Chapter 4

Electric Discharge Machining of Al-(SiC)p Composites

4.1 Need for EDM of Al-(SiC)p Composites

Metal Matrix Composites are gaining increasing attention in the aerospace, defense and automotive industries. These applications require good performance under high cycle fatigue loading conditions. The system of particulate SiC reinforced aluminium alloys is popular out of many metal matrix composites system currently in use or under investigations. The availability of relatively inexpensive sources of SiC, along with the ability of discontinuous MMC system to be fabricated by traditional processes such as extrusion, rolling and powder metallurgy, combined to make the Al / SiC system attractive.

Interesting studies on the machining of MMC materials have been conducted using a variety of cutting tool material by traditional methods. (Capelloe et al 1999 and Hooper, 1999). Material removal is due to chip formation caused by shearing, micro fracture and dislodging of individual grain. The cutting forces required in machining composites cause rapid tool wear as well as decreased efficiency and loss of dimensional accuracy (Ricci 1987 and Cronjager 1992). In addition the material removal mechanism in MMC’s often cause surface flaws and residual stresses.
Hence the reinforced components often make them difficult or uneconomical to machine by traditional methods. Consequently non-traditional machining process such as Electrical discharge machining (EDM) have become candidates for processing of MMC’s. Recent studies conducted by Ramulu (1997,1988,1991) Arivazaghan and Rajadurai (1997) demonstrated that SiC reinforced aluminum metal matrix composites can be machined by the EDM process. Hence a study in EDM of composites is essential to get thorough knowledge about its efficiency in machining these materials. In this chapter a basic study involved in EDM of these composites and the different methods used to increase its efficiency are presented.

4.2 EDM OF Al-(SiC)$_p$ COMPOSITES WITH ROTARY ELECTRODE

Electrical discharge machining (EDM) is one of the non-traditional techniques widely used on electrically conducting materials such as high strength/die steels. It was estimated that EDM accounts for about 7% of all machine tool steels (Moser 2001). The technology makes sense in many industrial applications because of its ability to machine hard materials that are otherwise difficult if not impossible to machine by conventional processes. It also has the ability to produce geometrically complex shapes.

Frank Muller and Monagan (2001) reported that even though the introduction of SiC in the Al matrix improved its hardness, while electrical discharge machining of these composites, the MRR was reduced to larger extent. The decrease in MRR was due to the insufficient debris removal at the machining gap. To increase its speed and MRR, a large electrical current
discharge is normally used, but this inevitably compromises the dimensional accuracy of the machined product (Tamg et al 1995). Therefore an EDM system that allows an accurate and timely response to the demands of multiple small lot production has become essential primarily for the reason of efficiency but also for defect free production.

The EDM process can be very unstable due to arcing when too much debris clogs the gap. Researches have been conducted on other mean of clearing the debris from the gap between the electrode and work piece without using the rotating electrode. Kagaya et al (1986) and Sato et al (1980) have presented the micro hole drilling and boring of stainless steel and other materials by using rotating electrodes.

Soni et al (1993, 1994) used rotary EDM to machine titanium alloy and die steel with a solid electrode. From these experiments it was confirmed that the rotary motion imparted to the electrode has improved the MRR and surface finish. Hence in this chapter an EDM process with rotary electrode was used to machine Al-SiC composites to improve its machining efficiency

4.3 EXPERIMENTAL DETAILS OF ROTARY EDM

The experiments were carried out using an Electronica-M-T-3822 machine, which was equipped with transistor switched power supply. The electrode was fed downwards under servo control into the work piece. Figure 4.1 depicts the experimental setup. Copper and brass cylindrical electrodes of 12mm diameter were used as tool. Kerosene was used as a dielectric fluid. The dielectric fluid was circulated with a pressure of 35 N/cm²
by lateral flushing. MRR is proportional to the product of the energy transferred per pulse and the pulse frequency. Changing the pulse current at a constant frequency varies the energy of the pulse. Hence all the experiments were performed with pulse current, pulse duration and volume percentage of SiC as variables. The pulse currents selected for this study were 5, 8 and 11 A. The selected pulse durations were 88, 176, and 264 microseconds (μs).

Blind hole drilling operations were carried out for a depth of 10mm on aluminium alloy (LM25) reinforced with 20 and 25 volume percentage of SiC particle. The composition of the alloy is given in Table 4.1. The MRR and TWR were calculated by measuring the average amount of material removal. The MRR and TWR were measured by using an electronic balance of sensitivity of 0.1mg. The surface roughness of the machined surfaces was measured with the help of Surtronic 3+. The Ra values are used to quantify the surface roughness. The cut off length for each measurement was 0.8mm. The topography of the EDMed surfaces was analyzed with photographs. The recast layer of the EDMed surfaces was analyzed with the transverse section of EDM surfaces. An optical microscope was used to obtain magnified view of the transverse section of the EDMed surfaces.

**Table 4.1 Composition of Aluminium Alloy**

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>6.25-7.5%</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.2-0.4%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>Balance</td>
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</table>
Figure 4.1 Schematic diagram of the rotary EDM
4.3.1 Rotating Tool Assembly

The primary objective of the present work is to study the effect of rotary EDM on the machining efficiency of the EDM process. Several works has been carried out in this aspect of machining. Ramulu et al (1988, 1989) used modified EDM to cut SiC-TiB2 and Al/SiCw with plate electrode. Soni et al (1993, 1994) used rotary EDM to machine titanium alloy and die steel with a solid electrode. Amongst these studies, little research was found on using rotary EDM with brass and copper electrode. The conventional EDM techniques lack axial rotation during machining. However, the modern technical fabrication system has compensated for the limitation of EDM. The revised facility of EDM imparts a rotation to the electrode in its vertical axis. Therefore a mechanism to rotate the tool was developed.

The electrode was rotated and sunk simultaneously to machine a hole in the work piece. An electric motor was used to rotate the electrode (tool). A V belt was used to transmit the power from the motor to the electrode. The speed of the rotating electrode was controlled with the help of a regulated power supply. Figure.4.2 shows the schematic diagram of the rotary electrode set up.

