Chapter 2

Literature review

This chapter provides a review on past work conducted on electrical discharge machining of tool and die steels and advanced materials. Experimental investigations on surface grinding of advanced materials have also been discussed. The last section of the chapter provides a review of available literature on EDSG process and its behavior during machining of the different kind of materials. The study of material removal and its mechanism for the machining processes have been one of the primary concerns of researchers for several years. It becomes easier to predict the effect of various input parameters of the process after complete understanding of its material removal mechanism. In the past, many researchers have explained the material removal mechanism of hybrid machining processes by developing thermal models to predict the effect of energy interactions in different hybrid machining processes.

2.1 Electrical discharge machining of tool and die steel

This section provides a review of past research work conducted on electrical discharge machining of tool and die steel. This material has wide applications in tool and die making industries.

Lee et al. (1988) investigated the microstructure analysis of AISI D2 die steel machined by electrical discharge machining. The study concluded that the heat affected region consists up of two layers and the thickness of the white layer was correlated with the depth of the surface cracks developed on the machined surface. It was also observed that at constant dielectric and flushing conditions the thickness of recast layer mainly depends upon the current and pulse on-time, irrespective to the size and type of tool steel material.

Abu Zeid (1997) conducted an experimental study to observe the effect of current and pulse on-time on the fatigue life of AISI D6 tool steel. The results of the study concluded that electrical discharge machining has a significant deteriorating effect on fatigue life of AISI D6 tool steel. The discharge energy has been found to be responsible for the thickness, uniformity and solidification cracking of recast layer. The chemical
composition of recast layer reveals that greater content of carbon was reported on recast layer as compared to the steel substrate (Abu Zeid, 1997; Ojha et al., 2010).

Wong et al. (1998) reported experimental study on mirror-finish phenomenon in electrical discharge machining using a fine powder mixed with dielectric fluid suspended in inter-electrode gap. Machining was performed on different types of steels at selected range of input parameters. The findings of the study concluded that proper settings of tool polarity, pulse parameters and powder characteristics can develop mirror type surface finish on the machined surface. The beneficial features of powder mixed EDM was reported as shorter machining time, more uniform dispersion of electrical discharges and stable machining. Based on the experimental study it was claimed that type of material composition, powder properties and machine settings can generate mirror type surface finish on workpiece surface.

Guu and Hocheng (2001) proposed the effect of machining parameters of rotary EDM such as discharge current, pulse on-time, workpiece rotation on material removal rate and surface roughness. The material removal rate and surface roughness was found to increase with an increase in rotational speed of tool electrode. The results obtained from the study were later on compared with conventional EDM. The study reveals a significant improvement in MRR and SR with recast layer.

Lee and Tai (2003) conducted EDM of D2 and H13 tool steels. The formation of surface cracks during machining was investigated by considering surface roughness, white later thickness and the stress induced by EDM. The results of the experimental study indicate that if pulse voltage is maintained at 120 V then the possibility of surface cracks can be reduced by selecting current between 12 to16A and pulse-on duration between 6 to 9µs. This study provides an overview for the detection of the formation of surface cracks under selected machining conditions. The proposed study provide useful information to enhance the quality of EDM of tool steels.

Singh et al. (2004) conducted experimental study to observe the effects of machining parameters like pulsed current on material removal rate, diametral overcut, electrode wear rate and surface roughness during electric discharge machining of En-31 tool steel. The investigations indicates that the output parameters of EDM increases with
the increase in pulsed current and the desirable machining rates are achieved with copper and aluminum electrodes (Singh et al., 2004).

Pham et. al has discussed some recent developments in variants of micro-EDM like wire, drilling, milling and die-sinking. Deliberate issues related to factors and procedures influencing the accuracy, positioning approaches during EDM and electrode grinding have been suggested in the experimental study (Pham et al., 2004). A prediction model for surface roughness was developed on the basis of data received during online monitoring of the process (Pham et al., 2005).

Guu (2005) conducted a detailed study of surface morphology, surface roughness and micro-crack on AISI D2 tool steel by electrical discharge machining. It was observed that the surface integrity after EDM can be determined by the impact of discharge energy during machining. At low value of pulse energy, appreciable surface finish was obtained for AISI D2 die steel. The surface roughness and the depth of the micro-cracks were found to be proportional to the input power of EDM. The atomic force microscopy (AFM) analysis of micro-cracks provides detailed information for the post treatment of AISI D2 die steel machined by EDM.

Singh et al. (2005) conducted experimental investigations into EDM of AISI 6150 tool steel with varying pulsed current and four different tool electrodes. The study reveals that the performance measure such as MRR increases with an increase in pulse current and the best optimal machining rates were achieved by copper-tungsten tool electrode.

Kansal et al. (2005) established optimum machining conditions for powder mixed electrical discharge machining of AISI D2 die steel. In this experimental work, the effect of graphite powder addition in the dielectric fluid was investigated on MRR, TWR and SR. The experimental results concluded that the addition of graphite in the dielectric fluid caused significant improvement in MRR with appreciable decrease in TWR and SR.

Amorin and Weingaertner (2007) reported the performance of graphite and copper tool electrodes during electrical discharge machining of AISI P20 tool steel. In this study effect of prominent EDM parameters on the performance of the process were investigated. The measured machining characteristics are material removal rate, volumetric relative wear and surface roughness of the workpiece. The material removal rate for graphite tool electrode was found to be higher at negative tool polarity. The lowest values of volumetric
relative wear were achieved with graphite and copper tool electrodes at positive tool polarity. The study concluded that good surface finish was obtained with copper tool electrodes using negative tool polarity.

Pradhan and Biswas (2009) presented neuro-fuzzy and regression models to predict MRR. The effect of input parameters like gap current, on-time and duty factor was investigated on MRR. The model predictions of both techniques were compared and found that fuzzy based model has better predictive capability as compared to regression model.

