

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Wire electrical discharge machining (WEDM) has now become widely accepted non-traditional material removal process to produce parts with complex profiles and shapes. The term EDM (Electrical Discharge Machining) is referred to as the machining process that uses an electrode to remove metal, or any other conductive material, from a work-piece by generating sparks between conducting surfaces. During machining, energy from the sparks created between the electrode and the workpiece is dissipated by the melting and vaporizing of the workpiece material. In a WEDM machine the electrode is in the form of a thin wire.

During the WEDM cutting process, a thin wire will cut through the conductive workpiece following a programmed path. The thin wire electrode is fed from reel to reel. Sparks generated from the thin wire of electrical will progressively erode an electrically conductive work-piece along a programmed path.

In the recent years, there has been much improvement in the WEDM machining process control. However, researchers are struggling to reveal a new method to improve WEDM efficiency, the objectives are the same: to enhance the capability of machining

performance, to get better output product, to develop technique to machine new materials and to have better working conditions (Norliana et al, 2007). Parameter selection of the WEDM machine to achieve the highest cutting efficiency and accuracy is still not fully understood. This is mainly due to the nature of the complex stochastic process mechanisms in WEDM (Puertas & Luis, 2003).

2.2 Wire Electrical Discharge Machining (WEDM)

WEDM has become very popular machining method and has become a mainstream metalworking process and it is not unusual to find a WEDM machine in the average job shop or tool room. WEDM was first introduced to the manufacturing industry in the late 1960s. The development of the process was the result of seeking a technique to replace the machined electrode used in EDM (Ho et al, 2004). Since the introduction, although the basic principle of WEDM has not changed, the process has advanced dramatically in the size, complexity, speed and accuracy of the metal-cutting it can perform even as the equipment has become more affordable, more reliable, and easier to operate.

WEDM has high process capability and is widely used in the manufacturing of gears, moulds, cam wheels, bearing cage, and various types of tools.



Figure 2.1: Example of products made using WEDM (source: AGIE Charmilles Group's website – www.gfac.com)

Pandley & Shah (1980) classified the EDM process into three main categories as shown in figure 2.2 below:

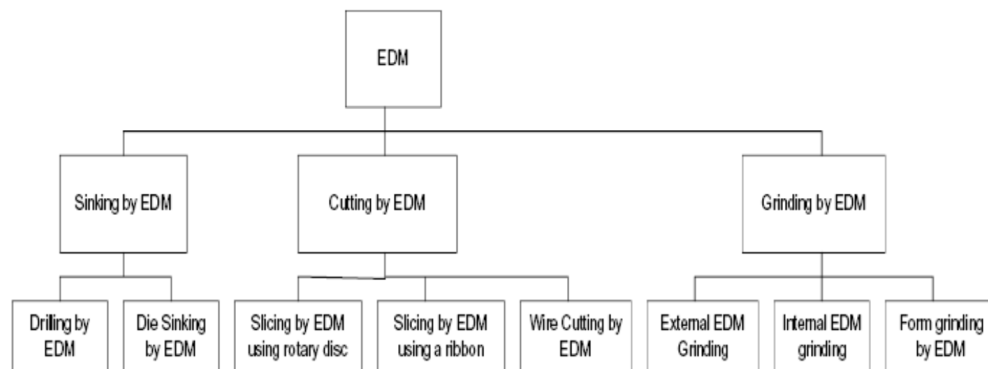


Figure 2.2: Classification of EDM processes (Pandley & Shah, 1980)

Figure 2.3 in the following page shows the operating concept of WEDM. In this process, a slowly moving wire travels along a prescribed path and removes material from the workpiece. WEDM uses electro-thermal mechanisms to cut electrically conductive materials. The material is removed by a series of discrete discharges between the wire electrode and the workpiece in the presence of dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The area where discharge takes place is heated to extremely high temperature, so that the surface is melted and removed. The removed particles are flushed away by the flowing dielectric fluids.