A mechanical tachometer was used to measure the speed of the rotating electrode. Experiments were conducted to identify the variables that are likely to have significant influence on the responses. In this study M.R.R, T.W.R and Surface roughness were considered as responses. These values for the stationary and rotating electrode were compared.
Figure 4.2 Schematic diagram of rotary EDM electrode setup
4.4 RESULTS AND DISCUSSION OF EDM OF Al-(SiC)_p COMPOSITES WITH ROTARY ELECTRODE

The performance of an EDM process depends on the strength of the pulse produced and pulse frequency. In addition to this the amount of volume percentage present in the base alloy of the Al-SiC composite also significantly affects the material removal and electrode wear. Hence in the present study the effect of variables namely polarity, current, electrode material, volume percentage of SiC, pulse duration and rotation of electrode on MRR, TWR and surface roughness of Al-20%SiC and Al-25%SiC composites was studied and the results are as follows.

4.4.1 Material Removal Rate (MRR)

Figures 4.3 and 4.4 represent the variation of MRR with discharge current for copper and brass electrodes while machining Al-(SiC)_p. Figure 4.3 depicts the MRR with discharge current for 20-volume % SiC particulate and the variation of MRR with discharge current for Al-25% SiC is shown in Figure 4.4. According to Figures 4.3 and 4.4, the MRR was more when the electrodes were at positive polarity than at negative. Yan et al (1997) and Wang (2000) observed a similar phenomenon which confirms that using positive electrode polarity in EDM causes a higher MRR under higher discharge energy. This phenomenon might be attributed with the transfer of energy during the discharging process (Wang, 2000). It was inferred from the Figures 4.3 and 4.4 that the MRR with brass electrode was more than the copper electrode with increasing pulse current irrespective of the electrode polarity and volume percentage of SiC. This might be due to the high specific resistance with the brass electrodes (6.4x10^-4 Ω cm) than the copper electrode (1.71x10^-4 Ω cm), which increase the spark intensity and the electrode gap (Wang 2000).
Figure 4.3 Effect of discharge current on MRR of Al-20% SiC

Figure 4.4 Effect of discharge current on MRR of Al-25% SiC
Figure 4.5 shows the effect of pulse duration on MRR on different electrodes. The MRR decreased with the increase in the pulse duration. A short pulse duration caused less surface vaporisation whereas long pulse duration may cause the plasma channel to expand and to decrease the energy density for the workplace. In EDM, the dielectric fluid acts as an insulator. The electrode (tool) and the work piece convect away a small amount of heat generated by the discharges and flushes off the discharge by products from the electrode gap. As machining proceeds the concentration of the debris in the gap increased rapidly. (Wang 2000).

The effect of rotation of electrode in comparison with the stationary electrode is shown in Figure 4.6. For any given current the MRR was more for the rotary electrode than stationary. This increase in MRR was due to the effective flushing of the rotary electrode. The rotation of the electrode imparts a whirl and effectively flushes the gap (resulting in increased MRR) and the machined surface was better than that obtained with a stationary electrode. The debris in the machining gap consists of products of dielectric decomposition and eroded metallic particles. The conducting particles remain suspended in the gap and exert significant influence on the dielectric breakdown characteristics. The ignition time delay \( T_d \) was a function of the particle concentration and the relationship was given by

\[
T_d = C \ln\left(\frac{N_c}{N_a}\right)
\]  

(4.1)

Where \( C \) is a constant, \( N_c \) is the critical particle concentration and \( N_a \) is the average particle concentration.
Figure 4.5 MRR Vs Pulse duration

Figure 4.6 Effect of electrode speed on MRR
Effective spark discharges are characterized by a finite time delay before the pulse current reaches the nominal value. When the \( N_{cr} \) equals to \( N_a \), then the plasma channel preferentially takes the same path as that of the previous pulse, which was not completely localized. This leads to process instability due to inadequate flushing in the case of stationary electrodes. When the cylindrical electrode rotates, due to the centrifugal action, a new layer of dielectric fluid was thrown in to the machining gap. This induces a conducive atmosphere for effective discharge and encourages process stability. The enhanced discharge increased the MRR and efficiency (Koshy 1993). The rate of debris formation is increased at higher pulse current whereas in the case of rotary electrode; a small whirl imparted to the electrode brings about a significant increase in MRR. Insufficient ejection force causes part of the molten metal to remain as a recast layer. The recast layer reduces the MRR in the case of stationary electrode (Koshy 1993).

### 4.4.2 EWR

The EWR of electrode was obtained from the weight difference of electrode before and after the performance trial.

\[
EWR = \frac{(W_i - W_f)}{((\text{density of electrode} \times t) \times 1000)}
\]

\( W_i \) = initial weight of electrode in grams.

\( W_f \) = final weight of electrode in grams

\( t \) = period of trial in minutes
Figures 4.7 and 4.8 show the curves of EWR versus discharge current for different polarities of copper and brass electrode. The EWR on the negatively connected electrode was less than the positively connected electrode irrespective of the electrode material and the volume percentage of SiC. This is due to the increase in MRR with the positively connected electrode. It was also observed from the Figs.4.7 and 4.8. that as the current increased, the EWR also increased irrespective of the electrode material and polarity. A high current may generate an increased discharging energy and cause a high electrode wear. The increase in MRR increases the debris at the gap, which increases the wear on the electrode [Wang and Yan, 2000]. The EWR was more in brass electrode than the copper electrode for a particular current and pulse duration since the MRR was more with brass electrode. Ramulu et al (1989) also experienced the high wear rate with brass electrode. The melting point of brass electrode used in this investigation is lower than the copper electrode and hence, it resulted in high wear rate. On machining Al-SiC with different volume % of SiC, the EWR was more as the vol % of SiC increased. This increase in wear was due to abrasive nature of SiC particle and decreased conductivity of the material Fig 4.9. shows the relationship between EWR with pulse duration. The EWR decreases in an inverse relation with pulse duration as similarly observed by Wang and Yan (2000) . This phenomenon is attributable to the brass electrode which has a good thermal conductivity. Thus heat generated during the machining was easily removed. The heat removal facilitates a reduction of the temperature around the surface of the electrode for a long pulse duration, which reduces the EWR.
Figure 4.7 EWR Vs Discharge Current on machining Al-20%SiC

Figure 4.8 EWR Vs Discharge Current on machining Al-25%SiC
The EWR on machining different volume % of SiC with brass electrode in rotating condition is shown in Figure 4.10. The EWR on machining with rotary electrode was less in comparison with stationary electrode. In conventional electrode, the loosened SiC deposition occurred in a localized area, which inhibited high electrode wear. Frequent arcing during static EDM was also found to add carbon deposits on the electrode surface.