The machining efficiency of wire electrical discharge machining can be improved with precise adjustments of machining parameters such as, pulse width, pulse interval, dielectric fluid pressure, wire tension, servo reference voltage, etc (Kapoor et al., 2012). The effect of various input parameters of WEDM like pulse on time, pulse off time, gap voltage, peak current, wire feed and wire tension have been investigated on material removal rate of hot die steel (H-11) (Singh and Garg, 2009 ; Garg et al., 2010). The material removal rate found to be increases with an increase in pulse on time and peak current while decreases with an increase in pulse off time and servo voltage.

In WEDM of stainless steel grade 304L, gap voltage, pulse on time and pulse off time are found to be significant factors, whereas wire feed and flushing pressure are the non significant factors for MRR (Parashar et al., 2010).

Powder mixed electrical discharge machining (PMEDM) of EN-8 steel was conducted by Ojha et al. to optimize material removal rate and tool wear rate (Ojha et al., 2011). The effect of current, duty cycle, angle of electrode and concentration of chromium powder in the dielectric fluid were investigated on performance of PMEDM. The study concluded that the concentration of powder has a significant effect on MRR whereas, current and electrode angle are found to be dominant parameters for TWR.

The experimental trials on micro-EDM was carried out under different levels of applied energy, voltage, maximum current and pulse duration in order to identify the effects of these process conditions on the obtainable surface roughness, wear ratio, craters and spark gap. The study reveals that the grain size of the material has dominant effect on the quality of the machined part. The results of the investigation have revealed that, by refining the material microstructure, a better surface finish can be achieved (Elkaseer et al., 2013).
2.2. Electrical discharge machining of advanced materials

Hocheng et al. (1997) studied the effect of machining parameters like current, on-time and crater size produced by single spark during machining of SiC/Al composite. The experimental results were compared with the results obtained from heat conduction model of material removal rate for composite and steel. It was observed that crater size for the composite is larger than steel and SiC particles can interfere with the discharges. For the effective machining of SiC/Al composite, high peak current and shorter pulse on-time are recommended. This study provides useful information for the machinability of metal matrix composites (MMC) by EDM under optimal conditions.

Liu (1997) proposed electrical discharge milling of polycrystalline diamond (PCD). This process involves the use of DC source instead the use of pulsed generator and water based emulsion as a dielectric fluid. This process was used to machine the surface of PCD, cubic boron nitride (CBN) and ceramics effectively. The effect of pulse on-time, peak current and tool polarity was investigated on the performance characteristics of the process.

Muller and Monaghan (2001) have reported experimental results for the electrical discharge machining and laser cutting of silicon carbide particle reinforced aluminum alloy matrix (PRMMC) composites. This study suggested different material removal mechanism for these individual processes. The surface integrity and sub surface damage of material under these processes have also been compared. It was concluded that both EDM and laser cutting processes are suitable for the processing of SiC (PRMMC) composites. MRR for laser cutting process was found to be higher as compared to EDM. However, EDM provides less thermal damage to the workpiece as compared to laser cutting during machining.

Liu (2003) conducted electrical discharge machining of conductive TiN/Si₃N₄ ceramic composites by die sinking EDM to study electrode wear rate. The copper and brass tool electrodes were used to study the electrode wear rate during the machining of composites. The study reveals that surface roughness was found to have a greater dependence on pulse energy. It was observed that higher pulse energy caused severe thermal damage to the sub surface. The electrode wear rate of brass was found to be greater than that of copper tool electrode during machining.
Lauwers et al. (2004) investigated the material removal mechanism of electrical conductive ceramic composites through analysis of debris and sub surface quality machined by brass tool electrode. The experimental study reveals that the mechanism of material removal involves melting, evaporation and spalling with oxidation of base material.

Singh et al. (2004) predicted the effect of current, pulse on-time and flushing on the performance measures such as material removal rate, tool wear rate, taper, radial overcut and surface roughness during EDM of cast Al-MMC with 10% SiC_p reinforcement. The kerosene oil was used as a dielectric fluid during experimentation. Brass tool electrode of 2.7mm diameter was used to drill the workpiece. Taguchi’s L_{27} OA was used to study the effect of three machining parameters at three levels on the machining characteristics. The study reveals that MRR was observed to be higher at larger current and pulse on-time settings at the cost of tapercity, radial overcut and surface finish. It was also observed that flushing pressure of dielectric fluid has considerable effect on MRR and TWR.

Chiang (2008) developed mathematical models for investigating the influence of machining parameters like discharge current, pulse on-time, duty factor and discharge voltage on performance characteristics like MRR, EWR and SR during EDM of Al_{2}O_{3}+TiC mixed ceramic. The study concluded that discharge current and duty factor has a significant effect on MRR. However, effect of discharge current and pulse on-time was found to be significant on EWR and SR. The MRR was reported to increases with an increase in discharge current, duty factor and discharge voltage, whereas EWR increases with an increase in duty factor and discharge voltage. The SR was found to increase with an increase in discharge current and discharge voltage.

Ponappa et al. (2010) analyzed the effect of process parameters such as pulse on-time, pulse off time, gap voltage and servo steel on surface finish and taper during EDM of sintered magnesium based nano composites. The experiments were designed with Taguchi’s experimental design technique. The results claimed that pulse on-time and servo speed are identified as major influential parameters. The microstructural changes and the effect of particle reinforcement were also investigated.

Janmanee and Muttamara (2010) have reported the effect of different electrode materials, discharge current, on-time, off-time, open circuit voltage and electrode polarity on EDM of tungsten carbide. During the machining, the negative tool polarity was found to
be desirable for MRR. It was also concluded that the MRR for the powder metallurgy tool electrode was higher as compared to solid tool electrode. The MRR of graphite tool electrode was found to be higher and also reported better surface finish with higher EWR at higher values of discharge current.

Singh and Pandey (2014) conducted rotary disk electrical discharge machining of Nimonic 75 super alloy to observe the effect of peak current, peak voltage, pulse on-time, pulse off-time, speed and aspect ratio of disk electrode on material removal rate, disk electrode wear rate and surface roughness. The study concluded that the aspect ratio of disk electrode and peak current significantly affect the process machining characteristics. The rotation of disk causes efficient removal of debris and stabilised machining which results in minimum recast layer.