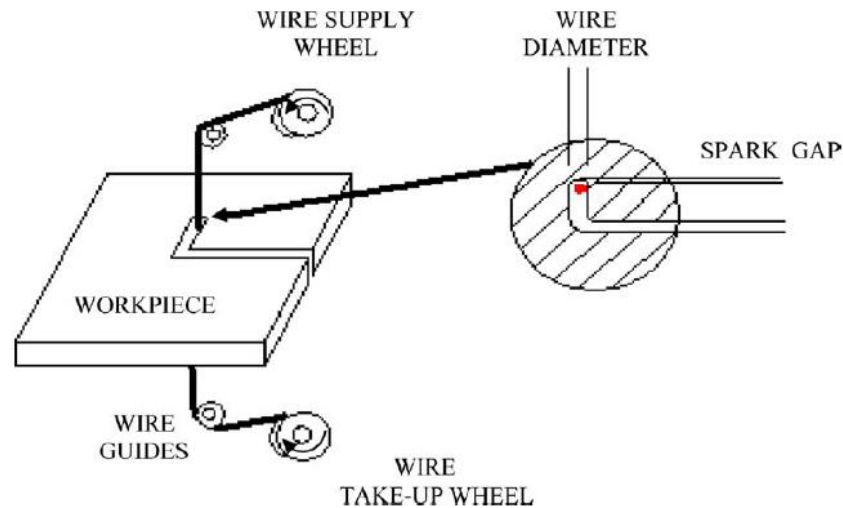


Figure 2.3: Wire electrical discharge machining (WEDM) process

WEDM process is usually used together with CNC and the workpiece is to be cut completely through. The melting temperature of the parts to be machined is an important parameter for this process rather than strength or hardness. The surface quality (R_a) and material removal rate (MRR) of the machined surface by wire EDM will depend on different machining parameters such as applied peak current, pulse on time, pulse off time, flushing pressure of dielectric fluid, wire feed rate, wire tension, spark gap voltage, and wire materials. WEDM process is commonly conducted on submerged condition in a tank fully filled with dielectric fluid; nevertheless it also can be conducted in dry condition. This method is used due to temperature stabilization and efficient flushing in cases where the workpiece has varying thickness.

Ho et al (2004) have classified research areas in EDM machining process as shown in the Figure 2.4. Investigation into the influences of machining input parameters on the performance of WEDM have been widely reported. Several attempts have been made to develop mathematical model of the process (Hewedy et al, 2005) and Lee & Tai, 2003).

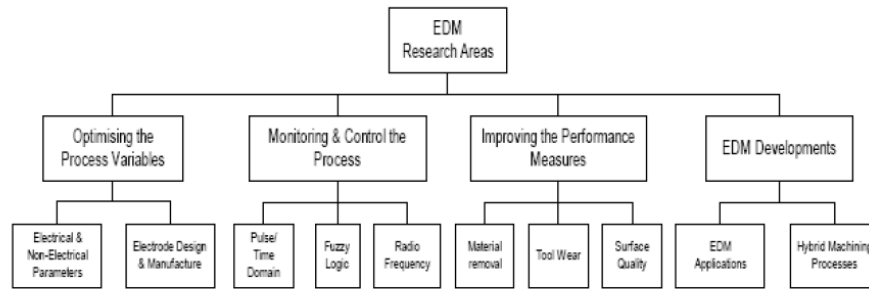


Figure 2.4: Classification of major WEDM research areas (Ho et al, 2004)

This research project is focusing on improving the performance measures of material removal rate (MRR) and surface finish (R_a). These responses are mainly depend on the discharge energy, electrical pulse parameters and discharge distribution in space and time and flushing condition (Kozak et al, 2004). Hascalyk & Caydas (2004) reported that, surface roughness primarily depend on pulse duration, open circuit voltages and dielectric fluid pressure and wire speed not seeming to have much influence.

WEDM also have some limitation associated during machining processes including the use of electrically conductive material only, material removal rates are very low as compared to other processes and the work surface is damaged after processing with this technique (Ho et al, 2004). In addition, the selection of the appropriate parameters is also difficult and relies heavily on the operator's experienced and machining parameters tables provided by the WEDM machine builder.