In a rotary electrode, the carbide deposition was spread over a larger area on the circumference. The rotation of the electrode also contributed better heat transfer from the electrode thus bringing down the electrode surface temperature. It is also probable that the layer breaks down during the course of rotation before re-depositing in the successive cycles. Also the electrode wear was uniformly distributed over a larger area on the circumference of the rotary electrode, whereas it was confined to a local area in stationary electrode.

Figure 4.9 Progress of EWR with pulse duration
4.4.3 Surface Roughness

Surface Roughness was an important process response, which dictates the conditions with which the component has to be machined. If surface finish was the criterion then the material must be machined with low MRR. When the electrodes are connected at positive polarity, the craters on the workplace surface largely have an irregular profile, whereas for a negatively polarity, the craters are flat.

The variation in surface roughness with different pulse current levels and for different polarities of the electrodes were shown in Figures 4.11 and 4.12. Figure 4.11 depicts the variation of surface roughness with discharge current for Al-20% SiC and Figure 4.12 depicts the same for Al-25% SiC. It was also observed from the above Figure that the increase in discharge current
resulted in an increase in Ra value irrespective of the electrode, and volume percentage of SiC. This event is due to the increase in discharge energy, which subsequently causes a larger crater on the surface of the body. The increase in volume percentage of SiC effected an increase in the roughness value which was possibly due to the voids left on the surfaces by the SiC particles debonding (Koshy 1993 and Wang 2000).

Figure 4.13 presents the SR versus pulse duration under peak current. Increase in pulse duration resulted in less SR. The long pulse duration in the machining process expands the plasma channel, decreases the energy density and therefore induces a shallow crater on the surface of the workpiece (Wang 2000).

The variation in surface roughness with discharge current for various electrode rotational speeds is given in Figure 4.13. The roughness value decreases with increasing speed of the electrode at constant pulse current. The phenomenon of arching, which occurs frequently with a stationary electrode impairs the work surface.

The energy contained in a profile pulse is given by

\[ E = \int_{t_d}^{t_p} I(t) V(t) \, dt \]  \hspace{1cm} (4.3)

where \( t_d \) is the ignition time delay, \( t_p \) is the pulse on time, \( I(t) \) is the gap current, and \( V(t) \) is the working voltage. With increased peripheral speed of the electrode, the ignition time delay increases, thus bringing down the energy
Figure 4.11. Variation of Surface Roughness with Discharge Current of Al-20%SiC

Figure 4.12. Variation of Surface Roughness with Discharge Current of Al-25%SiC
Figure 4.13 Effect of electrode speed on Surface Roughness

transferred through the individual discharges for material removal. This diminishes the crater dimensions to give a better roughness value. Under conditions of effective flushing, the adherence of resolidified eroded particles on the work surface is reduced and the resulting surface presents a better finish than that of the one obtained with a stationary electrode. In the latter case, an increase in MRR is possible only at the expense of surface finish. On the contrary, in a rotary electrode the increase in MRR is accompanied by the production of a better surface

4.4.4 SEM study on EDM surface

Figures 4.14 and 4.15 shows the SEM pictures of the EDM surfaces of the Al-20% and Al-25% composites with copper and brass electrodes
respectively. Figure 4.4a shows the topography of EDM surface of Al-20% SiC while machining with stationary copper electrode and close view of the surface in Figure 4.14b. Figure 4.15a and 4.15b shows the topography and close view of EDM surface of Al-25% SiC while machining with stationary copper electrode respectively. The topography and close view of the EDMed surfaces obtained while machining Al-20% SiC with stationary brass electrode is shown in Figure 4.16a and 4.16b respectively. Figure 4.17a and 4.17b shows the same for the Al-25% SiC composites.

The EDM machined surface is composed of many microscopic craters associated with the random spark discharge between the electrodes. The crater structures with its high peaks adjacent to valleys of removed material are clearly evident. Comparing SEM pictures Figure 4.14 and 4.16 indicate that the formation of crater as a result of material removal process in EDM It was observed from the Figures that the size of the crater with brass electrode was more than the copper electrode. The close view of the EDM surfaces (Figures 4.14b and 4.16b) shows the recast layer of these composite materials. The feature of this recast layer is the formation of voids due to the imperfect joining of molten aluminium droplets. The rapid cooling rate results change in the microstructure of the EDMed surfaces which is evident as a white spot in the close view of the Figures.

The material removal of the composite material occurs through the process of melting and vaporization of the matrix material around the ceramic particle and at some point the entire SiC particle becomes detached. The detachment of SiC is clearly visible in Figures 4.15a and 4.17a. The close view of these Figures indicate that the void formation is more with increase in SiC
content in the base alloy. The SEM establishes that the decrease in number of crater formation and increase in number void formation due to the imperfect joining of molten droplets on the EDMed surface machined with stationary condition resulted in decreased MRR and increase in surface roughness value.