Singh and Kumar (2014) investigated the effect of control parameters like current, pulse on-time, pulse off time on surface roughness of Titanium alloy (Ti-6Al-4V). It was observed that current has a significant effect on surface roughness followed by pulse off-time. The effect of pulse on-time was observed to be least on surface roughness. The proposed optimal settings for the machining are pulse on-time (24µs), pulse off time (9µs) and current (5amp).

### 2.3 Surface grinding of hard materials

Grinding is one of the conventional and extensively used manufacturing processes in the industries. This process is used for almost all components manufactured in tool and die making industries. The process has the capability to produce finished products with high accuracy. It can be used for the machining of hardened tool steels that are difficult to machine with the other machine tools. The quality of surface developed while grinding depends on the configuration of the grinding wheel and its properties. As per the configuration, there are different kinds grinding processes like surface grinding, cylindrical grinding and shape grinding. The surface generated by the grinding mainly depends upon operating conditions such as wheel speed, depth of cut, area of contact and characteristics of cutting fluid. The researchers have made the efforts to improve the material removal rate and surface quality of the machined surface with enhanced life of the grinding wheel.
Fujihara *et al.* (1997) developed a novel grinding technology for the machining of ceramic based matrix composites and structural ceramics with electrolytic in-process dressing (ELID). The grinding operation was performed with cubic boron nitride (CBN) and diamond wheels using various grit sizes and bonds. The ELID grinding and conventional grinding was carried out by metal bonded wheels and resin bonded wheels respectively. The study reveals that ELID grinding provides increased stability in grinding force for high stock removal as compared to conventional grinding.

Zhong (2003) presented experimental work on grinding of aluminium based metal matrix composite reinforced with Al₂O₃ or SiC particles using grinding wheels made of SiC in a vitrified matrix or diamond in a resin bonded matrix. The grinding speed of 1100 to 2200 m/min, depth of 15mm and cross feed of 3mm for rough grinding mode was used. It was observed that diamond wheel of 3000 grit at a depth of 1mm produce ductile streaks on the Al₂O₃ and SiC particles. No subsurface damage was observed except with rare cracked particles during fine grinding with a diamond wheel.

Ilio *et al.* (2009) studied the relationship between modeling of force components, cutting energy and workpiece surface roughness while grinding of metal matrix composites. The horizontal surface grinder was used to perform the tests. The grinding wheel based on alumina abrasives was used to machine SiC reinforced aluminum alloy composites. The study explores the effect of shape, orientation and content of reinforcement on the grindability of workpiece material. The analysis of results was carried out by the empirical models used to predict the effect of control parameters.

Guo *et al.* (2011) investigated the machinability of Ti-6Al-4V using surface grinding by silicon carbide abrasives. The study includes the analysis of grinding force, specific grinding energy, surface topography, surface residual stresses and metallurgical structure alternation. It was reported that grinding force ratio and specific energy found to decrease when chip formation played a significant role during grinding. The workpiece was subjected to cutting traces and micro grooves after the grinding operation and was free from any surface cracks. High concentration of residual stresses was observed under plastic deformation, micro-structural transformation and thermal cycling of surface layer.

Pal *et al.* (2012) conducted an experimental study on surface grinding of EN24, EN31 and Die steel using tool and cutter grinding machine. The effect of machining
parameters such as work speed, grinding wheel grades and hardness of materials was investigated on surface roughness. The results of the study reported that the surface roughness was found to decrease with an increase in hardness of the material. However, increase in surface roughness was observed with an increase in rotational speed of the grinding wheel.

Thiagarajan et al. (2012) suggested modeling and optimization of cylindrical grinding of Al/SiC composites using genetic algorithms approach. The effect of grinding parameters such as, wheel velocity, workpiece velocity, feed and depth of cut on response parameters such as tangential grinding force, surface roughness and grinding temperature was studied. In this study genetic algorithm based optimization procedure has been developed to optimize the grinding parameters for maximum material removal rate. This study provides useful information to the manufacturing industries for the machining of Al/SiC composites.

Zhou et al. (2013) conducted numerical and experimental studies into temperature field during precision grinding of SiCp/Al composites. In this study, a triangle heat source model was used to determine the heat flow during grinding of SiCp/Al composite. A three dimensional finite element model was proposed to investigate the temperature distribution at different conditions of the process. The actual temperature recorded from the set up was compared with the predictions of the thermal model. The result of the study indicated that grinding temperature predicted by finite element method agrees well with the experimental data. The triangle heat source model was reported to be appropriate for the estimation of workpiece temperature during precision grinding.

Kulekci (2013) discussed the surface roughness characteristics of AISI 1040 steel using EKR46K grinding wheels. The effect of wheel speed, rate of feed and depth of cut was observed on surface roughness. The experimental results concluded that the effect of depth of cut and wheel speed have been found significant on the surface roughness. The optimum conditions for grinding of AISI 1040 steel includes wheel speed of 1500 rev/min and depth of cut of 0.05mm. The contribution of grinding parameter such as depth of cut, wheel speed and rate of feed toward surface roughness is 50%, 40% and 10% respectively.
2.4 Mechanism of spark assisted grinding processes

Koshy et al. 1996 investigated the machining mechanism of Electrical Discharge Diamond Grinding (EDDG). The combined effect of spark erosion and conventional grinding in EDDG has been illustrated in Figure 2.1. Bronze bonded diamond grinding wheel of 5.7 mm thickness (G80/100 C75) was used in the experimental study. The role of current and wheel speed on material removal rate, grinding forces and power has been investigated to elucidate the material removal mechanism. It was observed that spark discharges thermally soften the work material in grinding zone, and hence reduce the normal force and grinding power. The performance of EDDG was improved due to continuous in-process dressing and de-clogging of the wheel surface.

The said researchers studied the effect of wheel speed on MRR at selected values of gap current. It was found that at low values of current, the MRR first increases with an increase in wheel speed and then remain constant at higher speed. However, at higher values of current the trend of MRR with wheel speed is different which shows the steep rise of MRR within the entire selected range of speeds. The decline in the material removal capability of grinding wheel at 0 and 1A current is due to wheel glazing (Koshy et al., 1996). Graphitization of diamond abrasive causes excessive wear of diamond grains during grinding of high speed steel in EDDG process.

