline for the outer cylinder radius value is not available</td>
<td>No guidelines for the determination of electrode thickness</td>
<td>Direct application of disk heat source</td>
<td>Guideline for outer cylinder radius value is not available</td>
<td>The crater profile resulted is hemi-spherical</td>
<td></td>
</tr>
</tbody>
</table>

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However, due to the simplification from using a point heat source, the crater shape is hemi-spherical instead of having a bowl shape with a shallow bottom surface. A higher degree of accuracy can be introduced by using the disk heat source model with a trade-off in longer processing time. From discussion, one can conclude that a disk heat source model has potential to be further developed by incorporating a better approximation of heat flux radius and fraction of energy.

From the literature survey carried out and the inferences drawn by Yeo [118], the necessity of developing a hyperbolic heat conduction model using was felt and an attempt in this order has been carried out and represented in Chapter 3. While developing the hyperbolic thermal model the necessity to gain an insight on the issues related with Relaxation time was felt and hence few papers based on it were reviewed and are communicated herewith.

**Yue- kai Lu** [119] et al reported about the depth profile reconstruction of thermal relaxation time based on hyperbolic heat conduction equation in frequency domain. A non linear algorithm in this accord has been developed. They emphasized on the issues related to Fourier’s law while studying non-stationary/transient heat conduction problems.

**Ordóñez- Miranda and J.J.alvarado- Gil** [71] studied the system formed by a semi-infinite layer in contact with finite one, which is excited by a modulated heat source. It was concluded that the frequency range could be found in which the amplitude and phase of the spatial component of the oscillatory surface temperature showed strong oscillations when the thermal relaxation time of the finite layer was close to its thermalization time. Authors established a methodology to determine the thermal relaxation time was established. Also it has been communicated that the thermal relaxation time for metals, semiconductors is of the order of micro-seconds to pico seconds and this range has been selected while validating the thermal model.

Further in order to understand the phenomenon of WEDM process various research papers were referred and findings of few of them are communicated.

### 2.3 Literature communicated by other Researchers

**Bert Lauwers** et al [10] investigated the effect of grain size of WC and binder on various parameters like cutting rate, bending strength and surface quality. Six different
WC-based materials with varying WC grain size and different binder compositions (5 samples with cobalt and 1 sample with nickel) were chosen. It was observed that as the grain size decreases, material removal rate increases; which was not the case with the sample containing nickel. In general material with lower thermal conductivity and melting point, yields higher material removal rate, due to higher energy concentration and lower energy requirement.

Physical formation of cracks depends on several material properties such as tensile strength, Young's modulus, thermal expansion coefficient and thermal conductivity. A factor 'Resistance against crack formation' was defined and is represented by equation (2.18). The larger the value of this factor, the lesser is the chance for micro cracks. Various materials were investigated and it was found that materials with finer grain size show lower resistance against crack formation.

$$\text{Resistance} = \frac{\sigma}{E \alpha \beta}$$ \hspace{1cm} (2.18)

where, $\sigma$ = Tensile stress, $E$ = Young's Modulus, $\alpha$ = Coefficient of thermal expansion and $\beta$ = Biot number

$$\beta = \frac{h l}{\lambda}$$ \hspace{1cm} (2.19)

where, $h$ = heat transfer coefficient, $l$ = characteristic length, $\lambda$ = thermal conductivity.
The Biot number is a dimensionless number used in unsteady state and heat transfer calculations. It relates the heat transfer resistance inside and at the surface of a body. The resistance has a unit of temperature and expresses the amount of temperature deviation needed for the formation of micro cracks. It was concluded that WEDM reduces the bending strength of the machined component. This effect was more prominent in case of material with lower grain size due to low initial toughness. Carbide materials with finer WC grain sizes having a lower toughness, will give a stronger reduction in bending strength after EDM machining. The grain size also has a strong influence on cutting rate.

Kim Chang Ho [52] discussed the effect of binder content on machining of carbides. The spark vaporizes cobalt which leads to disintegration of carbide grains causing material erosion. The water vapour bubble caused due to spark collapses violently and the deionized water flushes away the eroded material. Data was obtained for each material while considering electrical conductivity, removal rate, and surface roughness as parameters. It was observed that the percentage of cobalt has an influence on the rate of erosion. A high Co- content worsens the final surface quality as a greater quantity of solidified metal deposits on the eroded surface. However it was observed that the surface roughness is unaffected by cobalt content during rough cut or after 3 or 4 finish cuts.

Dielectric performs several functions like insulation, ionization, cooling, and the removal of waste metal particles. As the voltage builds up, the water deionizes and becomes a conductor.

