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A REVIEW ON THE STATE OF THE ART IN WIRE ELECTRIC DISCHARGE MACHINING (WEDM) PROCESS

ANISH KUMAR [1], Dr. VINOD KUMAR [2], Dr. JATINDER KUMAR[3]

[1] Assistant Professor, Department of Mech. Engg., M.M.University
Mullana-Ambala-133203(Haryana)
[2] Assistant Professor, Department of Mech. Engg., Thapar University,
Patiala-147004(Punjab)
[3] Assistant Professor, Department of Mech. Engg., National Institute of
Technology, Kurkshetra(Haryana)

ABSTRACT

Electrical discharge wire cutting, more commonly known as wire electrical discharge machining (WEDM), is a spark erosion process used to produce complex two- and three-dimensional shapes through electrically conductive work pieces by using wire electrode. The sparks will be generated between the work piece and a wire electrode flushed with or immersed in a dielectric fluid. The degree of accuracy of work piece dimensions obtainable and the fine surface finishes make WEDM particularly valuable for applications involving manufacture of stamping dies, extrusion dies and prototype parts. The most important performance measures in WEDM are MRR (or cutting speed), surface roughness and kerf (cutting width). Discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, average working voltage and dielectric flushing conditions are the machining parameters which affect the performance measures. Over the years, the WEDM process has remained as a competitive and economical machining option fulfilling the demanding machining requirements imposed by the short product development cycles and the growing cost pressures. However, the risk of wire breakage and bending has undermined the full potential of the process drastically reducing the efficiency and accuracy of the WEDM operation. A significant amount of research has explored the different methodologies of achieving the ultimate WEDM goals of optimizing the numerous process parameters analytically with the total elimination of the wire breakages thereby also improving the overall machining reliability. This paper reviews the vast array of research work carried out from the spin-off from the EDM process to the development of the WEDM. It reports on the WEDM research involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity.

KEY WORDS*:* WEDM; Cutting rate; Material removal rate; Kerf; Recast layer; Spark gape.

1. INTRODUCTION

This paper provides a review on various academic research areas involving the WEDM process. It first presents the process overview based on widely accepted principle of thermal conduction and highlights some of its applications. The main section of this paper focuses on the major WEDM research activities, which include the WEDM machining characteristics and process optimization together. With the development of technology, the scientists and technologists in the field of manufacturing are facing more and more challenges. Technologically advanced industries such as aeronautics, nuclear reactors and automobiles have been demanding HSTR materials having high strength to weight ratio. Researchers in the area of materials science are developing materials having higher strength, hardness, toughness and other diverse properties. This also needs the development of improved cutting tool materials so that productivity is not hampered. It is a well established fact that during conventional machining processes an increase in the hardness of work material results in a decrease in the economic cutting speed. It is no longer possible to find tool materials which are sufficiently hard and strong to cut (at economic cutting speeds) materials such as titanium, stainless steel, nimonics, fiber-reinforced composites, ceramics and stellites. Production of complex shapes in such materials is still more difficult using conventional methods [1, 2]. Other higher level requirements such as better surface quality, low value of tolerances, higher production rates and miniaturization pose greater problems in machining of such materials. Making of holes (shallow entry angles, non-circular, micro holes, large aspect ratio, contoured holes and holes without burr) in difficult to machine materials is another area where extensive research is the need of the hour [3]. To meet such demands, a different class of machining processes known as non-traditional machining processes has been developed. These newer methods are also called unconventional in the sense that conventional tools are not employed for metal cutting. Instead, the energy in its direct form is utilized to remove the material from the work piece. The range of application of the newly developed machining processes is determined by the work material properties such as electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. The use of these processes is becoming increasingly unavoidable and popular at the shop floor [4].

2.0 WEDM PROCESS

This section provides the basic principle and cutting process of the WEDM.

2.1 Overview of WEDM process

The very phenomenon of removal of metal by electrical spark was first noticed around the year 1700 by Benjamin Franklin. But the application of the principle took almost two hundred and fifty years. In 1948 the Lazarenkos, a Russian husband and wife first applied it to a machine for stock removal. They adapted the first servo-system to an EDM machine, which offered some apparent degree of control that is required. Initially EDM was used primarily to remove broken taps and drills from expensive parts. These were quite crude in construction with hand-fed electrodes. WEDM was first introduced to the manufacturing industry in the late 1960s [5]. The WEDM technology over conventional EDM technology was the result of an effort to replace the machined electrode which was often difficult to produce. The major evolution of the machining process followed only when in the late 1970s CNC system was incorporated into WEDM [6-7].

2.2 Principle of WEDM

WEDM is a widely accepted non-tradition material removal process. The material removal mechanism of WEDM is the same as that of electrical discharge machining. It has been widely accepted that the metal removal mechanism in EDM is predominantly a thermal effect in nature [8-9].The basic principle behind EDM process is a series of electric sparks between the work piece and wire electrode. The electrical discharging process generates a tremendous amount of heat causing melting or even evaporation in the local surface layers on both wire-electrode and work piece sides. The heat also causes vaporization of the dielectric fluid and induces high-pressure waves, which wash out the molten and/or vaporized metal into pieces from the work piece. Continuously injected dielectric fluid then carries the droplets of metal away. WEDM is considered as a unique adaptation of the conventional EDM process. However, WEDM utilizes a continuously traveling wire electrode made of thin copper, brass or tungsten material, which is capable of achieving very small corner radii. It is desirable that the wire electrode and work piece both be electrically conductive. **Figure 2.1** shows about the general application of WEDM cutting process.