Kozak (2002) investigated the abrasive electro-discharge grinding of advanced materials like polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN). This experimental study was conducted to explore the feasibility and application
of de-ionized water as a dielectric medium to address the environmental aspect of abrasive electro discharge grinding process. It was observed that a higher wheel rotating speed leads to faster material removal by the enhanced mechanical abrasion. This effect may also be due to improved hydrodynamic flushing action in the spark gap. The surface texture is improved with an increase in wheel speed due to increasing in abrasive-workpiece interactions per unit time with few craters. It was further reported that neural network prediction is better than multiple regression for limited data of experiments.

Yan et al. (2000) investigated the characteristics of Al$_2$O$_3$/6061Al composite using rotary EDM with a disk like an electrode. The study reveals that higher MRR can be achieved at the cost of higher electrode wear ratios. The experimental results of study concluded that effects of electrical parameters such as tool polarity, peak current, pulse duration and power supply voltage are seems to be more pronounced as compared to the non electrical parameters such as circumferential speed and reciprocating speed.

Later, Koshy et al. (1997) reported the behavior of WC-Ti cemented carbide machined by diamond grinding with electrical spark assistance incorporated at the wheel-work interface. It was observed that electrical discharges improve the grinding performance by effectively de-clogging the wheel surface which in turn increases MRR. Increase in discharge power causes excessive pull out of abrasives from the wheel surface. The loading of diamond wheel was observed due to the adherence of work material chips onto the bonded abrasive grains under pure grinding conditions i.e. at zero amperes current.

Wang and Yan, (2000) optimizes the blind hole drilling of Al$_2$O$_3$/6061Al composites during rotary EDM. The Taguchi experimental design technique was applied to determine the optimum conditions for the process. It was observed that optimum performance during machining can be achieved with copper tool electrode with an eccentric through hole. The significant contribution of electrical group parameters such as tool polarity, peak current, pulse duration and power supply voltage was observed as compared to non electrical group parameters such as rotational speed of tool electrode, flushing pressure and number of eccentric through-holes in the tool electrode. The study concluded that the effect of tool polarity and peak current was found to be significant on MRR, SR and EWR.
2.5 Experimental investigations in EDSG process

Shu and Tu (2003) investigated the combined electrical discharge machining and grinding. A metal matrix (Cu/SiCp) rotary composite tool electrode was used to study the electrical discharge machining and grinding (EDMG) technology. Surface roughness with EDMG operation was found to be lower than EDM due to participation of SiCp abrasives in tool electrode during machining. It was also concluded that, by selecting optimum machining parameters MRR can be achieved up to seven times as compared to normal EDM operation. The reason for increased MRR during EDMG was occurrence of combined grinding action in addition to EDM operation. It was reported that best EDMG process can be achieved only under optimum condition of SiCp abrasive size, tool electrode speed and current. The study revealed that during machining, SiCp abrasives passes through the resolidified zone and penetrates deep into the heat affected zone, at this situation MRR is recognized mainly due to grinding mechanism.

Jain et al. (2005) investigated specific energy in EDDG with specially fabricated bronze disk tool electrode. Later, the experimental results were compared with EDDG. It was observed that specific energy required in EDDG was lesser as compared to EDM with rotary disk electrode.

Shih and Shu (2008) developed experimental set up for electrical discharge grinding of AISI D2 tool steel using rotary disk tool electrode. It was suggested that higher MRR in EDG can be obtained at positive tool polarity, higher peak current and longer pulse durations. Similarly, for lower surface roughness parameters such as negative tool polarity, lower peak current and shorter pulse duration are suggested. In the study, parameters such as rotational speed, discharge direction and flushing direction have found no significant effect on MRR and SR. Negative polarity of tool electrode promoted micro crater’s crack density on the machined surface.

Yadav et al. (2008) investigated the effect of machining parameters on electro-discharge diamond grinding of high speed steel. It was observed that wheel speed and discharge current have most significant effect on EDDG. The study reveals that MRR increases with an increase in current at constant RPM. It was also observed that at particular level of current MRR was higher at higher RPM. This is because, with an
increase in current, more discharge energy is released to the workpiece, which causes the surface to be thermally softened and hence rapidly removed by the diamond abrasives.

The MRR during EDDG was found to increase with an increase in peak current at constant pulse on time. The MRR was also found to increase with an increase in pulse duration at a particular value of current. This is due to the fact that sufficient time was available to the workpiece for the conduction of heat, which thermally softened the large volume of workpiece material for the removal (Mohri et al., 1995). MRR during EDDG was found to increase with an increase in wheel speed due to higher gap current within the grinding zone. Taguchi experimental design methodology was applied to improve the performance measures and to predict optimized conditions for EDDG.

Kozak et al. (2001) investigated the problems occurs during abrasive hybrid machining processes. The experimental investigations were conducted during abrasive electrochemical machining (AECM) and abrasive electrical discharge grinding (AEDG). During the study, AEDG and AECM of titanium alloy and metal matrix composites was investigated. The rotational speed of the wheel electrode and electrical parameters related to EDM and ECM were selected as adjustable variables for AEDG and AECM process. The experimental study confirms that increase in productivity of AEDG process was observed due to improved hydrodynamic conditions of dielectric fluid by rotation of the wheel electrode. The study also reveals that the introduction of abrasion effects in AEDG and AECM leads to increased MRR. It was also confirmed by the authors that MRR of AEDG process can be improved up to five times than that of EDM and twice the EDG during machining of Al-SiC composite.

Swiecik (2009) conducted an experimental study on AEDG of titanium alloy (Ti6Al4V). In this study the effect of grinding conditions on the performance of AEDG process was investigated. The results of the study were compared with that of conventional grinding operation. The analysis of results concluded that the application of AEDG process had a substantial effect on removal of machining allowance and surface machining texture (SGT). During the study, the effect of electrical parameters, such as working voltage and intensity of current on the tangential force was investigated. It was confirmed that negative polariztion in AEDG was not effective during the machining of titanium alloy. Significant decrease in tangential force was observed when AEDG process was performed with
positive polarization. The highest percentage of decrease in tangential grinding force was observed i.e., 40% in grinding pass and 10% in a sparking pass in AEDG process.