2.3 WEDM Machining Parameter

Machining parameters play an important role in the WEDM machining process. The important parameters are: *Erosion Condition Number, Cutting Mode, Voltage of open circuit, ON Time, OFF Time, ARC ON Time, ARC OFF Time, Servo Voltage, Wire Tension, Wire Feed*, and others

Van Tri (2002) has categorized the EDM parameters in to 5 groups:

- a. Dielectric fluid - type of dielectric, temperature, pressure, flushing system.
- b. Machine characteristics - servo system and stability stiffness, thermal stability and accuracy.
- c. Tool - material, shape, accuracy
- d. Workpiece.
- e. Adjustable parameters - discharge current, gap voltage, pulse duration,
- f. Polarity, charge frequency, capacitance and tool materials.

According to Ayu (2006), WEDM machining parameters had more significant effect than the electrical parameters. Her finding concluded that the most significant WEDM machining parameters are pulse duration, voltage, peak current and interval time. Tosun et al (2004) described the highly effective parameters on both kerf and MRR were found as open circuit voltage and pulse duration whereas wire speed and dielectric flushing pressure were less effective factors. Previous findings of previous researchers indicated that the electrical parameters are more significant than non-electrical parameters on the machining characteristic.

2.3.1 *Pulse Duration (ON Time)*

All the work in the WEDM is done during pulse duration (On time). The rate of erosion is affected mainly by pulse parameter. When the spark gap is bridged, current will be generated and the work will be done. The longer the spark is switched on, the higher will be the material removal. Consequently the resulting craters will be broader and deeper; therefore the surface finish will be rougher. Alternatively, shorter duration of sparks will give better surface finishing.

2.3.2 *Pulse Interval (OFF Time)*

While most of the machining takes place during on time of the pulse, the off time during which the pulse rests and the re-ionization of the die-electric takes place, can affect the speed of the operation in a large way. Longer is the off time greater will be the machining time. But this is an integral part of the EDM process and must exist. The off time also governs the stability of the process. An insufficient off time can lead to erratic cycling and retraction of the advancing servo, slowing down the operation cycle. In addition, the interval time also provides the time to clear the disintegrated particles from the gap between the electrode and workpiece for efficient cut removal. Too short pulse interval will increase the relative wear ratio and will increase the surface roughness of the machine surface (Othman, 2008).

2.3.3 *Servo Voltage*

The preset voltage determines the width of the spark gap between the leading edge of the electrode and the work piece. High voltage settings increase the gap and hence the flushing and machining. Some material may be necessary for high open-circuit voltage due to high electrical resistance and high discharge voltage (Norliana et al, 2007 and Ayu, 2006).

2.3.4 *Peak Current*

Peak current is also another important primary input of WEDM process. The stronger the discharge current, material removal rate (MRR), overcut and surface roughness (R_a) will increase. On other hand, it decreases the rate of electrode wear (Othman, 2008). To minimize the electrode wear and keep the current density between the tolerance limit it is necessary to select an appropriate value of current (Tosun et al 2004).

2.4 Machining Characteristics

WEDM performance is mainly measured by the material removal rate (MRR), spark gap (kerf) and surface roughness (R_a) of the work-piece. These three machining characteristics have been identified by the previous researchers as the most significant machining criteria that can influence the WEDM performance (Hascalyk & Caydas, 2004). Determining the optimum machining parameters of WEDM to machine certain

material is very crucial. Thicker oxide layer formed due to thermal oxidation during WEDM process is expected (Othman, 2008) and can reflect the surface finish of the machined surface.