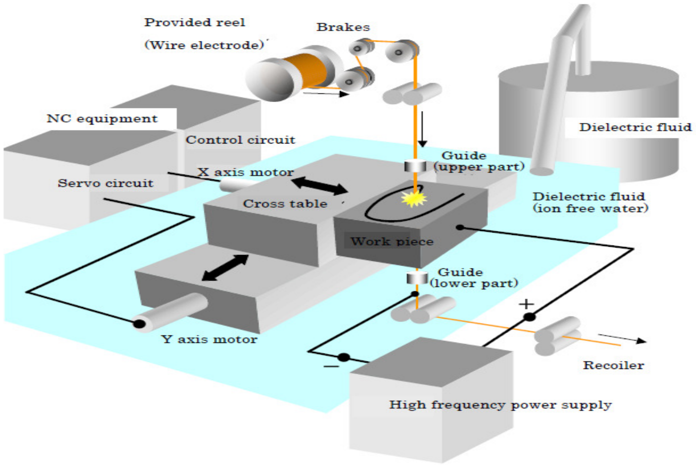

Figure 2.1 Wire electrical discharge machining Process [8]

2.3 Understanding the sparking phenomena in WEDM [9]

Shumacher **[9]** rightly chose his paper's title, which summarizes the current understanding of sparking phenomena in Electro discharge machining. The title of his paper was 'After 60 years of EDM the discharge process remains still disputed.'

In 1943 Lazarenko proposed the basic mechanism of EDM and since then the very nature of spark is yet not properly understood among scientific community. There are differences in opinion regarding the spark ignition theories as well as in respect to metal removal procedure, such as thermal effects, thermal shocks, mechanical stress etc.

2.4 Types of Wire Materials and Its Application [10]

One of the first decisions that the WEDM user must be concerns is the choice of wire electrode material. EDM wires are usually made from a variety of materials, depending on the work piece material and its applications. There are many type of wire materials which is commonly used such as brass, zinc coated brass, tungsten, copper and so on. Usually, wires are distinguished mainly by their flexibility, which essential for taper machining and by their traction resistance which favors accuracy. The ideal wire electrode material has three important criteria, there are, high electrical conductivity, sufficient mechanical strength and optimum spark and flush characteristics. Based on the information gather through readings, there is no perfect wire that excels in every criterion therefore; some compromises may require depending upon the desired results and application. Below is the list of the most frequently used wires with their general fields of applicon [11, 12].

2.5 Parameters for Wire EDM

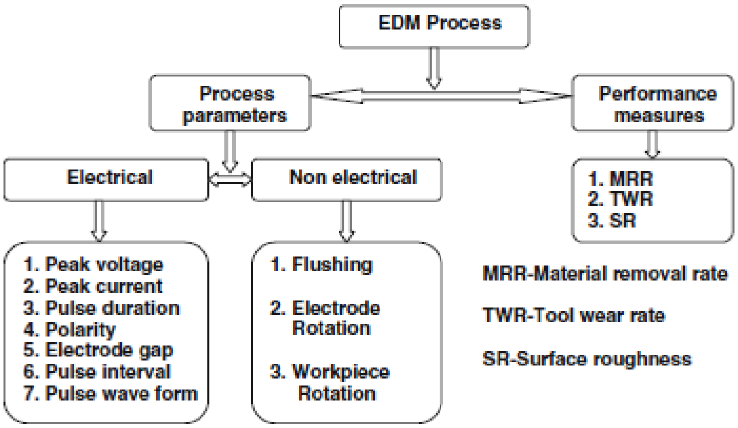

Figure 2.2 Process parameters and Performance measure of WEDM [12]

Since Wire EDM is a necessary process with a high cost, it is required that the appropriate machining parameters are selected for an economical machining operation. The machining parameters can be set for optimum machining with the knowledge of the effect of the machining parameters on the Wire EDM performance measure, such as surface roughness.

2.6 Major areas of WEDM research

The authors have organized the various WEDM research divided into two major areas namely WEDM process optimization together with WEDM process monitoring and control.

2.6.1 WEDM Process Optimization

The most effective machining strategy is determined by identifying the different factors affecting the WEDM process and seeking the different ways of obtaining the optimal machining condition and performance. WEDM process plays a crucial role in producing an optimal machining performance. This section shows some of the analytical and statistical methods used to study the effects of the parameters on the typical WEDM performance measures such as CS, MRR and SR.

2.6.2 Factors affecting the performance measures

WEDM is a complex machining process controlled by a large number of process parameters such as the pulse duration, discharge frequency and discharge current intensity. Any slight variations in the process parameters can affect the machining performance measures such as surface roughness and the energy distribution strategy in fast cutting wire EDM [13-14]. It was experimentally confirmed that a stable high cutting speed can be achieved without detriment to the electrode wire only by applying discharge pulses with high power density and then raising the pulse density to the greatest possible extent. An extreme long discharge duration causes low energy efficiency, while excessively high pulse density results in incurable instability with low discharge efficiency **[15]**. Luo**[16]** analyzed the energy distribution strategy in fast cutting wire EDM. It was experimentally confirmed that a stable high cutting speed can be achieved without detriment to the electrode wire only by applying discharge pulses with high power density and then raising the pulse density to the greatest possible extent. An extreme long discharge duration causes low energy efficiency, while excessively high pulse density results in incurable instability with low discharge efficiency. Minami et al. **[17]** proposed a coloring method of titanium alloy using WEDM during the finishing without any other post treatment. When machining in water, a molten and resolidified surface created by electrical discharge process was colored directly by the interference phenomenon of light in the anodic oxide film formed with electrolysis reaction. The thickness of the oxide film controlled by the average working voltage determined the color tone.