Rajurkar et al. (1995) reported machining characteristics of AEDM by conducting experiments on Al-SiC composite and titanium alloy. The objective of the study was to investigate the effect of abrasion on EDM performance. The enhancement of MRR due to abrasion was investigated in comparison to EDM, EDG as a function of wheel speed and pulse on-time. The experimental results indicated that an increase in wheel speed causes an increase in MRR due to the contribution of abrasion effect in AEDM.

Choudhary et al. (1999) experimentally investigated the effect of current on MRR and grinding forces during EDDG of high speed steel. It was observed that the increase in gap voltage and duty factor at a particular value of current causes decreases in tangential force during machining.

Renjie Ji et al. (2010a) developed a new technology of machining SiC ceramics with compound electrical discharge milling and mechanical grinding (Figure 2.2). Pulse generator and water-based emulsions were used as the machining fluids in this process. The study concluded that the process has capabilities to develop good surface quality over a large surface area of SiC ceramics. The effects of pulse duration, pulse interval, peak voltage, peak current and feed rate were investigated on the performance parameters, such as material removal rate, relative electrode wear ratio and surface roughness.

Figure 2.2: Schematic illustration for ED milling and mechanical grinding of SiC ceramic (Ji et al., 2010)
Taguchi design with $L_{25}$ orthogonal array was selected to analyze the experimental data. The analysis of their experimental observations reveals that SR increases with an increase in peak current for any value of the peak voltage, and increases with an increase in peak voltage for any value of the peak current. REWR was found to decrease with an increase in peak current at constant value of the pulse interval, and increases with the increase of pulse interval at constant value of the peak current. The MRR was observed to increase with an increase in pulse duration, peak current, and peak voltage. It was also found that the thickness of the recast layer formed by electrical discharge milling increases with an increase of pulse duration, peak current, and peak voltage. The unprocessed surface of SiC was observed to be rougher than the machined surface. The grinding traces observed on the machined surface validated the presence of grinding action during machining.

Renjie Ji et al. (2010b) have suggested an optimal combination of levels of combined ED milling and grinding. A mathematical model was developed to establish the relationship of selected input parameters with machining characteristics. This process was used to machine SiC ceramics with superior surface quality. To understand the behavior of combined machining process, the effect of tool polarity, pulse on-time, pulse off-time, discharge current and open voltage on MRR, TWR, and SR have been investigated with Taguchi experimental design. Analysis of the experimental results confirms that open voltage has a significant effect on MRR, whereas discharge current and pulse off-time were found to be less important parameters for MRR. For TWR, open voltage, discharge current and pulse on-time were observed to be significant parameters, whereas pulse off-time has less significant effect on TWR.

Renjie Ji et al. (2010c) investigated the mechanism of material removal in combined electrical discharge milling and mechanical grinding. In this study, the effect of input parameters on material removal rate, relative electrode wear ratio, and surface roughness was examined. The experimental results indicated that MRR increases rapidly from finish machining to rough machining mode. SR was found to increase rapidly from finish machining to rough machining mode due to increasing in single pulse energy with an increase in pulse on-time, peak current, and peak voltage. This is because the crater size generated by a single pulse increases with an increase in pulse energy. Microstructure analysis of the machined surface revealed the presence of uneven fusing structure, globules
of debris, shallow craters, and micropores. Whereas the surface machined at finish machining mode is smooth, and covered with little craters and pockmarks.

Renjie Ji et al. (2012a) conducted machining of silicon carbide (SiC) ceramics with end electrical discharge milling and mechanical grinding to investigate the effect of tool polarity on the process performance. The motor driven tool used was mounted on the rotary spindle during machining and made up of steel wheel with uniform-distributed diamond abrasive sticks in the circumference (Figure 2.3 (a-b)). The experimental results proved that the positive polarity of the tool electrode has developed a better machined surface on the workpiece. The contribution of peak voltage, peak current, and pulse off-time was found to be significant toward MRR. Parameters like peak voltage and pulse off-time are having a more pronounced effect on the EWR.

![Figure 2.3: (a) Schematic illustration for end ED milling and mechanical grinding (b) Tool photograph used in compound end ED milling and mechanical grinding process (Ji et al., 2012)](image)

Modi and Agarwal (2013) reported experimental findings on powder mixed electro-discharge diamond surface grinding (PMEDDG) process. Modeling and comparative analysis of the effect of input parameters such as current, pulse duration, wheel speed, duty cycle and powder concentration on PMEDDG of Ti-6Al-4V alloy were investigated. From the experimental study, it was concluded that highest MRR and lowest SR was obtained with Al-powder mixed dielectric fluid. The thickness of the white recast layer was found to increase with an increase in current, pulse duration and duty cycle and found to decrease with an increase in wheel speed. Analysis of variance in the study claimed that current, powder concentration and duty cycle has a significant effect on PMEDDG.
Yan et al. (2002) experimentally conducted surface modification of Al–Zn–Mg alloy with combined electric discharge machining (EDM) and ball burnish machining (BBM) (Figure 2.4). The effect of machining parameters like tool polarity, peak current, power supply voltage, and the protruding height of abrasive (ZrO$_2$), was studied to determine their effects on machining characteristics. The experimental results indicated that combined EDM and BBM have the potential to obtain fine finishing and flat surface on the workpiece. The experimental findings confirm that combined EDM and BBM can contribute maximum toward increase in corrosion resistance of the machined surface.

Lin et al. (2001) investigated the combined process of electrical discharge machining (EDM) with ball burnish machining (BBM) to improve surface integrity of (Al-Zn-Mg) aluminum alloy using Taguchi method. To execute burnishing effect after EDM, ZrO$_2$ balls were attached to the tool electrode in the experimental set up. The effect of parameters like tool polarity, power supply voltage, peak current, pulse duration, rotational speed of the electrode and servo reference voltage on material removal rate and surface roughness was investigated through L18 Taguchi design.