Any machined surface during machining processes will experience a disturbed layer which has different characteristics from those of the base metal. Surface integrity entails the study and control of surface topography, as well as surface metallurgy (Rival, 2005). Thermal sensitivity or chemical complexity of the material can also affect the surface integrity (Hascalyk & Caydas, 2004). Several other studies also have been carried out to determine the appropriate EDM machining parameters combination from the aspect of surface integrity. The surface crack formation for AISI D2 and H13 has been studied by Lee & Tai (2003). It was reported that crack formation and white layer thickness are related to the EDM parameters. Hascalyk & Caydas (2004) concluded surface integrity can be divided into two important categories; surface texture, which concern principally on the surface roughness and surface metallurgy, which concern to the nature of the surface layer produced during machining. Hence, the selection of the machining parameters including pulse-on time, pulse off-time, table feed rate, flushing pressure, wire tension, wire velocity, etc should be chosen properly according to the work-piece properties so that better performance can be obtained (Hascalyk & Caydas, 2004). However, based on previous findings, the significant selection of the appropriate machining responses for cutting DF2 using WEDM for this project is surface roughness (R_a) and material removal rate (MRR).

2.4.1 Surface Finish (R_a)

Surface topography or surface finish, also known as surface texture are terms used to describe the general quality of machined surface, which is concerned with the geometric irregularities and the quality of a surface (Rival, 2005). The quality of a machined surface is becoming more and more important to satisfy the increasing demands of sophisticated component performance, longevity, and reliability.

Fine surface finish is obtained by a combination of the proper electrode material, good flushing conditions, and the proper power supply settings. High frequency, low power and orbiting produce the best finish, as these conditions produce smaller, less defined craters in the work metal. Pandey & Shah (1980) have found that surface finish to be inversely proportional to the frequency of discharge. Assuming that each spark leads to a spherical crater formation on the surface of workpiece, the volume of metal removed per crater will be proportional to the cube of the crater depth.

Hewidy et al (2005) have investigated the WEDM performance on Inconel 601. This work has been established based on the response surface methodology (RSM). They have confirmed surface roughness increased with the increased of peak current and decrease with the increase of duty factor and wire tension. Many researchers concluded that the ideal surface finishes are rare to happen due various factors.

2.4.2 Material Removal Rate (MRR)

The removal of material in electrical discharge machining is based upon the erosion effect of electric sparks occurring between two electrodes. Several theories have been forwarded in attempts to explain the complex phenomenon of "erosive spark". The following are the theories:

- a. Electro-mechanical theory
- b. Thermo-mechanical theory
- c. Thermo-electric theory

Electro-mechanical theory suggests that abrasion of material particles takes place as a result of the concentrated electric field. The theory proposes that the electric field separates the material particles of the workpiece as it exceeds the forces of cohesion in the lattice of the material. This theory neglects any thermal effects. Experimental evidence lacks supports for this theory.

Whereby, thermo-mechanical theory suggests that material removal in EDM operations is attributed to the melting of material caused by "flame jets". These so-called flame jets are formed as a result of various electrical effects of the discharge. However, this theory does not agree with experimental data and fails to give a reasonable explanation of the effect of spark erosion.

Thermo-electric theory is best-supported by experimental evidence, suggests that metal removal in EDM operations takes place as a result of the

generation of extremely high temperature generated by the high intensity of the discharge current. Although well supported, this theory cannot be considered as definite and complete because of difficulties in interpretation.

Material removal rate is proved by the previous researchers as one of the most important output parameters, which decide the performance of WEDM machining processes (Sarkar et al, 2005). Rival (2005) have discovered factors such as current, voltage, pulse on time and interval time which to have significant effect on MRR and EWR. Most researchers also concluded EDM electrical parameters such as polarity, peak current, pulse duration and power supply voltage are highly influence the MRR for performance of EDM processes (Kozak et al (2004).

2.5 Electrode Wire

Brass wire is widely used in WEDM processes due to its good machining properties and can be die casted or extruded for specialized application. It possesses high tensile strength, high electrical conductivity, and good wire drawability to close tolerances. Other researchers such as Mahapatra & Parnaik (2007), Kung & Chiang (2008) used coated wire electrode to investigate WEDM machining performance. Coated brass wire can perform at higher cutting speed compared to brass wire electrode. Coated brass wire also can produce exceptional surface finish especially when WEDM tungsten carbide and often utilized for cutting PCD and graphite.