Puri and Bhattacharyya **[18]** analyzed the wire tool vibration in WEDM. They presented an analytical approach for the solution of the wire-tool vibration equation considering multiple spark discharges to investigate into the characteristic effect of wire vibration in WEDM. The selection of appropriate machining conditions for the WEDM process is based on the analysis relating the various process parameters to different performance measures namely the CS, MRR and SR. Traditionally; this was carried out by relying heavily on the operator's experience or conservative technological data provided by the WEDM equipment manufacturers, which produced inconsistent machining performance. Levy and Maggi **[19]** demonstrated that the parameter settings given by the manufacturers are only applicable for the common steel grades. Liao and Yu **[20]** studied the effect of specific discharge energy on machining characteristics under machining conditions. A quantitative relation between machining characteristics and machining parameters is derived. It was observed that materials having close values of specific discharge energy show similar machining characteristics under same machining conditions. The two most significant factors affecting the discharge energy (η) are discharge-on time and servo voltage. Discharge-on time and workpiece height have a significant effect on machined groove width. Sanchez et al. **[21]** discussed the influence of work thickness, corner radius and number of trim cuts on the accuracy of WEDM corner cutting. AISI D2 tool steel work material and brass wire were used. It was found that wire lag is responsible for the back-wheel effect in corner cutting and deviation was larger in case of the test-piece with smaller corner radius. It is not possible to achieve an optimum fit along the whole corner (both at $45^0$and at the exit). There was a reduction in dimensional error up to 50% in case of corners between 30^0 and 135^0.

Regener et al.**[22]** A wire electric discharge machining assisted dissectioning method have been presented, which combines high precision cutting, minimum generation of additional residual stresses during the cutting process and high precision measurement of the resulting distortion. A forged component made of the titanium alloy (Ti6Al4V) was investigated in a multiple cut procedure. A finite element based mechanical model for the estimation of the residual stress distribution in the component from the distortion data has been introduced and discussed. The obtained results from the presented two- and three-dimensional FE-models predicting the distortion, depending on the heat transfer parameters, was very promising in terms of an efficient use of computational resources due to advanced thermo-mechanical modeling. Ezugwu **[23]** reported the advancement in machining techniques to improve productivity and lowering the manufacturing cost without affecting surface finish, surface integrity, circularity and hardness variation of the machined component. There is a significant increase in temperature at the cutting tool and the workpiece during machining due to low thermal conductivity of titanium alloy (about 15W/m °C), nimonic alloy (about 11W/m °C) and silicon nitride (about 13W/m °C) relative to conventional steel or cast iron. The hybrid machining techniques combining heating of the workpiece and cryogenic cooling of the cutting tool demonstrates potential for improving the machining of difficult to cut nimonic and titanium base alloys.

2.6.3 Effects of process parameters on the cutting speed

Many different types of problem-solving quality techniques have been used to investigate the significant factors and its inter-relationships with the other variables in obtaining an optimal WEDM cutting speed. Choudhury and Baradie **[24]** reported the advantages and disadvantages of different tool materials with regard to the machining Inconel. It was found that rate of tool wear increases with increase in titanium and aluminium. During machining, cutting speeds can be increased up to ten times as compared to cemented carbide by using silicon-carbide whisker reinforced alumina tools. Alumina-TiC ceramic tools are best suited for high speed machining (over 400 n $\min^{-1}$) or high feed rate, whilst whisker reinforced alumina is suitable for a medium cutting speed (100-400 n $\min^{-1}$) with a low feed rate. Uncoated carbides tools are better cutting tools for machining Inconel-718. A common problem during machining Ni-base alloys is the development of V-shaped groove or notch at the depth of the cut line.

Guo et al. **[25]** analyzed the WEDM characteristics of particle reinforced material (Al_2O_3 in 6061 Al alloy). A method of orthogonal design was adopted to determine the main factors that affect the machining process. The result showed that the electrical discharge energy was closely related to machining stability. It was found that electric parameters have little influence on the surface roughness whereas these are important for the cutting rate. Whether high energy or the low energy was used, a coarse surface was always obtained. The result showed that the effect of the electrical parameters on the cutting rate was in turn the pulse duration, the voltage, the machining current and the pulse interval. In operation, large pulse duration, a high voltage, a large machining current and a proper pulse interval was selected to have high machining efficiency. Konda et al. **[26]** investigated the various potential factors affecting the WEDM performance measures into five major categories namely the different properties of the workpiece material and dielectric fluid, machine characteristics, adjustable machining parameters, and component geometry. In addition, they applied the DOE technique to study and optimize the possible effects of variables during process design and development, and validated the experimental results using (S/N) ratio analysis. Tarng et al. **[27]** applied a neural network technique with the application of a simulated annealing algorithm for solving the multi-response optimization problem. It was observed that the machining parameters such as the pulse on/off time, peak current, open circuit voltage, servo reference voltage, electrical capacitance and table speed are the critical parameters for the estimation of the CS and SR. Rozenek et al.**[28]** experimentally investigated the effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on the machining feed rate and surface roughness during wire elecrical discharge machining of metal matrix composite $AlSi_7Mg/SiC$ and $AlSi_7Mg/ Al_2O_3$. The machining feed rate of WEDM cutting composites significantly depends on the kind of reinforcement. The maximum cutting speed of $AlSi_7Mg/SiC$ and $AlSi_7Mg/ Al_2O_3$ composites are approximately 3 times and 6.5 times lower than the cutting speed of aluminum alloy respectively. Kuriakose and Shunmugam **[29]** optimized the WEDM process for Titanium alloys by non-dominated sorting genetic algorithm and found that there was no single optimal combination of cutting parameters, as their influences on the cutting velocity and the surface finish are quite opposite.