Figure 2.4: Schematic diagram of the experimental set up for combined EDM with BBM (Yan et al., 2002)
The experimental results indicated that the combined process can be used to improve surface roughness and removal of micro pores and cracks caused by the EDM. The study reveals that fine surface finish and surface modification can be achieved through combined EDM and BBM process.

Xie and Tamaki (2008) performed dry electro-contact discharge (ECD) dressing of metal-bonded #600 diamond grinding wheel for grinding of various granites. Figure 2.5 shows the results of ECD dressing of granite. It has been found that Dry ECD dressing can not only protrude fine diamond grains from wheel metal-bond surface without any damage, but also eliminate bond-tail behind the protruded grain.

![Figure 2.5: Crack growth around micron-scale indentation: (a) inside crystal mineral and (b) near crystal interface (Xie and Tamaki, 2008)](image)

Further, the influence of synthetic factors including granite structure, grinding parameters and dressing method on surface integrity of multi crystal granite was also investigated.

### 2.6 Modeling of advanced machining processes

The modeling of the machining process can be described as a mathematical formulation that establishes the relation between input and output parameters in order to predict the performance of the machining process. The purpose of modeling a machining operation is to develop a predictive capability for machining performance well in advance and finally to achieve optimum productivity, quality and cost (Rao, 2011; Van Luttervelt et al., 1998). The mathematical modeling of machining processes is required for the simulation of the process, design and optimization of the process and control of the process.
(Tönshoff et al., 1992). This section describes the modeling and optimization of advanced machining processes.

Abrasive Water Jet Machining Process (AWJM) utilizes energy of high velocity water jet mixed with abrasives to machine brittle materials. In this process high momentum of water jet is transferred to the abrasives particles for the erosion of material from the workpiece surface. AWJM machining process can effectively machine materials like copper, aluminum, lead, tungsten carbide, titanium, ceramics, silica glass and composites. Hashish used erosion model of Finnie (Finnie, 1960) to develop a model to determine combined depth of cut due to deformation and cutting wear. The use of the model was restricted to brittle materials only and the effect of abrasive particle size and shape has not been considered in the investigation (Hashish, 1989).

An investigation on mechanism of material removal for laser and abrasive water jet cutting was carried out by Singh J et al.. The mechanics of these two processes was studied to elucidate the mechanism of material removal for Ti-6Al-4V and A286 steel. In this study the effect of various control parameters on fatigue behavior of titanium and steel was investigated (Singh and Jain, 1995).

Arola and Ramulu (1997) discussed experimental study on the effect of material properties on surface integrity and texture of machined materials during AJM. Models of dry abrasive erosion were used to analyze the effect of material properties on the hydrodynamic erosion process. The study reveals that the depth of sub surface plastic deformation is inversely proportional to strength coefficient and was observed to be higher at the entry of jet.

Sang Choi and Heung Choi (1997) developed an analytical model for the evaluation of material removal by the single abrasive particle and the thickness of fracture developed on the work material during the machining process.

Hassan and Kosmol (2001) conducted finite element modeling of AWJM to observe the effect of abrasive particle on workpiece interaction. This model was used to predict the depth of deformation caused by the impact of abrasive particles. The primary objective of the study was to develop finite element model of AWJM for the prediction of the depth of cut without experimentation. This model was based upon performance of workpiece material under dynamic loading of AWJ conditions. This model was used to
determine the forces acting on abrasive particles. It was concluded that plastic deformation was highly confined to a smaller area during machining of materials.

Liu et al. (2004) developed computational fluid dynamics (CFD) models for ultra high velocity water jet using Fluent 6 flow solver. During the study the dynamic characteristics of downstream jet from very fine nozzle under steady state and turbulent flow conditions were investigated. Water and particle velocities in a jet were obtained under the effect of different input factors and boundary conditions to determine jet characteristics and kerf formation. It was observed from the study that there is an initial rapid reduction of axial velocity at center of the jet. However cross-sectional flow moves toward higher side at downstream side.

Wang and Wang (2010) conducted theoretical analysis to develop a flow for AWJ. The objective of the study is to predict behavior of abrasive particles during AJM. The study proposed a two fluid model. A control volume method was applied to solve the equations as well as a phase algorithm was developed to solve the pressure velocity distribution equations. A 2D quasi flow field outside the nozzle was assumed in AWJ analysis to validate the model.

Mostofa et al. (2010) presented CFD and theoretical analysis to optimize the mixing of components by multiphase approach. Water, the air and abrasives were mixed in mixing the chamber. The developed model was used to predict the effect of air and abrasives mixture on the process performance. The study concluded that the nozzle length has a considerable effect on the mixing of water, air and abrasives. The velocity of water jet considerably affects the erosion rate mostly at the wall of the nozzle. It was also reported that erosion in the nozzle body is higher at initial zone and volume fraction of the air increases with the increase in length of the nozzle (Rao, 2011).

Ultrasonic machining (USM) is one of the nontraditional modern machining processes. In this process, material is removed by the dynamic action of abrasive grains. The term ultrasonic is used to express the vibratory wave having a frequency above the upper limit of the human ear. The flow of abrasives is maintained by the abrasive slurry which drives the abrasives into the machining zone. The oscillatory tool moves perpendicularly to the work surface with high frequency. Each and every abrasive moves with high momentum and strike the work surface to remove the material. This process is
having the advantage of machining hard and brittle materials with better accuracy and high quality of surface finish.

Miller (1957) developed analytical models of MRR for USM to predict the performance of the process. The developed MRR model was based on plastic deformation of ductile materials. Later Kainth et al. (1979) reported a mathematical model to predict machining rate using properties of tool and workpiece materials.

Lee and Chan (1997) developed an analytical model to determine the effect of amplitude of the tool tip, static load and grit size of abrasives on MRR and surface roughness. The experimental results confirmed that an increase in amplitude of tool vibration, static load and grit sizes of abrasives causes increase in MRR and SR.