Chang-Ho Kim, Hae-do Jeong et al studied the effect of electrical conductivity of dielectric and cobalt percentage on output parameters such as metal removal rate and surface roughness value of sintered carbides cut by wire electrical discharge machining (WEDM). Although the dielectric is reused after filtering, small amount of sediments (eroded particles) remain in the fluid. Due to their presence, the conductivity of dielectric further increases. Finely dispersed waste particles, enable rapid building of ionization channels and yields a higher material removal rate. Based on the quantity of debris, the process may become stable or arcing occurs. Thus it is recommended to use clean dielectric. It has been observed that the ideal conductivity should vary from 5 to 10μS/cm to prevent corrosion.
As continuous flow of dielectric occurs, corrosion of workpiece due to intense electric field in the cutting area between WC and wire is observed. This phenomenon activates an electrochemical reaction that induces a fast and significant loss of cobalt. This leads to formation of micro cracks (inter-granular erosion/predominant) above the base layer (which remains unaffected) because of loose carbide granules; which appears like small pits and cracks. It was observed that the presence of mixed carbides (TiC, TaC) has no influence on the erosive process. X-ray diffraction pattern revealed that some amount of wire electrode material from the WEDM gets deposited onto the workpiece surface. Some elements of workpiece material were seen on the wire electrode surface during WEDM.

Scott F. Miller et al [65] investigated the effect of spark cycle on MRR. Generally, WEDM works on high frequency DC pulse (each pulse is termed as spark cycle). MRR was chosen as output parameter as it ultimately decides productivity and profitability of the process. It was identified to be dependent on five constraints during machining with WEDM as below:

- Spark on time
- Spark off time
- Short circuit
- Wire breakage
- Machine slide speed

Selection of optimum set of parameters was necessary to obtain maximum MRR. Four different materials (including tungsten carbide) were selected for experimentation. The experiments were conducted on wire-EDM (Make- Brother HS-5100) with copper wire of 0.25mm diameter. It was observed that high MRR also resulted in formation of a thick recast layer. It was observed that when cycle time (T) is very low, then electrical energy reaches very high level which leads to wire breakage; whereas at higher value cycle time the electrical energy is very low and spark is rare resulting in short circuit. WEDM is a process carried out in presence of deionized water; though corrosion is not a major phenomenon yet it is observed. Haruki Obara et al [34] carried out a study on corrosion in cemented carbides during wire EDM. Tungsten carbide (with cobalt as binder) specimens were chosen for
experimentation. Corrosion was observed on the cross section of machined surface. Several methods were suggested to reduce the effect of corrosion. Worktable is generally made of steel and the contact between it and material processed is favorable for corrosion. Using a sacrificial layer (Figure 2.23) is a very popular method for corrosion prevention. The base metal to be machined is attached with a sacrificial metal like zinc. With different positions of zinc plate, it was confirmed that the portion of workpiece in contact with zinc does not corrode whereas unprotected area showed signs of corrosion.

![Figure 2.23 Use of sacrificial layer [34]](image)

Another method of preventing corrosion is using an external power supply (Figure 2.24). The corrosion is mainly caused by flowing of current between workpiece and table; and hence a DC power source is applied between them. It has been observed that if external opposing current of equal magnitude is present, then corrosion can be avoided. Power supply of 1V and 2V were tested and 2V supply worked
satisfactorily. Both of these methods are found to be useful for material with thickness less than 20mm; similar tests were carried out using Nickel as binder and the phenomenon of corrosion was not observed. AC generator was used, as it maintains mean voltage of gap near 0V, thus preventing the electrochemical reaction which prevents corrosion. Hence it was concluded that DC generator causes corrosion while the AC one does not.

The spark generated during machining with WEDM produces a heat affected zone on the machined surface, which is termed as recast layer. It consists of craters and cracks, which deteriorates the surface properties and reduce the wear and fatigue life of EDM mechanical parts. To avoid such a situation, EDM- fluids are preferred as cutting medium.

**Jun Qu, et al [46]** proposed a new method to improve the surface texture of machined WC-Co components by using abrasive micro-blasting. The process was carried out using two sizes of SiC abrasive, two levels of air pressures, and three different time durations. It was observed [46] that the recast layer and heat affected zone can be eliminated by SiC micro-blasting in very short times. Larger size abrasives and higher air pressure leads to higher erosion wear rate and reduce the WEDM surface roughness more effectively.

**Jun Qu** et al [47] also investigated the surface integrity and roundness of parts created by the cylindrical wire EDM process. A mathematical model for the arithmetic average surface roughness on the ideal surface of a cylindrical wire EDM workpiece was derived. Effects of wire feed rate, part rotational speed on the surface finish and roundness for brass, carbide work-materials at high material removal rates were investigated. The pulse on-time and wire feed rate were varied to explore the best possible surface finish and roundness achievable by the cylindrical wire EDM process. This study has demonstrated that for carbide parts, an arithmetic average surface roughness and roundness as low as 0.68 and 1.7 mm respectively, can be achieved. Surfaces of the cylindrical EDM parts were examined using Scanning Electron Microscopy (SEM) to identify the micro cracks and craters on the surface. Cross-sections of the EDM parts are examined using the SEM to quantify the sub-surface recast layers and heat-affected zones under various process parameters. This study has demonstrated that the cylindrical wire EDM process parameters can be
adjusted to achieve either high material removal rate or good surface integrity and roundness.