Ozdemir and Ozek **[30]** investigated the machinability of nodular cast iron by WEDM using different parameters machining voltage, current, wire speed and pulse duration. Results indicates that increase in surface roughness and cutting rate clearly follows the trend indicated with increasing discharge energy as a result of an increase of current and pulse on time, because the increased discharge energy will produce larger and deeper discharge craters. The variation of surface roughness and cutting rate with machining parameters was mathematically modelled by using the regression analysis method. Saha et al**. [31]** analyzed the wire electrical discharge machining of tungsten carbide cobalt composite. A second order multi-variable regression model and a feed-forward back-propagation neural network model have been developed to correlate the input process parameters, such as pulse-on time, pulse-off time, peak current and capacitance with the process performance namely cutting speed and surface roughness. It was observed that neural network architecture provide the best result prediction although the proposed regression model was adequate and accepted. Rao et al**.[32]** discussed influence of parameters such as discharge current, voltage, wire speed, tension on WEDM machining of Brass for optimization of cutting speed, MRR and spark gap using four wires of different Cu percentage. It was observed that cutting speed decreases as thickness of work piece increases due to larger material need to be removed at larger thickness. With increase in current, there is an upward trend in the spark gap, MRR increases with an increase in discharge current. S. Sarkar et al. **[33]** modeling and optimization of wire electrical discharge machining of γ-TiAl in trim cutting operation. A second-order mathematical model, in terms of machining parameters, was developed for surface roughness, dimensional shift and cutting speed using RSM. The residual analysis and experimental result indicated that the proposed models could adequately describe the performance indicators within the limits of the factors that are being investigated. Finally the trim cutting operation was optimized for a given machining condition by desirability function approach and pareto optimization algorithm. It was observed that performance of the developed pareto optimization algorithm is superior compared to desirability function approach.

Romlay and Mokhtar **[34]** presented an optimization of the WEDM cutting parameter at welding joint area. The experiment was conducted during a gear shape optimization process by reducing the gear material and weight. Some area of the gear is welded for material joining process. The wire-EDM cutting process has been conducted by cutting at the single material and welding area. The parameters of cutting process such as wire speeds, wire tensions and wire voltage was considered to be optimized. The cutting condition at the single and double materials area has been compared. The result of the experiment shows that the cutting speed of the wire-EDM has been affected by changing cutting parameters. The material properties also give a big impact to the cutting process methodology. Poros et al. **[35]** develop the model of efficiency of cutting by application of dimensional analysis. The developed semi-empirical model should enable analysis of the influence of the most important process parameters and properties of machined materials on volumetric efficiency of cutting. The thermal nature of WEDM, the efficiency of cutting is lower for materials with a higher melting point. WEDM of cemented carbides B40 is concerned, the highest volumetric efficiency is 9.1mm3/min and it is 50% more than for the uncoated brass CuZn37 electrode and 17% more than for the zinc-coated electrode. WEDM of titanium alloy Ti6Al4V, the highest volumetric efficiency is 17.75mm3/min and it is 18% more than for the uncoated brass CuZn37 electrode and 16% more than for the zinc-coated electrode. The increase of discharge time from 3 to 7µs causes an increase of volumetric efficiency of cutting of cemented carbides B40: utilizing uncoated brass wire electrode 62%, and for zinc-coated wire electrode 138%, and for wire electrode coated CuZn50 160%. Jangra et al. **[36]** presented the optimization of performance characteristics of WEDM using Taguchi and Grey Relational Analysis on D_3 tool steel. The process parameters considered in this research work was T_{on}, T_{off}, Peak current, Wire speed and Wire tension. Taguchi's L_{18} Orthogonal Array was used to conduct experiments. Data related to the process responses viz. cutting speed, surface roughness value of the worked surface and dimensional lag have been measured for each of the experimental runs .The results showed that by using GRA, the optimal setting of process parameters for multiple performance characteristics was set with $A_5B_2C_1D_1E_2$.The cutting speed was observed 3.80mm/min with dimensional lag 0.008mm which is quite acceptable for rough cutting but surface roughness was poor.

2.6.4 Effects of process parameters on the metal removal rate

Material removal rate in WEDM is defined as the amount of material that is removed per unit time. Material removal rate is an indication of how fast the machining rate is. Since machining rate is very much related to the economic aspect, often it is a high preference objective to achieve. Thus a parameter that leads to higher material removal rate is important for the production. At the same time higher machining productivity must also be achieved with a desired accuracy and surface finish.The effects of the machining parameters on the volumetric MRR have also been considered as a measure of the machining performance. Scott et al. **[37]** have presented a study for the optimization of cutting parameters, which are effective for material removal rate and surface finish. They found that the surface finish increases with increasing discharge current, pulse duration and wire speed. Liao et al. **[38]** investigated the MRR, surface roughness, gap width, sparking frequency, average gap voltage and normal ratio in WEDM of SKD11 alloy steel by using Taguchi method. It was reported that table feed and pulse-on time have a significant influence on the metal removal rate, the gap voltage and the total discharge frequency, whilst the gap width and surface roughness are mainly influenced by the pulse-on time. Huang and Liao **[39]** presented the use of Grey relational and S/N ratio analyses, which also display similar results demonstrating the influence of table feed and pulse on-time on the MRR. Rajurkar and Wang **[40]** experimentally investigated the material removal rate for varying machining parameters. The experimental findings are used in a developed thermal model to analyze the wire rupture (breakage) phenomena. The probable causes leading to wire rupture are failure under excessive thermal load, failure through short circuiting and wire vibration, the most important among these being the thermal load.