The EDM process can be termed as a chip forming process where the chips are flushed away by a liquid dielectric. The size and density of the debris dictate the material removal rate and the quality of the electric discharge. As explained earlier the SiC particles in Al-(SiC)ₚ composites are not melted but they are removed from the matrix. The removed SiC particle provides a shield to the Al matrix. This shielding effect of the ceramic material is followed by a decreased material removal with increased SiC particle content. The exposure of entire SiC particles during EDM while machining Al (SiC)ₚ MMC results in a tendency for arcing to occur. This arcing arises due to the inadequate flushing conditions at the machining gap. Under the inadequate flushing conditions SiC particles trap sufficient molten aluminium droplets to form a conductive path between the electrodes. This conductive path created thus leads to abnormal arcing which reduces the material removal rate. (Hung et al 1994). To improve the efficiency of the EDM process by improving the debris removal a rotary electrode was developed.

The rotary motion to the electrode provides a centrifugal force to the electrode which removes the debris. The debris which has the removed SiC particles from the matrix is washed away by the dielectric which prevents the arcing of the electrode. The effect of effective debris removal on material removal was analyzed with the help of SEM photos.
Figure 4.14 SEM photograph of Al-20% SiC EDM surface machined with copper electrode (a) Topography (b) close view
Figure 4.15 SEM photograph of Al-25% SiC EDM surface machined with copper electrode (a) Topography (b) close view
Figure 4.16  SEM photograph of Al-20% SiC EDM surface machined with brass electrode (a) Topography (b) close view
Figure 4.17  SEM photograph of Al-25% SiC EDM surface machined with brass electrode (a) Topography (b) close view
Figures 4.18 and 4.19 show the SEM picture of topography and close view of the EDMed surfaces with rotary brass electrode. Figure 4.18a represents the topography of the EDM machined surfaces of Al-20% SiC with rotary brass electrodes and the close view of the same is presented in Figure 4.18b. The topography and close view of the EDMed surface of Al-25% SiC while machining with brass electrode is shown in Figures 4.19a and 4.19b respectively. In comparison with Figures of stationary electrode (Figures 4.16 and 4.17) the EDM surfaces of Al-20% SiC and Al-25%SiC shows increase in frequency of crater. This increase in frequency of crater leads to the conclusion that the material removal rate increase with imparted rotary motion to the electrode. As discussed earlier, the decrease in MRR with stationary electrode was attributed to the shield effect of SiC particles during machining. The insufficient flushing condition at the machining gap was cited as the reason for this shielding effect (Frank Muller et al 2000). With the imparted rotary motion to the electrode, the unmelted SiC particles are washed away by the whirling action of the dielectric. The removal of the shielding effect of SiC particles exposes the original composite matrix to the plasma. The close view of the surfaces indicates that voids are formed due to the imperfect joining of molten droplets (Figure 4.18 b and Figure 4.19b). These voids are more with Al-25% SiC than Al-20%SiC. The effects of gas bubbles are also obvious in the recast layer, where they produce a kind of porosity. This porosity is a consequence of the gas / vapour resulting from the extremely high temperature which is trapped during the rapid resolidification. This phenomenon was also observed by Hung et al (1994), Muller et al(2000) and Le roux et al (1993). Hence from the SEM study, it was observed that EDMed surfaces machined with rotary electrode has increased number of crater formation and better joining of the molten aluminium droplets in comparison.
Figure 4.18 SEM photograph (a) Topography and (b) close view of EDM surface of Al-20% SiC with rotary brass electrode
Figure 4.19 SEM photograph (a) Topography and (b) close view of EDM surface of Al-25% SiC with rotary brass electrode
with EDMed surfaces machined with stationary electrode. The increased number of crater formation and better joining of molten aluminium droplets effected an increase in MRR and better surface roughness with rotary electrode than station electrode.

4.4.5 SEM Study of Electrode

The effect of rotation of electrode on electrode wear was analysed with SEM photographs. The SEM picture of surface of the brass electrode when they are in stationary and rotating condition is shown in Figure 4.20 and 4.21 respectively. The surface condition of the brass electrode in stationary condition (Figure 4.20) indicates that erosion of the surface and adherence of the melted surface as the result of arcing whereas the surface of brass electrode surface in rotary condition (Figure 4.21) does not show any trace of adherence of any meted material. The above phenomenon indicates that the tool surface was not subjected to severe arcing which reduces the wear rate. Hung et al (1994) analysed the Al-SiC EDM surface with SEM analysis and found that there was no trace of electrode material on or diffusing in to the EDM surface. Erosion was the main mechanism for the wear on the electrode.

4.5 MATHEMATICAL MODELLING AND OPTIMIZATION

In order to achieve economic of EDM process, optimal cutting condition have to be determined and so mathematical models need to be established. Multiple regression analysis is one such method widely used for the various types of statistical analysis. The objective of using multiple regression analysis is to learn more about the relationship between several independent
Figure 4.20 Topography of Stationary Brass Electrode

Figure 4.21 Topography of Rotary Brass Electrode
and dependent variables. Karthikeyan et al (1999) have optimized the electrical
discharge machining parameters based on the multiple regression analysis
models. Lin et al (2000) used neural network analysis to optimize the process
parameters of electrical discharge machining process.

Marty (1977) has modeled the electrode tool wear in EDM process
with multiple regression analysis and validated that with the experimental
values. Sreejith et al (1999) has conducted machining studies on composite
materials and to optimum machining parameters are analyzed using
mathematical model based on multiple regression analysis.

Jian et al (1999) has modeled the abrasive flow machining process
using multiple regression analysis and neural network and the effect of
machining parameters on material removal rate and surface finish was
analyzed. Uday da bade et al (2003) has used multiple regression analysis to
analyze the various parameters affecting surface roughness in the machining
studies using round insert milling cutter. The efficiency of EDM process
depends on material removal rate, surface finish of the work piece and tool
wear of the electrode. In this study, a mathematical model was developed
relating the various process parameters of EDM. The modeled equations are
then optimized using Genetic Algorithm.