Juhr H. et al [45] observed that it is possible to reduce the heat affected zone (rim zone) of the machined cemented carbide component by using a needle pulse energy source. Due to the use of a pulse of less than 500ns, it is possible to reduce pulse energy to such a level to just obtain the cut with considerable reduction in heat affected zone. It was also seen that the properties of the machined component can also be enhanced by choosing the right set of parameters. The recast layer is mainly formed on account of main cut. The finishing cuts also superimpose same effect on previously formed layer. Therefore, although the surface roughness is improved, the recast layer is still formed. The surface roughness obtained after pulse shaping was also quite better and so the number of finishing cuts required are reduced, leading to increase in productivity.

Mu-Tian Yan et al [70] developed and performed a study on feasibility of use of a fine finish power supply. The developed power supply using anti electrolysis circuitry and CPLD-based pulse control circuit was able to provide low discharge energy pulses with a frequency of 500 kHz. Discharge duration as short as 150 ns and peak current as low as 0.7A were obtained through the adjustment of the capacitance and current-limiting resistance in the discharge circuit respectively. Higher value of capacitance results in higher discharge energy and thus contributes to longer discharge duration. The peak current increases slightly with the increase of the pulse on-time. A higher current limiting resistance, results in a lower peak current. Experimental results demonstrated that the developed fine-finish power supply could reduce the cobalt depletion in recast layer of tungsten carbide, than a standard DC power supply. A fine surface finish of 0.22 mm Ra was achieved by means of four finish machining operations with proper machining settings.

Scott et al [91] used a factorial design method to determine the optimal combination of control parameters in WEDM; the measures of machining performance being the metal removal rate and the surface finish. An optimization for process parameters was carried out using the analysis of variance technique. It was observed that the discharge current, pulse duration, and pulse frequency are significant control factors for both the
metal removal rate and surface roughness; which is in tune with the previous researchers.

**Mahapatra S S et al [60]** carried out series of experiments on Tool steel for optimizing the process parameters. Rough cutting operation in WEDM is treated as a challenging one because improvement of more than one machining performance measures viz. metal removal rate (MRR), surface finish (SF) and cutting width (kerf) are sought to obtain a precision work. These desired effects depend on machining parameters like discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow rate.

Using Taguchi’s parameter design, significant machining parameters affecting the performance measures were identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow. It was observed that combinations of factors for optimization of each performance measure are different. In this study, the relationship between control factors and responses like MRR, surface finish and kerf width were established by means of nonlinear regression analysis, resulting in a valid mathematical model. Among other performance measures, the kerf width, which determines the dimensional accuracy of the finishing part, was observed to be extremely important. The internal corner radius to be produced in WEDM operations is also limited by the kerf. The gap between the wire and workpiece usually ranges from 0.025 to 0.075 mm and is constantly maintained by a computer controlled positioning system.

Finally, genetic algorithm, a popular evolutionary approach was employed, to optimize the wire electrical discharge machining process with multiple objectives. The material removal rate determines the economics of machining and rate of production where as kerf denotes degree of precision. The study demonstrates that the WEDM process parameters can be adjusted to achieve better MRR, surface finish and cutting width simultaneously.

**Y S Tarng et al [97]** has utilized a feed forward neural network to associate the cutting parameters with cutting performance. A simulated annealing (SA) algorithm is then applied to the neural network for solving the optimal cutting parameters based on a performance index within the allowable working conditions. Experimental results have shown that the cutting performance of wire-EDM can be greatly enhanced using
this new approach. In this paper, the experiments were performed on a Sodick A350-S CNC wire-EDM machine. A feed forward neural network was adopted to model the wire-EDM process. The feed forward neural network composed of many interconnected artificial neurons that were often grouped into input, hidden and output layers. SUS-304 stainless steel specimens with different thicknesses were used in the experiments. A 28-4 fractional factorial experiment was designed to reduce the number of training samples. The machined surface roughness ($R_a$) was measured by a 3D-Hommelewark profilometer. Experimental results have shown that the use of this approach can systematically help in identifying the cutting parameters for obtaining an optimum production rate in wire-EDM.

T. A. Spedding et al [95] have also attempted optimization of the process of parametric combinations by modeling the process using artificial neural network (ANN) and characterizes the WEDMed surface through time series techniques. A feed forward back propagation neural network based on a central composite rotatable experimental design was developed to model the machining process. For optimization of the WEDM process a uniform precision, rotatable central composite experiment was performed to investigate the performance, productivity, and workpiece surface texture, in order to model the process. Pulse width, time between two pulses, wire mechanical tension, and wire-feed speed were selected as the control parameters. Cutting speed, workpiece surface roughness and waviness were selected as the output parameters. The ANN developed model was used to predict the process performance.