Hewidy et al. **[41]** modeled the machining parameters of wire electrical discharge machining of Inconel- 601 using RSM.The analysis of the response parameters using RSM technique had the advantage of explaining the effect of each working parameter on the value of the resultant response parameter. The volumetric metal removal rate generally increased with the increase of the peak current value and water pressure. Mahapatra and Patnaik **[42]** optimized the parameters using Taguchi method on D2 tool steel as work material in WEDM process. It was observed that discharge current, pulse duration, dielectric flow rate and the interaction between discharge current and pulse duration are most significant parameters for cutting operation. Mathematical models were developed for optimization of MRR and surface finish using non linear regression method. The optimal parametric setting for MRR was observed to be discharge current (24 amp), pulse duration (6.4 μ sec.) and for surface finish it was found to be dielectric flow rate (1.4 bar), 16 amp discharge current, 3.2 μ sec. pulse duration and 1.4 bar dielectric flow rate. Ramakrishnan and Karunamoorthy **[43]** used multi response optimization method using Taguchi's robust design approach for WEDM. Each experiment had been performed under different cutting conditions of pulse on time, wire tension, delay time, wire feed speed and ignition current intensity. Three responses namely material removal rate, surface roughness and wire wear ratio had been considered for each approach. It was observed that the Taguchi's parameter design is a simple, systematic, reliable and more efficient tool for optimization of the machining parameters. It was indentified that the pulse on time and ignition current had influenced more than the other parameters. Manna and Bhattacharyya **[44]** optimized the machining parameters using the Taguchi and Gauss elimination method. The test results were analyzed for the selection of an optimal voltage and pulse on period was the most significant and influencing parameters for controlling the metal removal rates. Kozak et al. **[45]** analyzed the machining of low electrical conductive material (Si_3N_4) by WEDM. It was observed that there was a significant change in cutting velocity depending upon the clamp position. As the cut approaches the clamp, there was an increase in MRR. A reduction in MRR occurs when the wire moves away from the clamp. Hence, it was found that actual MRR depends on the individual machining geometry and relative position of wire electrode with respect to clamping. To reduce the energy loss due to drop voltage in the work piece, the machining of Si_3N_4 was carried out with silver paint applied over the work piece. A significant increase in MRR was observed due to silver coating. Kumar et al. **[46]** investigated on WEDM parameters on machining Incoloy800 super alloy. The process parameters considered in this research work was Gap voltage, T_{on}, T_{off} and Wire feed. Taguchi's L_9 Orthogonal Array was used to conduct experiments. Optimal levels of process parameters were identified using Grey Relational Analysis and the relatively significant parameters were determined by Analysis of Variance. The variation of output responses with process parameters were mathematically modelled by using non-linear regression analysis method and the models were checked for their adequacy results. The optimal 'process parameters' based on Grey Relational Analysis for the Wire-Cut EDM of Incoloy 800 include a 50 V Gap Voltage, 10 μs pulse on-time, 6 μs pulse off-time and 8mm/minute Wire Feed rate. While applying the Grey-Taguchi method, The Material Removal Rate shows an increased value of 0.05351 g/min to 0.05765 g/min, the Surface Roughness shows a reduced value of 3.31μm to 3.10 μm and the Kerf width shows an reduced value of 0.324to 0.296 mm respectively, which are positive indicators of efficiency in the machining process. Thus, it can be concluded that the Grey-Taguchi Method, is most ideal and suitable for the parametric optimization of the Wire-Cut EDM process.