4.5.1 Mathematical Modelling

The purpose of mathematical modeling relating the response and their
process parameter was to facilitate the optimization of machining MMC’s in
EDM. The basic model assumed was
\[ \text{MRR} = \alpha I^a T^b S^c \]  

(4.4)

where \(a, b, c,\) and \(\alpha\) are constants and

\(I = \) current in amperes \\
\(T = \) pulse duration in microseconds \\
\(S = \) speed of rotation in rpm

Taking log on both sides,

\[ \ln \text{MRR} = \ln \alpha + a \ln I + b \ln T + c \ln S \]  

(4.5)

The same model is valid for tool wear rate and surface roughness and the respective constants for both of them, are found out in a similar way.

Thus, the objective function is:

\[ \text{MRR} = \alpha I^a T^b S^c \]  

(4.6)

The constraints are

\[ \text{TWR} = Y I^d T^e S^f \]  

(4.7)

\[ \text{Ra} = Z I^g T^h S^i \]  

(4.8)

Using multiple linear regression, the above equation is solved and, the values of \(X, Y, Z,\) \(a, b, c, d, e, f, g, h, j\) are obtained and hence the model was established. The constants of regression equations are listed in Table 4.2
4.5.2 Optimization

Optimization of machining characteristics of Al/SiCp composites in EDM is to find an optimal solution for a given objective subjecting it to the constraints. If the objective is to maximize the MRR for different volume fraction of composites and the constraints involved are minimum TWR and surface roughness, then linear programming is a strong tool to optimize. In this study the mathematical models were optimized using Genetic Algorithm programme by treating the problem as a linear programming problem.

4.5.3 Genetic Algorithm (GA)

GAs are search algorithms based on the mechanics of natural selection and natural genetics. Simple GAs have been applied successfully to single objective optimization problems. A GA has the characteristics of maintaining a population of solutions and can search in a parallel manner for many non-dominated solutions. It requires no gradient information and produces multiple optima rather than a single local optimum. The flow chart of a GA is shown in Figure 4.22.

Genetic algorithm starts with an initial set of random solutions called population. Each individual in the population is called a chromosome, representing a solution to the problem at hand. Chromosome is a string of symbols, it is usually, but not necessarily, a binary bit string. The solution code may also be of real numbers, in which case the GA is called real coded GA. The initial population evolve through successive iterations are called generations. During each generation, the chromosomes are evaluated, using some measures
Figure 4.22 Flow chart of the GA
of fitness. To create the next generation, new chromosomes, called offspring are formed by either crossover operator or by modifying a chromosome using a mutation operator. Cross over selects some of the parents and offspring chromosome based on the fitness values, and mutation operator rejects the other so as to keep the population size constant form a new generation. Fitter chromosomes have higher probabilities of being selected. After several generations, the algorithms converge to the best chromosome, which hopefully represents the optimum or sub optimal solution to the problem.

The problem is of constrained optimization in nature. The strategy followed here is, rejecting strategy, where the infeasible chromosomes are rejected. The random number generator is based upon the logic developed by Goldberg (2000). The function assigns a basic value (less than 1) from the user, and generates a set of random numbers, based upon the value for each generation the seed values, also changes. The initial population is generated with this random number generator. The infeasible chromosomes are rejected and the population consists only of feasible chromosomes. The initial population undergoes crossover and mutation in the successive generations. The population size is maintained a constant throughout.

The mutation used is, dynamic mutation which gives high precision values. In mutation not the whole chromosome is changed but only a characteristic only on a variable, of the chromosome. Random numbers are generated for each gene of each chromosome in the population. The gene of chromosome with a random number less than the mutation probability is chosen for mutation. Such mutated genes are checked for boundary conditions and the constraints. If they don’t satisfy the conditions, they are rejected. Since the
<table>
<thead>
<tr>
<th>Material</th>
<th>Electrode</th>
<th>Polarity</th>
<th>Objective function</th>
<th>Constraints</th>
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</thead>
<tbody>
<tr>
<td>Al-20% SiC</td>
<td>Brass</td>
<td>Positive</td>
<td>$MRR = 100.2671 I^{1.4841} T^{0.4979} S^{0.0614}$</td>
<td>$EWR = 182.144 T^{1.0482} S^{-0.0216} &lt; 2.19$</td>
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<td>Copper</td>
<td>Negative</td>
<td>$MRR = 213.927 I^{1.4066} T^{-0.6213} S^{0.0725}$</td>
<td>$EWR = 21.014 I^{1.0979} S^{-0.1144} &lt; 0.30$</td>
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<tr>
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<td>Copper</td>
<td>Positive</td>
<td>$MRR = 123.927 I^{1.4066} T^{-0.6213} S^{0.0725}$</td>
<td>$EWR = 51.014 I^{1.0979} S^{-0.1144} &lt; 0.30$</td>
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<tr>
<td></td>
<td>Al-25% SiC</td>
<td>Brass</td>
<td>$MRR = 99.7632 I^{4.2432} T^{0.4290} S^{0.0698}$</td>
<td>$EWR = 467.687 I^{1.8586} T^{1.2951} S^{0.1982} &lt; 2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_a = 1.3086 T^{1.6705} S^{0.0462} &lt; 7.4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>Negative</td>
<td>$MRR = 123.927 I^{1.4066} T^{-0.6213} S^{0.0725}$</td>
<td>$EWR = 21.014 I^{1.0979} S^{-0.1144} &lt; 0.30$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_a = 1.3086 T^{1.6705} S^{0.0462} &lt; 7.4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>Positive</td>
<td>$MRR = 123.927 I^{1.4066} T^{-0.6213} S^{0.0725}$</td>
<td>$EWR = 21.014 I^{1.0979} S^{-0.1144} &lt; 0.30$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_a = 1.3086 T^{1.6705} S^{0.0462} &lt; 7.4$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 Constants of Regression Equation and Optimized Equations
problem is a maximizing problem, the selection used is top rank population selection. The chromosomes, after crossover and mutation, are sorted in descending order of their objective function values. Since the population size is a constant, the top ‘n’ chromosomes are chosen for next iteration, where ‘n’ is the population size. The steps are repeated, the given number of times and, if the solution did not converge, the number of generations must be increased, suitably to obtain converging solution. The optimized equations for Al-20%SiC and Al-25%SiC satisfying the objective functions are listed in Table 4.2. The obtained equations for MRR are compared with the experimentally obtained values and are listed in Table 4.3.