Optimal process parametric combinations corresponding to different surface roughness and waviness requirements were identified from the predictions of the model. It was found that the cutting speed of the process had an upper limit and reduced rapidly with a decrease of required surface roughness value from 2.9 µm. The WEDMed surface profiles were also assessed by a three-group characterization scheme. A similar height distribution, approximately Gaussian in nature, was observed between different surfaces obtained through different machining conditions. This phenomenon can be attributed to the additive nature of the WEDM process.

Y. Cheng et al [14] have carried out experiments with different values of discharge current, pulse duration time and interval time in electro-discharge machining, in order to investigate their effects on the material removal rate, surface quality and
dimensional accuracy of the tool as well as product. Optimum pulse duration and pulse interval values in EDM either produce the highest erosion rate or fine surface finish which has been obtained to be of prime importance to the machining process.

Experiments were carried out on a CNC-326 electro-discharge machine with HEIDENHAIN TNC-306 controller. Steel with composition of Carbon 0.08 – 0.13, Manganese 0.40 – 0.80, Sulphur 0.05 and Phosphorus 0.05, having a hardness of HB235 was used as the workpiece. Copper with composition of Copper 0.80, Aluminum 0.10, Iron 0.05 and Nickel 0.05, having a hardness of HV115, was used as the tool material. The dielectric fluid used in experiments was Castrol SE-185 having a hydrocarbon base with a kinematic viscosity of 1.9 cSt at 238°C. The experimental results have indicated that the current value and the ratio of the pulse duration and the pulse interval exert the greatest influence on surface quality, the erosion rate, and also on the relative wear of electrode. To achieve a high machining rate and the desired surface finish, a multi-stage erosion machining process has been advised, while the gap voltage selected should be as small as possible. However, a relatively large gap voltage is more suitable to achieve a super-fine surface finish.

H. Selçuk Halkaci et al [92] have studied the effect of spark on, spark off time on surface roughness. They obtained a series of trend lines indicating surface roughness of the machined surfaces (Ra, Rz, and Rmax values) with respect to EDM machining parameters namely; spark time, pause time, and discharge power. Eight different spark time, seven different pause time values, and three different power (current) values were used in the experiments. Experimental data are presented in form, and fitting equations are derived for the plotted data. The curves are fitted as exponential function of the form; \( R = A t^B \). Where numerical values of the coefficients A and B are calculated and tabulated for various different machining conditions. The results clearly indicate the prominent influence of discharge power on the surface roughness.

J. Valentinčič, D. Kuser et al [103] have studied the effect of process parameters on machined surface. To achieve high removal rate and low electrode wear (during rough cut) by a sinking electrical discharge machining process (EDM), appropriate average surface power density is required in the gap between the workpiece and the electrode. Since machining surface varies with the depth of machining, the rough machining
parameters have to be selected on-line to obtain appropriate average surface power density in the gap.

The systems for on-line selection of the rough machining parameters of EDM process presented in the literature either have hardly acceptable disadvantages or they are very complex. Thus, a simple solution could be a significant step towards better automation of the EDM rough machining and micro electrical discharge machining (MEDM). In this paper, a system for on-line selection of the machining parameters according to the given machining surface was communicated. The selection of the machining parameters is based on the acquisition of only one process attribute, i.e. the percentage of short-circuit discharges.

R. A. Mahdavinejad and A. Mahdavinejad [61] have communicated that the machining of tungsten carbide (WC-Co) is very difficult because of high hardness. Among conventional methods, this material could be machined with pendulum grinding method, where special and expensive discs were used. However, the material removal rate is very low and other limitations in machining parameters and workpiece shapes are imposed. Among non-traditional methods, electro discharge machining is considered as the most suitable process for machining this material. However, the process is unstable especially when die sinking machines are used; this is due to generating open circuit, short circuit and arcing pulses. They have communicated the analysis regarding instabilities while machining WC-Co composites and the ways to monitor/control it.

Luis Llanes et al [59] studied the flexural strength evolution for two WC-16% Co cemented carbides, with different mean carbide size, subjected to sequential and upgrading electrical discharge machining. It was compared with the fracture behavior exhibited by a reference surface finish condition, attained through conventional mechanical grinding and polishing using diamond as abrasive. Considering that rupture is related to existing defects, (either introduced during sample elaboration or induced by machining), a detailed fracto-graphic examination by scanning electron microscopy was conducted to discern fracture origins. The experimental findings indicate that the flexural strength of WC-Co hard metals may be strongly affected by EDM, depending upon the correlation existing between natural defects, as given by particular micro structural parameter and EDM induced flaws. An analysis of the
resulting linear elastic fracture mechanism approach permits one, to establish a clear connection between surface integrity and fracture resistance. Quantitative discrepancies between the estimated and experimentally measured critical flaws for all EDM related grades are rationalized through existence of local residual tensile stress of considerable magnitude of the shaped surface. Release of this stress through final mechanical and annealing treatment is pointed out as quiet effective alternative for improving the fracture behavior of WC-Co cemented carbides shaped by EDM.