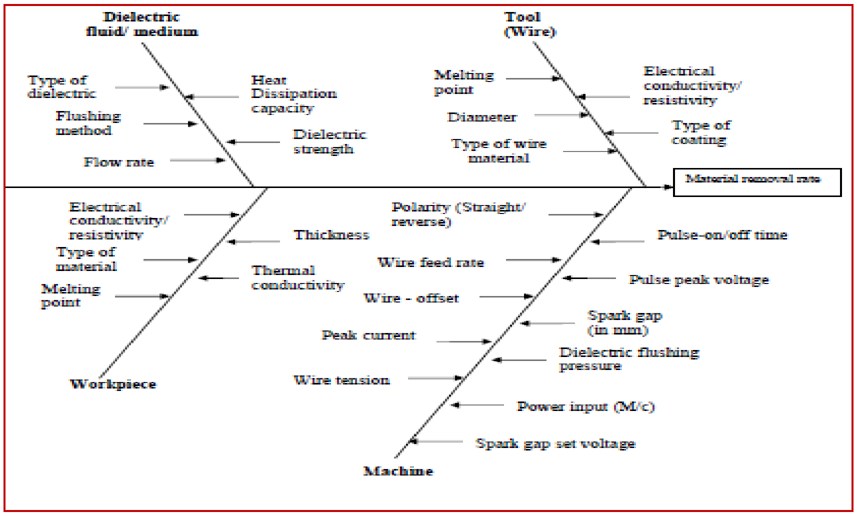

Figure 2.3: Cause and Effect diagram for MRR in WEDM

2.6.5 Effect of Machining Parameter on Spark Gap

The work piece and the wire represent positive and negative terminal in a DC electrical circuit and always separated by a controlled gap which is constantly maintained by the machine. This gap must always be filled with dielectric fluid, which acts as an insulator, cooling agent and also function as flushing in order to flush away the erode particles from the work zone . During wire-cut process, the sparking occurs between the side and machine surfaces of the work piece. The sparking area consist only the front of the electrode diameter (180°) as it progresses into the cut while the clearance is equal to the spark length of the wire electrode. The side clearance is known as spark over-cut and the total width of the machined opening is called the kerf width **(Figure 2.4 a and 2.4 b)**. In wire-cut operations, the spark gap ranges between 0.0008” to 0.002” (0.02 - 0.05 mm). However, the most common sparking gap that can be achieved is about 0.001” (0.03 mm) **[47]**.

Sparks are formed through a sequence of rapid electrical pulses, generated by the machine’s power supply thousands of times per second. Each spark forms an ionization channel under extremely high heat and pressure, in which particles flow between the wire electrode and the work piece, resulting in vaporization of localized sections. The vaporized metallic debris created by this process, from both the work piece and wire material, is subsequently quenched and flushed away by the flow of dielectric fluid through the gap.

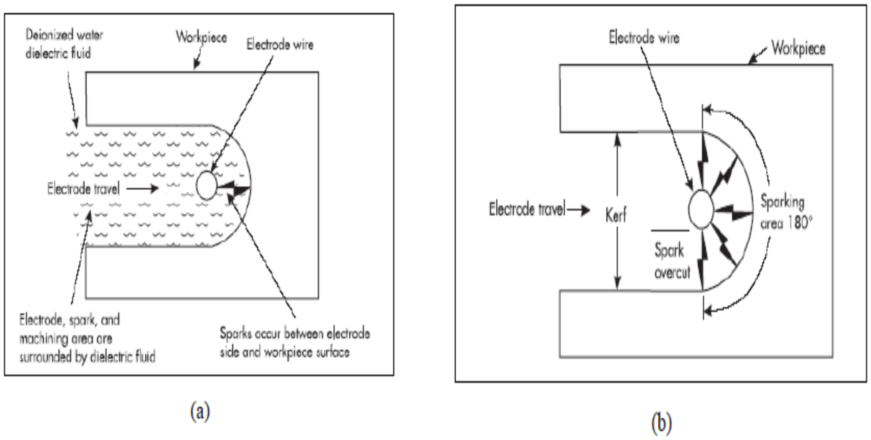

Figure 2.4 (a): Wire-cut sparking from the electrode side.
Figure 2.4(b): Wire-cut sparking area **[47]**.

Literature review survey showed that not many researchers have investigated the correlation between the machining parameters and spark gap in the EDM process. Although it may speculated that the spark gap would affect the machining characteristics such as surface roughness, electrode wear and material removal as it has been evidenced for other work material, information on details the effect of the spark gap on the machined surface is very scarce and rather vague in the open literature.

According to Luo **[48]** failure to evacuate surfeited debris in the spark gap will cause arcing damages to the tool electrode and the work piece. The main cause for an unstable EDM process is arcing. Therefore, in order to avoid arcing, the spark gap size should always be increased to evacuate more debris. To increase the spark gap, open circuit voltage must be increased, instead of introducing debris into the spark gap. However, in precision EDM it is found that by increasing voltage to increase the spark gap does not improve in process stability. He suggested that by applying a small spark gap size and certain amount debris are able to maintain process stability in precision EDM case. Wong et al. **[49]** claimed that the effect due to increase in the spark gap on the volume of micro crater is not so significant based on their experimental results on the erosion characteristics of the micro crater size. At the lower energies and varies spark gap (1-3.5 µm), the estimated eroding efficiency is higher than higher energies were applied. Further investigation was conducted in the correlation of spark erosion on the work piece. Spark erosion is found to be different effect for different types of working materials. All changes that could be detected were due to the high temperatures that were produced on the machining cutting zone. However, in some cases, the craters which are developed by certain distance of spark gap during discharge can provide better hold for lubricants thus, increases the service life of the tool. In others, if the gap is too close between the wire and the work piece, a short circuit may happen and causing the wire to break **[50]**.

2.6.6 Effects of process parameters on the Surface Roughness

During each electrical discharge, intense heat is generated that causes local melting or even evaporation of the work piece material. With each discharge a crater is formed on the work piece. Some of the molten material is produced by the discharge is carried away by the dielectric circulation and the remaining melt re-solidifies to form an undulating terrain. Scott et al. **[51]** have presented a study for the optimization of cutting parameters, which are effective for material removal rate and surface finish. They found that the surface finish increases with increasing discharge current, pulse duration and wire speed.