4.6 EDM OF Al(SiC)<sub>p</sub> COMPOSITES WITH ROTARY TUBE ELECTRODE

From the experimental results, it is confirmed that the MRR, EWR and SR produced by EDM drilling with a rotating electrodes are better than those values found in the case of stationary electrode. Effective flushing at the machining gap by the dielectric was attributed as the reason for the enhanced performance. Several researchers studied the performance of various flushing methods in electric discharge machining. Yan and Wang (1998) studied the machining characteristics of Al-Al<sub>2</sub>O<sub>3</sub> composites with a tube electrode. The rotating tube electrodes were tested under different flushing conditions namely side flushing, injection flushing and suction flushing. With increased dielectric pressure, the injection and suction flushing was confirmed to produce higher material removal rate and better surface finish. To enhance further knowledge, a rotating brass tube electrode with varying hole diameter was used on girth to drill the Al-SiC work piece.
<table>
<thead>
<tr>
<th>Material</th>
<th>Electrode</th>
<th>Polarity</th>
<th>Current (Amperes)</th>
<th>Pulse Duration (µs)</th>
<th>Electrode Speed (rpm)</th>
<th>Predicted Value</th>
<th>Observed Value</th>
<th>% deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-20%SiC</td>
<td>Brass</td>
<td>Negative</td>
<td>5</td>
<td>88</td>
<td>270</td>
<td>35.93</td>
<td>33.13</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>5</td>
<td>176</td>
<td>270</td>
<td>31.76</td>
<td>29.44</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>Negative</td>
<td>11</td>
<td>88</td>
<td>200</td>
<td>29.87</td>
<td>33.14</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>5</td>
<td>264</td>
<td>270</td>
<td>23.42</td>
<td>23.45</td>
<td>1.2</td>
</tr>
<tr>
<td>Al-25%SiC</td>
<td>Brass</td>
<td>Negative</td>
<td>5</td>
<td>88</td>
<td>270</td>
<td>21.44</td>
<td>18.53</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>5</td>
<td>176</td>
<td>200</td>
<td>23.24</td>
<td>19.25</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>Negative</td>
<td>8</td>
<td>88</td>
<td>270</td>
<td>25.95</td>
<td>23.78</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Positive</td>
<td>5</td>
<td>264</td>
<td>270</td>
<td>14.06</td>
<td>11.54</td>
<td>21</td>
</tr>
</tbody>
</table>
In this study, the performance of the brass tube electrode was tested by varying the EDM parameters namely, discharge current, and electrode hole diameter, speed of the electrode on MRR, EWR and SR. The brass tube electrodes of hole diameters of 1.5mm, 2.5 and 3.5 mm are selected for the study and they were rotated at 270 and 750rpm.

4.7 EXPERIMENTAL DETAILS OF ROTARY TUBE ELECTRODE

The material to be machined was 6025 Al- alloy reinforced with SiC particles, at a composition of 20 and 25 volume percent of SiC. The size of the SiC particles is of 20 μm.

The experiments are conducted using an Electronica electrical discharge machine series – MT-3822, which was equipped with a transistor switched power supply. The electrode was fed downwards into the work piece under servo control in this EDM machine. A brass hollow tube electrode was used on girth to drill the work piece. The hole diameter on the brass electrode was varied between 1.5mm to 3.5 mm. Commercial kerosene was circulated as the dielectric fluid. The dielectric fluid was injected at a pressure of 35 N/cm² through the tube electrode.

MRR is proportional to the product of the energy transferred per pulse and the pulse frequency. Changing the pulse current at a constant frequency varies the energy of the pulse. All the experiments were conducted with pulse current, pulse duration, volume percentage of SiC, tube hole diameter and speed of the electrode as variables. The pulse currents selected for this study were 5, 8 and 11 Amperes. The selected pulse durations were 88, 176 and 246μs. The tube electrodes were rotated at 270 and 750 rpm.
The material removal rate and electrode wear rate were evaluated for each cutting condition by measuring the average amount of the material removed and the required cutting time. Changes in the tool weight, material weight, and elapsed time were recorded after each machining. The MRR and EWR were measured by using an electronic balance of sensitivity 0.1 mg. The surface roughness of the SiC/6025 Al composite was measured with the help of Surtronic 3+. The Ra values are used to quantify the surface roughness. The cutoff length for each measurement was taken as 0.8mm.

The rotary mechanism shown in Figure.4.2 was fitted with tube electrodes and experiments were conducted to investigate the effect of the variables that are likely to influence the responses variable. In this study, MRR, EWR, and SR are considered as response variables. These values are compared for stationary, rotating electrode and rotating tube electrode.

4.8 RESULT AND DISCUSSION OF ROTARY TUBE ELECTRODE

Al-20% SiC and Al-25% SiC composites were machined with brass electrodes having eccentric holes of diameter 1.5 mm, 2.5 mm and 3.5 mm. The effect of the tube electrode in machining of the above composites was tested by measuring the MRR, EWR and SR while varying the input variables. The input variables selected for this study are discharge current, polarity, volume of SiC, pulse duration, hole diameter of the tube electrode and speed of rotation of the electrode.
4.8.1 MRR

The effect of discharge current on MRR for Al-SiC composites when the brass electrode was kept at different status are shown in Figures 4.23 and 4.24. Figure 4.23 shows the effect of discharge current on MRR for Al-20% SiC and Figure 4.23 shows the same for Al-25% SiC. MRR is proportional to the product of energy transferred per pulse frequency. From the Figure 4.23, it could be observed that the material removal rate in the case of rotating tube electrode is much higher than the rotating solid electrode. This is due to the superior debris removal effect of the rotating tube electrode than the solid rotating electrode at the machining gap. It is to be noted that in EDM sparks alone provides effective material removal whereas arcs are related to process instability. Under inadequate flushing condition, concentration of the conducting particle grows and causes process instability. When the process is under instability condition, the arcs are the predominant discharge mechanism rather than spark, which produces low MRR.