Y S Liao et al [56] discussed the important concept of specific discharge energy (SDE); the actual energy required to erode a unit volume of material. The SDE should be constant for a specific material. Experimental results reveal that the relative relationship of SDE between different materials is invariant as long as all materials are machined under the same machining conditions. It was also observed that materials having close value of SDE demonstrate very similar machining characteristics such as machining speed, discharge frequency, groove width and surface finish of the machined surface under the same machining conditions. This result can be applied for the determination of the setting of the machining parameters for different materials. The concept discussed is encouraging for the adaptive control of WEDM process.

In continuation with the findings of Liao and from the literature survey carried out it can be concluded that the signature analysis of current as well as voltage needs to be analyzed and in tune with this a modified experimental setup is developed and communicated in Chapter 4. A brief literature in this regards is referred and communicated herewith. Almost all the studies concerned with material deal with the effect of electrode material and machining conditions on machinability in WEDM or die sinking EDM.

Levy and Maggi [55], have compared the influence of material properties of different steels on machining characteristics, but only qualitatively. The material properties such as melting point, density, specific heat, thermal conductivity, yield strength, etc., all affect machining characteristics. In general, the material removal rate and machining characteristics during the WEDM process depend on the distribution of the energy supplied to the gap, by the electrical current. Various thermal models proposed for EDM [7, 8, 18, 19, 20, 43, 44, 94, 104 and 105] show that the complexities and the
stochastic nature of multiple discharges render difficulties in analyzing the process theoretically.

During the past few decades, WEDM has gradually become one of the most powerful non-traditional machining processes; however selection of cutting parameters for faster cutting speed, higher accuracy and better cut surface quality greatly, depends upon the operator's experience. Most of the time the machining parameters are chosen well on the safer side so that, wire rupture is avoided. This practice is a compromise on cutting speed. In some cases where the job thickness is non-uniform, or there are sharp bends in the job profile, the machining parameters need to be readjusted in the middle of the process. This judgment becomes extremely difficult even for an experienced operator and a sacrifice of productivity becomes inevitable. Most of the WEDM machines have a positional feedback system to maintain the narrow gap between wire and workpiece, but the process control is manual even for the most up-to-date computer numerical control (CNC) WEDM machines. A suitable on-line process control strategy was therefore evolved by [81, 84, 110] to meet the stringent precision and accuracy requirements and for prevention of cutting failure. The present work is an attempt in this direction.

J C Rebelo et al [86, 87] discussed that the Electro-discharge machining (EDM) is essentially a thermal process with a complex metal-removal mechanism, involving the formation of a plasma channel between the tool and workpiece electrodes; resulting in metallurgical transformations, residual tensile stresses and cracking. These properties determine the operational behavior of the material and can be included in one term, surface integrity.

Results of different experimental analysis to characterize the surface integrity of steels, used in the production of moulds after EDM were presented. The roughness of the surface, the metallurgical structure, the residual stress state and the surface crack network of the near-surface layers, in the electro-discharge steels were studied, as well as their dependence on the main processing parameters, were examined and discussed quantitatively and qualitatively.

Y.S. Liao et al [57] discussed the pulse-generating circuit which uses low power circuit for ignition and additional high power one for machining. However, for finishing process it was observed that the energy generated by the high-voltage sub-
 Circuit is too high to obtain a desired fine surface, no matter how short is the assigned pulse-on time. In order to obtain good surface roughness, the traditional circuit using low power for ignition is modified for machining as well.

With the assistance of Taguchi quality design, ANOVA and F-test, machining voltage, current-limiting resistance, type of pulse-generating circuit and capacitance were identified as the significant parameters affecting the surface roughness in finishing process. After analyzing the effect of each relevant factor on surface roughness, appropriate values of all parameter were chosen and a fine surface of roughness $Ra = 0.22\mu m$ was achieved. The improvement was limited because finishing process becomes more difficult due to the occurrence of short circuit attributed to wire deflection and vibration when the energy is gradually lowered.

Rajurkar and Wang [84] developed a sparking frequency monitor to detect the thermal load for on-line control in order to prevent the wire from rupture. The rupture of wire is associated with the thermal load and it leads to instability in the process which is a measure hurdle for on line monitoring/adaptive control. Extensive experimental investigations were carried out to determine the variation of machining performance outputs viz., MRR and Surface finish with overall control parameters. The relationship between the machining rate and surface finish under optimal machine settings was determined by means of a multi-objective model. The thermal model accounts for the input energy density caused by different wire velocity. A temperature distribution along the wire electrode indicates that the highest temperature occurred near to the exit of the workpiece region. It was also observed that the material removal rate in WEDM increases initially with the decrease of pulse interval time. However, at a very short interval time, the gap becomes unstable which leads to a reduction in the machining rate.