Hascalyk and Caydas **[52]** have studied surface roughness against open circuit voltage and dielectric fluid pressure. It was found that surface roughness increased when the pulse on time and open circuit voltage was increased. Because of greater discharge energy, the surface roughness is affected by on-time and open voltage. Again depending on the nature of the work material, the surface roughness varies. Because of higher thermal conductivity in annealed work piece roughness value is higher than quenched/tempered samples. In this case, rapid dissipation of the heat through the sample happens instead of concentration on the surface. When compared against different dielectric fluid pressure, surface roughness shows slightly decreasing trend with increasing pressure. This result is explained by the cooling effect and also increasing pressure helps the debris to be cleared out easily. The cutting performance with increasing dielectric fluid pressure improves because the particles in the machining gap are evacuated more efficiently. Yan et al. **[53]** have examined the effect of pulse-on time on surface roughness. It is found that the surface roughness increases with increasing pulse-on time. As increasing pulse-on time generates high discharge energy, it widens and deepens discharge craters of work piece surface. Also more reinforced particle in the work piece contributes to poor surface integrity. Most of the WEDM machine discharges current proportional to the current on time. The higher pulse on time imparts higher discharge energy that causes violent sparks and results in a deeper erosion crater on the surface. Accompanying the cooling process after the spilling of molten metal, residues remain at the periphery of the crater to form a rough surface.

The study of surface roughness at different duty factors, wire tension and flushing water pressure. From experimental results it is demonstrated that the surface roughness slightly increases with the increase of peak current value up to a certain value and then vigorously increase with any increase of peak current. The authors have explained the phenomena by the fact that increase in peak current causes an increase in discharge heat energy at the point where the discharge take place. The overheated pool of molten metals evaporates forming gap bubbles that explode when the discharge ceases. This takes away molten metals away and forms crater on the surface. Successive discharges thus resulted in worse surface roughness. From SEM micrograph of WEDM surface at different peak current it is again demonstrated that the depth of the crater depend on the discharge heat energy which again on the peak current value. The effect of duty factor on surface roughness demonstrated that with the increase with duty factor roughness slightly decreases. This is because increases of duty factor imply decrease in off time, which allow gas bubbles to decrease in number and to be smaller as a result of applying the heat energy for a shorter time. When the discharge ceases, these small gas bubbles will collapse containing lower pressure energy. The result is decrease in surface roughness. Wire tension effect on surface roughness demonstrated that with increasing tension, roughness decreased almost in a linear fashion. Since increase of wire tension minimizes the wire bending which leads to a dynamic stability condition and improves surface roughness. Surface roughness also decreased with increasing flushing water pressure to a certain limit after which the adverse effects of the force again produce worse roughness[54]. The SKD11 alloy steel (anode) as material and 0.25 mm diameter brass wire as electrode was used. Addition to pulse on time, table feed rate effect was also studied. From the analysis of the results, it was found that the surface roughness is mainly influenced by the pulse-on time. A larger table feed and a smaller pulse-on time is recommended by the authors for the reason that a longer pulse-on time will results in higher value of surface roughness. However, for table feed rate doesn't affect roughness, even though it can not be increased without constraints because of the risk of wire breakage. Kanlayasiri and Boonmung; **[55]** investigated the effect of machining variables on the surface roughness of DC53 die steel in Wire EDM by using full factorial method. It was reported that the surface roughness of the test specimen increases when the two parameters namely pulse-on time and pulse-peak current are increased and there is no effect of wire tension and pulse-off time on the surface roughness. The advancement in machining techniques to improve productivity and lowering the manufacturing cost without affecting surface finish, surface integrity, circularity and hardness variation of the machined component. There is a significant increase in temperature at the cutting tool and the work piece during machining due to low thermal conductivity of titanium alloy (about 15W/m °C), nimonic alloy (about 11W/m °C) and silicon nitride (about 13W/m °C) relative to conventional steel or cast iron. The hybrid machining techniques combining heating of the work piece and cryogenic cooling of the cutting tool demonstrates potential for improving the machining of difficult to cut nimonic and titanium base alloys. Bamberg and Rakwal **[56]** investigated the electrical discharge machining of p-type gallium-doped germanium with a relaxation type pulse generator and small wire diameter to enhance slicing rate and surface characteristics in WEDM. Full factorial method was used. The maximum surface roughness obtained for the different molybdenum wires (50, 75 and 100µm diameter) was observed to be are 3.31, 3.48 and 3.54 µm (Ra) respectively, using voltage of 150V with 68.8nF capacitor. It was found that 50µm molybdenum wire achieved the fastest machining time with a maximum slicing rate of 7.59mm² using a capacitor of 9.9nF and a voltage of 150V. The discharge energy was below the critical one with no cracks and smallest kerf losses.

2.6.7 Effects of process parameters on the Kerf or Gap Width

The kerf or gap width in WEDM consists of the diameter of the micro wire and two lateral discharge gaps. It is illustrated in the F**igure 2.5**.

In WEDM gap width is defined as the additional gap created on each side of the wire after machining. It is measured by subtracting the wire diameter from the total gap width cut and then dividing the result by two. The gap width is a very important parameter when it comes to accurate machining. The machining path accuracy, the level of sophistication achievable in miniaturization depends on the minimum gap width possible. Thus for µWEDM it is a major challenge to reduce the gap width as much as possible. Studies on parameters are needed in detail for understanding the co-relation with gap width and how it can be further improved **[57].** It was found that the gap width and surface roughness are mainly influence by pulse on time. But it was found out that only current on time, but also the applied energy influence the gap width. Also from the finding of other research work involved focused on the following parameters: Open circuit voltage, Peak current, Pulse duration or pulse on time and Wire tension.