The tube electrode in which the dielectric is forced through the small hole further enhances this debris removal. Forcing the dielectric in the tube increases the pressure, which increases the debris removal. In addition to that, in the case of tube electrode the peak current through a relatively smaller cross section of the hollow tube, which increases the MRR (Yan 1993).

Increase in percentage of SiC in the work piece increases the SiC particle concentration at the machining gap. SiC particle at the machining gap induces process instability, which reduces the material removal rate (Figure 4.24).
Figure 4.23 Effect of discharge current on MRR for 20% SiC

Figure 4.24 Effect of discharge current on MRR for Al-25% SiC
Figure 4.25 shows the effect of pulse duration on MRR. From the Figure, it was observed that the MRR was low when the electrode was kept at low as well as at high pulse duration. The MRR was at its maximum for a medium range of pulse duration. The short pulse causes less vaporization, where as long pulse duration cause the plasma channel to expand. The expansion of the plasma channel causes less energy density on the work piece. The optimal pulse frequency requires detailed experimentation (Wang et al 2000).

The effect of the hole diameter of the tube electrode for various discharge current on MRR is shown in Figure 4.26. It was inferred that the MRR decreases as the hole diameter increases irrespective of the volume percentage of SiC. As the hole diameter increases, the pressure of the dielectric medium which was injected through it decreases. The decrease in the pressure reduces the debris removal rate, which inhibits the MRR (Wang et al 2000).

Figure 4.27 shows the effect of rotational speed on MRR at various discharge current. It was inferred that the increase in speed of the electrode resulted in an increase in MRR. This increase in MRR was due to the effective increase in the flushing of the tube electrode at the machining gap as the speed increases. The rotating tube electrode imparts a whirl to the dielectric, which flushes the machining gap effectively. The speed of the whirl increases as the speed of the tube electrode. According to the Koshy(1993) and Mohan et al (2002), the centrifugal force generated by the rotating tube electrode throws a new layer of dielectric in to the machining gap. This new layer of dielectric induces an atmosphere for better machining and prevents arcing, which improves the MRR.
Figure 4.25 Effect of pulse duration on MRR

Figure 4.26 Effect of Electrode hole diameter on MRR
Effect of Tube Electrode Speed on MRR

The EWR of an electrode was obtained from the weight difference of the electrode before and after each machining. Figure 4.28 and 4.29 show the curves of EWR Vs discharge current for different polarities of the brass electrode with and without hole of Al-20% SiC and Al-25% SiC respectively. The EWR was more when the electrodes were kept at positive polarity than at negative irrespective of the volume percentage of SiC. This is due to the increase in MRR with the positively connected electrode. It was also inferred that, the EWR with the tube electrode was more than the solid electrode at
different mode, since the MRR with the tube electrode was more than the solid electrode (Mohan et al. 2002). In comparing the Figures 4.28 and 4.29, the EWR for Al-25% SiC was more than the Al-20%SiC. This increase in wear was due to the SiC particles abrasive nature. Increase in SiC percentage decreases the conductivity, which increases the EWR.

The relation between EWR and pulse duration is shown in Figure 4.30. The EWR decreases in an inverse relation with pulse duration, irrespective of the polarity as similarly observed by Wang and Yan (2000). The long pulse duration provides a better heat removal around the surface of brass electrode, which is normally a good thermal conductor. The decrease in temperature on the surface of the electrode causes less wear on the electrode (Mohan et al. 2002).

Figure 4.31 depicts the effect of electrode hole diameter on the EWR. The increase in electrode hole diameter causes a decrease in EWR. This may be due to that as the electrode hole diameter increases, the injection pressure of the dielectric medium decreases. The decrease in the injection pressure effects a less debris removal at the machining gap. Since the debris is not fully removed from the machining gap, the machining will take place between the debris on the surface of the work piece and the electrode, which causes arc instability. This arc instability increases the EWR (Yan et al. 1993).
Figure 4.28 Effect of discharge current on EWR for Al-20% SiC

Figure 4.29 Effect of discharge current on EWR for Al-25% SiC
Figure 4.30 Effect of pulse duration on EWR

Figure 4.31 Effect of electrode hole diameter on EWR
4.8.3 Surface Roughness

The variation in SR with different discharge current for different status of the solid and tube electrode is shown in Figures 4.32 and 4.33. Figure 4.32 shows the variation of SR with discharge current for Al-20% SiC and Figure 4.33 shows the same for Al-25% SiC. With reference to these Figures, the Ra value was more when the electrode was connected at the positive polarity than at negative. It was also observed that increase in discharge current resulted in an increase in Ra value. These events may preferentially result in larger discharge energy, subsequently causing a larger crater on the surface of the work piece. Injecting dielectric through the tube electrode reduces the shielding effect of SiC by washing them. The washing of SiC exposes the aluminium material. Machining Al with EDM increases crater on the surface (Frank Muller and John Monaghan 2000). The increase in vol% of SiC effected an increase on the roughness value. This is due to the debonding of SiC particles that leaves voids on the surface of the work piece. (Yan et al 1993 and Wang et al 2000). In comparison with the solid electrode, the tube electrode effected a decrease in Ra value. The effective flushing with the tube electrode reduces debris adherence with the work piece. The reduction in debris adherence improves the surface finish of the work piece (Mohan et al 2002).

Figure 4.34 shows the effect of pulse duration on surface roughness under peak current. The surface roughness value increased with increase in pulse duration. This is due to the long pulse duration in the machining process may expand the plasma channel and decrease the energy density. Eventually, the long pulse duration produces a shallow crater on the surface of the work piece (Mohan et al 2002).
The variation of surface roughness with discharge current for various tube electrode hole diameter is shown in Figure 4.35. Increase in hole diameter effected an increase in Ra value. This may be due to the effective flushing with smaller diameter of the tube electrode. The increase in injection pressure reduces the recasting of the debris with the work piece. The decrease in debonding of the debris improves the surface finish (Yan et al 1993).