Lok and Lee [58] successfully processed two advanced ceramics (Sialon and Al$_2$O$_3$-TiC) using WEDM. They compared the machining performance in terms of, MRR and surface finish through observations obtained by processing the ceramics under different cutting conditions. The extent of the surface damage resulting from this thermal machining process was evaluated further. They further commented that it is feasible to process advanced engineering ceramics from the oxide and non-oxide group (using the Wire-cut EDM process), provided that the resistivity is less than the
particular threshold value of 100 Ω-cm. However, the Volumetric Material Removal Rate (VMMR) for processing these ceramics materials were found to be very low as compared with cutting metals such as alloy steel SKD-11, and the surface roughness achieved (with the Wire-cut EDM process) was inferior to that with the die sinking EDM process. The thermal spalling erosion mechanism of the Wire-cut EDM process was found to have a damaging effect on the surface of the machined ceramics, as reflected by the severe drops in the mean flexural strength. They further concluded that the ways and means of improving the surface finish and the surface integrity of the machined ceramics should be addressed by future researchers.

Huang et al [37] communicated that to obtain a precise workpiece with good surface quality, some extra repetitive finish cuts along the rough cutting contour are necessary. An attempt has been made to study the influence of machining parameters (pulse-on time, pulse-off time, table feed-rate, flushing pressure, distance between wire periphery and workpiece surface) on the machining performance of WEDM in finish cutting operations. The gap width, surface roughness and depth of white layer of machined workpiece surface were measured. They concluded that pulse-on time and the distance between wire and workpiece are two significant factors affecting the machining.

Rozenek et al [88], reported experimental investigations of the effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on the machining feed rate and surface roughness during wire electrical discharge machining (WEDM) of metal matrix composite AlSi7Mg/SiC and AlSi7Mg/Al2O3. They concluded that the machining characteristics of metal matrix composites by WEDM are similar to those which occur in the base material (AlSi7Mg aluminum alloy); but the machining feed rate of WEDM for cutting composites significantly depends on the kind of reinforcement.

Tosun and Cogun [99], investigated the effect of machining parameters on wire wear ratio based on the weight loss of wire in WEDM. They introduced a statistical approach to determine the optimal machining parameters for minimum size of wire craters in WEDM. It was observed experimentally that the increasing pulse duration and open circuit voltage increase the wire wear ratio (WWR); whereas the increasing wire speed decreases it. The variation of workpiece material removal rate and average
surface roughness were also investigated in relation to the WWR. The variation of the WWR with machining parameters was modeled statistically by using regression analysis technique. The level of importance of the machining parameters on the WWR was determined by using analysis of variance (ANOVA) method.

K H Ho, S T Newman et al [37] reviewed the vast array of research work carried out from the spin-off of EDM process to the development of the WEDM. They reported on the WEDM research involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. The paper also highlights the adaptive monitoring and control of the process, investigating the feasibility of the different control strategies of obtaining the optimal machining conditions.

Fuzu-Han et al [30] studied the influence of various machining parameters on surface roughness. It has been communicated that the surface roughness can be controlled by controlling discharge energy per pulse which can be given by equation (2.20).

\[
E = \int_{0}^{t_0} u(t) i(t) \, dt
\]  

(2.20)

where, \( t_0 \) = discharge duration, \( u(t) \) = is discharge voltage, \( I(t) \) = discharge current, \( E \) = pulse energy per discharge

Increasing discharge energy per pulse increases surface roughness and MRR. They also concluded that under same discharge energy per pulse machining with short pulse and longer pulse leads to surface of almost same surface roughness, but with different morphology. Polarity also has effect on surface roughness and MRR. Reversing polarity we can get smooth surface as metal removal from workpiece reduces, but electrode wear rate increases. They further communicated that if constant pulse interval is maintained for same discharge energy by varying pulse on time, we can vary frequency leading to change in MRR and surface roughness.

I Puertas, et al [78] conducted experiments on Tungsten carbide to find out influence of various parameters on surface roughness and metal removal rate, using EDM. They observed that pulse time, pulse intensity factor, have great influence on surface and metal removal rate; as when pulse time and intensity are increased MRR
and Ra value also increase. Therefore to obtain good surface finish in case of tungsten carbide low values of pulse time should be used for intensity and pulse time.

**S. Keith Hargrove** et al [51] studied the effect of WEDM process while machining AISI4340. They concluded that the main cause of surface degradation is the thermal damage due to heat of spark which is a resultant of pulse on time, peak voltage and peak current. In order to justify their comments they carried out microscopic observation of specimens for recast layer, micro cracks and voids. They also concluded that, one can perform rough cut with high spark energy followed by an cut with low energy, leading to reduction in depth of thermal damage layer.

**Mustafa Ilhan Gokler** et al [69] carried out experiments on different grades of steels such as 1040, 2379, 2738 with different thickness, and combination of different set of parameters. For each set of experiments, the surface roughness was measured and plotted against the process parameter combination. The charts obtained can help further researchers as they incorporate the effects due to different parameters, material and its thickness on surface roughness. This prevents trial and error method (normally used) for selection of parameters.