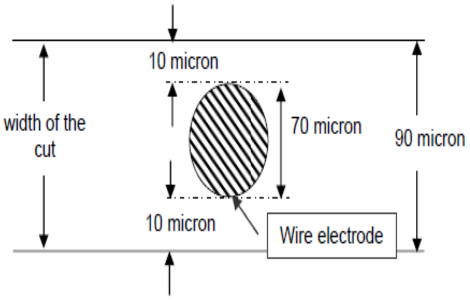

Figure 2.5: Kerf or Gap Width **[57]**

The dimensional accuracy of the kerf or gap width is very important in cutting micro parts. For WEDM, it is of practical need that the EDMed groove width should be predictable and under control. Depending on different machining condition, the groove width may vary. The internal corner radius to be produced in WEDM operations is also limited by the kerf. In order to have dimensional accuracy there is a need to know to control this EDM gap width. The input parameters of WEDM, like pulse on/off time, current intensity, open voltage, wire velocity affect the groove width.

Tosun et al. **[58]** have studied on kerf and material removal rate based on Taguchi Method. The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. They used commercial machine tool namely Sodick A320/EX21 EDM machine tool. CuZn37 master brass wire with 250 micron wire diameter was used in the experiment. Thus the work can not be termed as µWEDM. The study was conduced on AISI 4140 steel. Parameter levels were 100 and 270 volt, pulse durations 0.3, 0.6 and 0.9 micron second, wire speeds 5, 8 and 12.5 m/min and flushing pressures was 6, 12 and 18kg/cm^2. From their experimental results and statistical analysis they found that the most effective parameters with respect to kerf are open circuit voltage and T_{on} (pulse duration), whereas the effect of wire speed and dielectric flushing pressure on the kerf was insignificant. Yan et al. **[59]** have machined Al_2O_3 p/6061 Al composite where pulse-on time, cutting speed, the width of slit and surface roughness were studied. Also location of wire breakage and the reason of it were explored. They found that the material removal rate, the surface roughness and width of the slit of cutting significantly depend on volume fraction of reinforcement. In the experimental investigation of gap width (width of slit) against pulse on time, it was found that the increasing pulse on time contribute to higher width of slit. But the result is very much influenced by the amount of reinforced particle in the work material since they very much influence the thermal conductivity and electrical conductivity of composite material. Parashar et al. **[60]** reported the statistical and regression analysis of kerf width using design of experiments have been proposed for WEDM operations. Each experiment has been performed under different cutting conditions of gap voltage, pulse ON time, pulse Off time, wire feed and dielectric flushing pressure. From experimental results, the kerf width was determined for each machining performance criteria. Results showed that, pulse on time and dielectric flushing pressure are the most significant factors, while gap voltage, pulse off time and wire feed are the less significant factor to the kerf width of wire EDMed SS304L.The developed model showed high prediction accuracy within the experimental region. The maximum prediction error of the model was less than 4% and the average percentage error of prediction was less than 2%. Shah et al. **[61]** investigated the seven different machining parameters in addition to varying the material thickness on the machining responses such as material removal rate, kerf, and surface roughness of tungsten carbide samples machined by WEDM. The design of experiments was based on a Taguchi orthogonal designs with 8 control factors with three levels each were selected. The results showed that the material thickness has little effect on the material removal rate and kerf but is a significant factor in terms of surface roughness. For thinner work pieces, in order to obtain a fine surface finish, the spark energy will have to be reduced, which also reduces the material removal rate. Datta and Mahapatra **[62]** presented the quadratic mathematical models to represent the process behavior of WEDM operation. Experiments have been conducted with six process parameters: discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow rate; to be varied in three different levels. Data related to the process responses viz. MRR, roughness value of the worked surface (a measure of surface finish, SF) and kerf have been measured for each of the experimental runs. The results showed that established mathematical models to highlight parametric influence on three selected process responses: material removal rate, surface roughness value and width of cut. Response Surface Method has been found efficient for prediction of process responses for various combinations of factor setting. Apart from modeling and simulation, application of grey based Taguchi technique has been utilized to evaluate optimal parameter combination to achieve maximum MRR, minimum roughness value and minimum width of cut; with selected experimental domain. This method was very reliable for solving multiples.

3.0 CONCLUSIONS

WEDM is a nontraditional machining process used for machining intricate shapes in HSTR materials such as titanium, nimonics, zirconium, and tungsten carbide. The material removal in this process takes place by controlled erosion through a series of repetitive sparks (electric current discharge) between electrodes, that is, between the work piece and the tool. Both the work piece and the tool are submerged in the dielectric liquid during the actual machining process. The material is removed from the work piece in the form of small craters due to the spark from the electrical current discharge. WEDM provides high accuracy, better surface finish, and repeatability; however the tradeoff is a very slow machining rate. The machining rate in WEDM is defined as the amount (weight) of the material removed from the work piece in a given time and/or the cutting velocity measured in millimeters per minute.

The ultimate goal of the WEDM process is to achieve an accurate and efficient machining operation without compromising the machining performance. This is mainly carried out by understanding the interrelationship between the various factors affecting the process and identifying the optimal machining condition from the infinite number of combinations. The adaptive monitoring and control systems have also been extensively implemented to tame the transient WEDM behavior without the risk of wire breakages. Moreover, several monitoring and control algorithms based on the explicit mathematical models, expert's knowledge or intelligent systems have been reported to reduce the inaccuracy caused by the vibration behavior and static deflection of the wire. With the continuous trend towards unattended machining operation and automation, the WEDM process has to be constantly improved to maintain as a competitive and economical machining operation in the modern tool room manufacturing arena. Researchers believe that the WEDM process due to its ability to efficiently machine parts with difficult-to-machine materials and geometries has it own application area unmatched by other manufacturing processes.

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