4.8.4 SEM study on EDM ed surface with rotary tube electrode

The effect of dielectric injection through the tube electrode was analysed with the help of SEM photographs. Figures 4.36a and b show the topography and close view of the EDMed surface of Al-20% SiC with rotary tube electrode and Figures 4.37a and b show the same for Al-25%SiC.In comparing the topography of the EDMed surfaces (Figures 4.36a and 4.37a) while machining with rotary tube electrode with the surfaces of stationary (Figure 4.16a, 4.17a)and rotary electrode (Figure 4.18a, 4.19a) it was observed that the craters formed on the EDMed surface with rotary tube electrode was more than at stationary and rotary electrode. The surface of the workpiece was bombarded by the plasma in a vertical direction and in the case of rotary tube electrode the dielectric is also directed in a vertical direction. At the time of machining, the unmelted SiC particles at the machining gap are washed immediately due to the injection of the dielectric which increases the material removal rate. The effective removal of SiC at the machining gap exposes the aluminium to the plasma which results large sized crater (Figure 4.36b). Increase in SiC vol% decreases the aluminium content which leads to the decrease in MRR. This decrease in MRR results in the formation of lesser number of craters on the surface and voids formed by the plucking of SiC particles (Figures 4.37a and 4.37b).
Figure 4.32 Effect of discharge current on surface roughness for Al-20% SiC

Figure 4.33 Effect of discharge current on surface roughness for Al-25% SiC
Figure 4.34 Effect of pulse duration on SR

Figure 4.35 Effect of electrode hole diameter on SR
Figure 4.36  SEM photograph of EDM surface of Al-20% SiC while machining with rotary tube electrode (a) topography (b) close view.
Figure 4.37 SEM photograph of EDM surface of Al-25% SiC while machining with rotary tube electrode (a) topography (b) close view
4.9 MATHEMATICAL MODELLING AND OPTIMIZATION OF ROTARY TUBE ELECTRODE

To summarize the effect of process parameters of the machining process on the response variables MRR, EWR and SR, empirical relations were developed. The commercial software “STATISTICA” was used to develop the empirical equations. STATISTICA constructs a non-linear regression expression by inputting all the experimental data. The non-linear estimation is a general curve fitting procedure that will estimate the kind of relationship between a dependent (response variable), and a list of independent variables. The regression model is expressed as

\[ Y = F(X_1, X_2, \ldots, X_n) \]  

(4.9)

It is assumed that a dependent variable to be a independent variables i.e.

\[ Y = A + B_1X_1 + B_2X_2 + \ldots + B_nX_n \]  

(4.10)

where A, B_1, B_2, \ldots, B_n are regression co-efficient. A least square method was assumed for minimizing the residual variants around the regression lines by minimizing the loss function. A Quasi-Newton method was used to minimize the loss function. This method will at each step, evaluate the function at different point in order to estimate the first order derivative and the second order derivatives. The above information will then be used to follow a path towards minimizing the loss function. Equations based on the above procedures were developed for MRR, EWR and SR.
MRR = \( B_0 \cdot I + B_1 \cdot \frac{1}{T} + B_2 \cdot \frac{1}{D} + B_3 \cdot N + B_4 \cdot \frac{1}{V} + B_5 \cdot P \) \hspace{1cm} (4.11)
\[ R^2 = 0.94076 \quad B_0 = 2.749537 \quad B_1 = -337.931 \quad B_2 = 14.31188 \]
\[ B_3 = -0.067679 \quad B_4 = 1396.407 \quad B_5 = 1.556111 \]

EWR = \( B_0 \cdot I + B_1 \cdot \frac{1}{T} + B_2 \cdot \frac{1}{D} + B_3 \cdot N + B_4 \cdot V + B_5 \cdot P \) \hspace{1cm} (4.12)
\[ R^2 = 0.947935 \quad B_0 = 1.645509 \quad B_1 = 542.4196 \quad B_2 = 8.362997 \]
\[ B_3 = -0.33136 \quad B_4 = 0.827430 \quad B_5 = -1.14124 \]

SR = \( B_0 \cdot I + B_1 \cdot T + B_2 \cdot D + B_3 \cdot N + B_4 \cdot V + B_5 \cdot P \) \hspace{1cm} (4.13)
\[ R^2 = 0.89002 \quad B_0 = 0.689815 \quad B_1 = 0.00749 \quad B_2 = 1.284722 \]
\[ B_3 = -0.014266 \quad B_4 = 0.431852 \quad B_5 = 2.140741 \]

Where \( I \) = discharge current (amp), \( T \) = pulse duration (microseconds), \( D \) = hole diameter of the electrode in mm, \( N \) = rotational speed of the electrode (rpm), \( V \) = Volume % of the SiC particle, \( P \) = polarity of the work piece (+1 = positive, -1 = negative).

From the above regression model it could be stated that the peak current the hole diameter and volume percentage of SiC significantly affect the MRR, EWR and SR. The model shows that for higher % of SiC and increase in hole diameter there is an increase in SR and decrease in the MRR, and EWR. The maximum and minimum values, standard deviation and mean values of the input variables for the MRR, EWR and SR were found out.

To optimize the values of the input variables, a genetic algorithm programme was developed using C++ language. The mean, standard deviation, minimum and maximum values of the variables are substituted in the algorithm and optimized. The optimized values were given in the Table 4.5 below.
Table 4.5 Optimum Values of rotary tube machining

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Current</td>
<td>6.2A</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>133μs</td>
</tr>
<tr>
<td>Speed</td>
<td>334 rpm</td>
</tr>
<tr>
<td>Hole diameter of the electrode</td>
<td>1.52 mm</td>
</tr>
<tr>
<td>Polarity of the electrode</td>
<td>+Ve</td>
</tr>
<tr>
<td>%Vol of SiC</td>
<td>20%</td>
</tr>
<tr>
<td>MRR</td>
<td>69.58 mm³/min</td>
</tr>
<tr>
<td>EWR</td>
<td>26.40 mm³/min</td>
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</tbody>
</table>