**Aminollah Mohammadi** et al [3], conducted experiment on cemented steel in order to find out effect of process parameters on surface roughness. Taguchi’s technique was used for experimental design, significant factors were analyzed by ANOVA, on the basis of signal to noise ratio. They have concluded that power is only one significant factor, which influences surface roughness of components manufactured using WEDM.

**Ozlem Salman**, et al [72], conducted the experiments to find out effect of different electrode materials on surface roughness of EDM ed parts using Cu, WC Cu, graphite electrode with different materials. No significant effect was observed on roughness except for processing tungsten carbide; where it shows considerable different values of surface with different electrodes. They have also developed mathematical relationship between process parameters and surface roughness, which predicts surface roughness values for a combination of parameters very close to actual ones.

**Donald C. Zipperian** [120], discussed in detail the procedure for proper metallographic specimen preparation, as below:
Chapter 2 Literature Survey

1) Documentation: The initial specimen condition and the proceeding micro structural analysis; metallography provides a powerful investigation tool.

2) Sectioning and Cutting: Depending on the area of sample to be studied and for easy handling, the samples need to be cut. Proper cutting process is to be used so as to ensure that, the minimum damage is observed in the microstructure.

3) Mounting: The mounting operation has important functions like, it protects the specimen edge and maintains the surface integrity; fills voids in porous material, improves handling of irregular shaped samples. The majority specimen mounting is done by encapsulating the specimen into a compression mounting compound, casting into ambient castable mounting resins and gluing with thermoplastic glues.

4) Polishing: Rough polishing using grinding wheel is done in order to remove damage produced during cutting and planer grinding. It is followed by smooth polishing with hands using a polish paper or emery grade paper.

5) Etching: The purpose of etching is to optically enhance micro structural features such as grain size and phase features. Chemical etching selectively attacks specific micro structural features. Suitable etchant depending on the material being observed is to be selected.

6) Metallographic analysis: Metallography of microstructure provides the information regarding phase structure, grain size, solidification structure, casting voids, cracks etc.

7) Further the hardness measurement, tensile strength measurement etc. can be carried out as per requirements.

A systematic methodology was defined which is helpful for sample preparation.

Further the manuals [25], provided by Electronica were referred in order to get an in depth knowledge of the machining capabilities (as the machine used for experimentation is of Electronica make). The factors such as wire compensation and over cut (not mentioned by any of the previous researchers), need to be attended as they lead to inaccuracies in the machined component. Proper care while programming in ELAPT (the language compatible with WEDM, Electronica make) needs to be taken in order to avoid these inaccuracies which are undesirable. The
inaccuracy have been measured in terms of over cut and taper which is considerably higher on the inner cuts compared to starting surface of the cut.

As the material selected for current study is tungsten carbide necessity of shortly reviewing its details (though briefly) was felt and hence this part of literature survey is dedicated towards review of tungsten carbide.

2.4 Literature based on Carbide

2.4.1 Tungsten Carbide

Tungsten monocarbide (WC, usually referred to as tungsten carbide) was discovered by Henri Moissan in 1893, during his search for a method to make synthetic diamonds [90]. He found that the hardness of WC is comparable to that of diamond. This material however, proved to be so brittle that its commercial use is seriously limited. Subsequent research was focused on improving its toughness, and significant contributions to the development of cemented carbides were made in the 1920’s by Karl Schröter [29, 90].

Employing cobalt (Co) as a binding material, Schröter developed a compacting and sintering process for cemented tungsten carbides (WC-Co) which is still widely used to manufacture WC-Co composites. Tungsten carbide is sintered material made up of carbide (WC) granules held together by cobalt (Co) binder. The cobalt binder glues and pulls the carbide granules together under great tension. Carbide granules are brittle and hard while cobalt (Co) is ductile and tough. Most of the further developments were modifications of the Schröter’s process, involving replacement of part or all of the WC with other carbides, such as titanium carbide (TiC), tantalum carbide (TaC), and/or niobium carbide (NbC) [54].

Following are the types of carbides commonly used in industries:

1. Tungsten compounds especially in cemented carbide form, are preferred materials for machine tools. The structure contains a metal matrix where carbide particles are the aggregate and a binder material like cobalt/nickel serves as matrix. The binding material not only forms lattice structure, but also enhances some properties of material like machinability, etc.

2. Titanium carbide in cemented form is another widely used material for tools. Metal Aluminides like Ni$_3$Al increase their strength at elevated temperature.
3. Silicon carbides due to their attractive mechanical properties and chemical stability at elevated temperature are well suited for high friction applications. Silicon Carbides find some typical industrial applications such as, tribological, structural components and electronic applications.

1. Straight grades [54]

Straight grades, sometimes referred to as unalloyed grades, are nominally pure WC-Co composites. They contain 3-13 w/o (weight percent) Co for cutting tool grades and up to 30 w/o Co for wear resistant parts. The average carbide particle size varies from sub-micron to eight microns. Straight grades are used for machining cast iron, nonferrous alloys, and non-metallic materials.