Wang and Rajurkar (1996) suggested a realistic model based on stochastic and dynamic nature of the USM process. This model was purely meant for brittle materials only.

Komaraiah et al. (1988) conducted experimental investigation into USM of glass, porcelain, ferrite and alumina using various types of tool materials. This study reveals the effect of mechanical properties of the workpiece and different tool materials on surface roughness and accuracy. The effect of size, type of abrasives, amplitude of tool oscillations and workpiece rotation was also investigated on MRR.

Rotary USM is a hybrid machining process which removes material due to the combined effect of USM and grinding process. This process has the potential of higher MRR and accuracy with minimum surface damage. The rotary mode of USM has found positive effects on machining characteristics as compared to conventional USM.

Hu et al. (2002) proposed an analytical model for MRR during rotary ultrasonic machining of ceramics. This study was conducted with experimental design of five factors at two levels to develop a correlation between machining parameters and MRR. The study investigated the crack propagation on the workpiece surface during machining.

Kumar and Khamba (2009) proposed a mathematical model to analyze MRR during rotary USM. Taguchi multi-objective optimization technique was used to predict the optimum combination of machining parameters like type of abrasive slurry, size and concentration of abrasives, tool material and rating of the machine during machining of satellite. Singh and Gill (2009) applied fuzzy modeling and simulation on ultrasonic
drilling of porcelain ceramic with hollow stainless steel tool electrodes to measure the performance characteristics.

WEDM is a thermoelectric process in which heat energy of the spark is used to remove material from the workpiece (Jain, 2009). The workpiece and tool electrode are electrically conductive in WEDM. It utilizes a continuously traveling wire electrode made up of copper, brass or tungsten. On the release of appropriate voltage, discharges occur between the wire and the workpiece in the presence of dielectric fluid. WEDM has been widely accepted as advanced machining process used to produce the intricate shapes and profiles. It is used in industries for modern tooling applications. High strength to weight materials such as advanced ceramics and composite materials can be easily machined by this process.

Several attempts have been made in the past to study the effect of various process parameters on the performance measures like cutting rate, surface finish and MRR with help of different mathematical modeling techniques.

Huang and Liao (2003) used grey relational and S/N ratio analysis to examine the effect of parameters such as table feed and pulse on-time on MRR. Tosun et al., (2003) experimentally determined the effect of pulse duration, open circuit voltage, wire speed and dielectric fluid pressure on SR. It was observed that an increase in pulse duration, open circuit voltage and wire speed causes an increase in surface roughness; however increase in dielectric fluid pressure cause a decrease in surface roughness (Rao, 2011).

Saha et al., (2004) developed a finite element model to predict the temperature distribution on workpiece during WEDM. This model was used to optimize the different parameters to prevent wire breakage during the process. The transient analysis mapped the heat distribution profile of the wire at any point on the wire. This model was used to predict the temperature distribution profiles of the wires made up of different materials. This same model was used to develop the smart electro discharge machining system attached to sensor to improve the cutting speed and minimize wire breakage.

Kanlayasiri and Boonmung (2007) proposed a mathematical model using regression method to evaluate the pulse on-time and peak current for minimum surface roughness. Hargrove and Ding (2007) developed an FEA program for the modeling of temperature distribution of the workpiece under different machining conditions. The
thickness of heat affected layers obtained at different settings of control parameters was computed on the basis of critical temperature value. This study was found to be supportive in developing advanced control strategies to enhance complex machining capabilities and machining rates with minimum surface damage. Table 2.1 summarizes the year wise developments in electrical discharge surface grinding carried out by various researchers.

### 2.6.1 Thermal Modeling of EDSG Process

Some of the researchers in the past have reported thermal models for independent EDM and conventional grinding process. Erden and Kaftanoglu presented a thermal model based on the uniform distribution point source assumption. In this model, the main assumption is that source points covers the electrode surface intersecting the spark channel. It was reported that only 10-20% of the total molten material is removed at the end of the pulse. Later on model was also developed for spark created by EDM in a liquid media (Erden and Kaftanoglu, 1981; Eubank et al., 1993). Most of the thermal models developed for grinding are mainly focused on the heat transfer to the workpiece with specified heat flux and with or without convection at the workpiece surface. Some models have been reported on thermal modeling of grinding by Soneys et al., Malkin et al. and Zang et al. (Snoeys et al., 1978; Malkin, 1984; Zhang et al., 1992).

Yadav et al. (2002) developed finite element model to predict the temperature distribution and thermal stresses due to Gaussian heat flux profile during EDM. First the model was used to identify the temperature of the workpiece and then thermal stress field is estimated using temperature field. The effect of input parameters like current and duty cycle on temperature and thermal stress distribution was investigated.

Yadava et al., (2002) proposed mathematical thermal model for the cut-off grinding. In this study, the modeling of heat flux profiles with energy partition was developed to investigate the temperature distribution on the workpiece surface after machining. The effect of cutting speed \(V_s\) on the heat flux \(q_{wg}\) was explained on the basis of specific grinding energy \(U_g\) and they are related to each other by following equation (Malkin., 1989).

\[
U_g = \frac{F_c V_s}{MRR_V} = \frac{F_c V_s}{V_f A}
\]  

(2.1)
Here, \( F \) is a tangential force, \( V_s \) is grinding speed related to RPM of grinding wheel, \( \text{MRR}_v \) is volumetric material removal rate and \( A \) is the area of crossection of the workpiece top surface.

Erden (1983) suggested an empirical relationship to evaluate radius of a spark for the selected pairs of electrodes and dielectric. The relationship between spark radius \( R(t) \) and time \( (t) \) is given as:

\[
\frac{t}{K} = KQ^n \tag{2.2}
\]

Where \( Q \) is discharge power and \( m, n \) and \( K \) are empirical constants. These constants are defined in terms of experimental coefficient \( L, M \) and \( N \) determined experimentally for different electrode materials.

\[
K = \frac{L}{lM + 0.5N} \quad m = 0.5N, \quad n = N \quad (l \text{ is discharge length}) \tag{2.3}
\]

Model for calculation of the discharge radius during machining was proposed by Pandit and Rajurkar (Pandit and Rajurkar, 1980).

\[
T_b = \frac{E_0}{kT_{b0}^{0.5}} \tan^{-1} \left[ \frac{4\alpha t}{R^2} \right]^{0.5} \tag{2.4}
\]

Where, \( T_b \) is boiling the temperature, \( E_0 \) is energy density, \( \alpha \) is thermal diffusivity, \( t \) is the time at which radius is calculated, and \( k \) is thermal conductivity of workpiece material.