The ideal wire electrode material for this process has three important criteria:

- a. High electrical conductivity.
- b. Sufficient mechanical strength
- c. Optimum sparks and flushes characteristics.

As discussed above, there is no “perfect” wire that excels in every situation, and some compromises become necessary, depending upon the desired results and application. And all the three factors are very closely related and interdependent.

2.5.1 Copper wire

Copper was the original material first used in WEDM. It is an excellent conductor with 100 IACS (International Annealed Copper Standard) value (Othman, 2008). Although its conductivity rating is excellent, its low tensile strength, high melting point and low vapor pressure rating severely limited its potential. Under the electro-thermal condition, predominant during WEDM, copper wire wears rapidly and its tension ability is rather poor, resulting, therefore, in machining instabilities, due to high degree of short circuits, especially in the machining of small curvature (Ayu, 2006).

2.5.2 Brass Wire

Brass was the first logical alternative to copper when early EDM researchers were looking for better performance. Brass EDM wire is a

combination of copper and zinc, typically alloyed in the range of 63–65% Cu and 35–37% Zn. The addition of zinc element provides significantly higher tensile strength, lower melting point and higher vapor pressure rating, which more than offsets the relative losses in conductivity. Brass quickly became the most widely used electrode material for general purpose wire EDM. It is now commercially available in a wide range of tensile strengths and hardness.

2.5.3 Coated Wire

Coated wire is commonly employed in WEDM process to increase substantially the cutting speed and cutting precision. Since brass wires cannot be efficiently fabricated with any higher concentration of zinc, the logical next step was the development of coated wires, sometimes called plated or “stratified” wire. They typically have a core of brass or copper, for conductivity and tensile strength, and are electroplated with a coating of pure or diffused zinc for enhanced spark formation and flush characteristics.

Originally called “speed wire” due to their ability to cut at significantly higher metal removal rates (Puertas & Luis, 2003), coated wires are now available in a wide variety of core materials, coating materials, coating depths and tensile strengths, to suit various applications and machine requirements. Although more expensive than brass, coated wires currently represent the optimum choice for top all-around performance, and their relative economics are covered in a later section.

Zinc coated high conductivity copper alloy offers a number of superiority; high temperature toughness, high current efficiency and high discharge performance make it the best electrode wire for high speed, high precision fine machining. The core is made of copper-alloy, therefore good in workability and superior straightness which is optimum for automatic wire connection.

2.6 DF2 Cold Work Tool Steel

DF2 is a general purpose oil-hardening tool steel suitable for a wide variety of cold work applications. Its main characteristics include: good machinability, good dimensional stability during hardening, and a good combination of high surface hardness and toughness after hardening and tempering.

Typical material analysis, physical properties and other information about the DF2 steel is listed in **Appendix A**.

2.7 Design of Experiment

Design of experiment (DOE) is series of tests in which purposeful changes are made to the input variables of a process or system so that the reasons for change in the output responses can be observed and identified.

There are several reasons for designing complete factorial experiments rather than, for example, using a series of experiments investigating one factor at a time. The first is that factorial experiments are much more efficient for estimating main effects, which are the averaged effects of a single factor over all units. The second and very important reason is that interaction among factors can be assessed in a factorial experiment but not from series of one-at-a-time experiment. Interaction effects are important in determining how the conclusions of the experiment might apply more generally. Complete factorial systems are often large, especially if an appreciable number of factors are to be tested. Often an initial experiment will set each factor at just two levels, so that important main effects and interactions can be quickly identified and explored further.

The choice of factors and the choice of levels for each factor are crucial aspects of the design of any factorial experiment, and will be dictated by the subject matter knowledge and constraints of time or cost on the experiment. The levels of factors can be qualitative or quantitative. The range of values for quantitative factor must be decided on how they are going to be measured and the level at which they will be controlled during the trials. Meanwhile, the quantitative factor is parameters that will be determined discretely (Lee & Li, 2001).