2. Alloyed grades [54]

Alloyed grades are also referred to as steel cutting grades or crater resistance grades, which have been developed to prohibit catering during the machining of steel. The basic compositions of alloyed grades are 3-12 w/o Co, 2-8 w/o TiC, 2-8 w/o TaC, and 1-5 w/o NbC. Average carbide particle size of these grades is between 0.8 and 4 μm.

2.4.2 Physical Properties [54]

The physical properties of these composites depend on micro structural features such as, grain size, size distribution, grain shapes, orientation, disorientation, and the volume fraction of the carbide phase. The hardness, toughness, and fracture strength of WC-Co composites range from 850 to 2000 kg/mm² (Vickers hardness, HV), from 11 to 25 MPa (critical stress intensity factor, plane strain fracture toughness, KIC), and from 1.5 to 4 GPa (transverse rupture strength, TRS), respectively. Also, it is known that the wear resistance of these materials is five to ten times higher than that of a typical tool steel. It should be noted at the outset that while the relationships between the mechanical properties and the mean grain size, carbide volume fraction are known, the influence of grain shape, size distribution, and interface character distribution are not yet clear. Furthermore, it is not clear how changing these micro structural characteristics beyond normally observed ranges alters the properties of the composites.

Tungsten carbide cements (Mainly WC) (WO₃+ CO₂): Energy of formation of oxygen is 349 kJ/mole at 273K. An older and successful way of overcoming the
brittleness of ceramics is to make a sort of composite called a cermet. The best example is the cemented carbides used for cutting tools. Brittle particles of tungsten carbide (WC) are bonded together with a film of cobalt (Co) by sintering the mixed powders. If a crack starts in a WC particle, it immediately runs into the ductile cobalt film, which deforms plastically and absorbs energy. The composite has a fracture toughness of around 15 MPa, even though that of the WC is only 1 MPa.

Michael Schretter et al [64] emphasized on development of application-specific grades. The success of these grades led to application of tungsten carbide in more difficult wear situations. They also commented that it is possible to combine high hardness with the necessary toughness. Precise analysis of the application conditions allows use of the best possible hard metal material for frictional wear and impact applications. Cobalt (Co) has proven to be the optimal binding metal for tungsten carbide (WC) as it overcomes the problem of brittleness. In general for WC-Co carbides, with an increased WC content, the carbide becomes harder, more brittle and more wear resistant; with an increased binding-metal content it becomes less brittle and tougher (impact resistant).

By varying the grain size and the Co content, a wide combination of properties can be obtained, allowing applications ranging from inserts for mining tools, metal working tools and wear parts to the machining of cast iron, non-ferrous metals and non-metals. The core material for the manufacturing of hard metal is tungsten oxide. Tungsten powder is produced through a hydrogen atmosphere-reduction process. After precise analysis of various parameters, carbon is added and tungsten carbide is produced at a temperature of 1,500°C to 1,700°C.

**Summary of Literature Survey**

WEDM process is dependent on wide range of process parameters as well as the material being processed also affects the performance. All the process parameters individually affect the process; but the pulse related parameters viz. current, voltage and spark on time predominantly affect the output parameters like surface roughness, material removal rate and the surface quality which has been confirmed by various researchers [31, 55, 74, 80]. It is basically a thermal process wherein erosion of material is due to melting/evaporation which is result of high temperature provided by
the sparks. The temperature attended affects the quality and condition of the surface obtained.

The parameters such as voltage, current and spark time predominantly monitor the intensity of energy incident. The rupture/removal of materials depend upon the temperature developed due to energy-density and the interaction-time. Excessive temperature leads to post process issues such as heat affected zone, recast layer and cracks. Also the dielectric and its flushing rate have a significant role in formation of recast layer [39]. The temperature leads to wire breakage which makes the process unstable [79, 81, 108 and 109]. The energy incident decides the intensity of spark which along with the interaction time decides the crater depth and size. The crater size governs the surface roughness and amount of material removed. It is always pertinent to measure the actual pulsing voltage and current characteristic of the effective pulse through suitable circuits, to enumerate any theory with practice. It has also been verified experimentally that the wire material governs the stability of spark/process and affects the MRR. Hence, the pulse related parameters are considered for current study and an appropriate circuit has been developed in order to measure the current, voltage and the number of sparks.

Due to high hardness of Tungsten carbide conventional machining processes are uneconomical and results obtained are unsatisfactory. WEDM is only one practicable and widely accepted option for machining Tungsten carbides. Cobalt is highly conductive while the carbide granules, resists the flow of current. Thus, the current from the spark flows through the binder material and around carbide granules. The spark vaporizes the cobalt/binder material and disintegrates the carbide grains on tiny spots on the surface, and the water vapour bubble caused by the spark collapses violently. The deionised water flushes away the melted cobalt and pieces of WC grains. This is a challenging and typical erosion characteristics and this aspect has been focused while analyze the thermal modeling developed.

In view of the detailed literature survey carried out; the necessity of developing a hyperbolic heat conduction equation has been felt and is addressed in Chapter 3.