Balaji and Yadava, (2013) developed a simulation model to simulate the EDDSG process. This investigation involves the simulation of each constituent process namely EDM and surface grinding. The effect of different types of dielectric fluids, duty factor and energy partition during EDDSG on temperature distribution was reported in the study. It was observed that the spark contributes dominantly to the temperature of the workpiece.

The predicted results from the model can be used for the improvement in surface integrity and machining performance of the machined surface.

2.7 Summary

Among the discussed literature, it is evident that a lot of work has been done on machining of Tool steel and advanced materials by conventional and non-conventional machining processes. The outcome of the past research is to improve the material removal rate and surface finish of the machined component.
<table>
<thead>
<tr>
<th>Year</th>
<th>Authors (Year)</th>
<th>Tool material</th>
<th>Work material</th>
<th>Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>P. Koshy, V.K Jain and G.K Lal</td>
<td>IAI Diamond Wheel, 5.7mm thick,100mm Dia,G80/100C75, Bronze bond</td>
<td>High speed steel (20%W, 4% Cr, 5% V) 5.6mm wide</td>
<td>Investigated material removal mechanism of electrical discharge diamond grinding.</td>
</tr>
<tr>
<td>1996</td>
<td>P. Koshy, V.K Jain and G.K Lal</td>
<td>IAI Diamond Wheel, 5.7mm thick,100mm Dia,G80/100C75, Bronze bond</td>
<td>Cemented carbide (86%WC, 2.5% TiC, 6% TaNb C, 5.5%CO) Grain size 2-3µm, width 5.6 mm</td>
<td>Metal bonded diamond wheel used to machine high speed steel. Simple model was proposed to evaluate the reduction in normal force caused by electrical discharges.</td>
</tr>
<tr>
<td>2000</td>
<td>C.C Wang, B. H Yan</td>
<td>Copper, cylindrical shape, dia 12.7mm</td>
<td>10 vol. % Al₂O₃/6061 Al Composite</td>
<td>Optimization of blind hole drilling of Al₂O₃/6061Al composite using electro discharge machining by using Taguchi method.</td>
</tr>
<tr>
<td>2001</td>
<td>J. Kozak and K. E. Oczos</td>
<td>PCD Wheel electrode</td>
<td>Titanium alloy and MMC</td>
<td>Methodology for Hybrid Machining process evaluation. AECG and AEDG with PCD wheel electrode used for machining of titanium alloy and MMC.</td>
</tr>
<tr>
<td>2002</td>
<td>B. H. Yan et. al.</td>
<td>Copper, ring shape, 4.75-5mm thick</td>
<td>Al-Zn-Mg Alloy, 13mm thick</td>
<td>Surface modification of Al-Zn-Mg Alloy by combined electrical discharge machining and ball burnish machining.</td>
</tr>
<tr>
<td>2003</td>
<td>K.M Shu and Hung Rung Shih</td>
<td>Cu/SiCₚ Composite tool electrode</td>
<td>HPM 50 mold steel</td>
<td>Electrical discharge grinding of HPM 50 mold steel using Metal Matrix composite electrode.</td>
</tr>
<tr>
<td>2006</td>
<td>H. R Shih &amp; K.M Shu.</td>
<td>copper rotary disk electrode</td>
<td>AISI D2 tool steel</td>
<td>Electrical discharge grinding of AISI D2 tool steel using a copper rotary disk electrode.</td>
</tr>
<tr>
<td>2007</td>
<td>S. Kumar and S.K. Choudhury</td>
<td>Metal bonded diamond grinding wheel</td>
<td>High Speed Steel</td>
<td>Prediction of wear and surface roughness in EDDG of high speed steel by design of experiments and neural network.</td>
</tr>
<tr>
<td>2013</td>
<td>Renjie Ji et al.</td>
<td>Steel wheel with uniform distributed abrasive sticks</td>
<td>SiC ceramic blank</td>
<td>Hybrid machining process is used in machining of SiC. The process used multiple cylindrical copper and abrasive electrodes mounted on the turntable.</td>
</tr>
<tr>
<td>2013</td>
<td>Manoj Modi and Gopal Aggarwal</td>
<td>Bronze bonded diamond wheel</td>
<td>Ti-6Al-4V alloy</td>
<td>Powder mixed Electro-discharge machining</td>
</tr>
<tr>
<td>2013</td>
<td>P.S Balaji and Vinod Yadava</td>
<td>Diamond wheel metal bonded</td>
<td>High speed steel</td>
<td>Finite element simulation of EDDSG.</td>
</tr>
</tbody>
</table>
From the extensive review of available literature it is observed that lot of work is published on the machining of advanced materials with common machining parameters such as pulse on-time, pulse off-time, discharge current, duty factor and gap voltage. In order to enhance the machinability and surface finish of hard materials there is urgent need to investigate the effect of combined (hybrid) machining process on the machining of most usable hard materials like AISI D2 Die steel and Al$_2$O$_3$ ceramic based metal matrix composites. There is also a need to explore the effect of hybrid energies during machining of hard and conductive materials. From the review of the literature it is cleared that the quantum of energy released during the machining process can be controlled by the process parameters to improve material removal and surface finish of the workpiece.

Also, very little information is available on the effect of non-electrical parameters such as abrasive particle size (APS), abrasive particle concentration (APC) and rotational speed of the tool electrode on the performance of EDM. Apart from this published literature, limited information is available on the machining of composite materials by the composite tool electrodes. The outcome of the study will enhance the opportunities of composites toward manufacturing technology.