# CURRENT RESEARCH TRENDS IN WIRE ELECTRICAL DISCHARGE MACHINING (WEDM): A REVIEW

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**ABSTRACT:** Wire Electrical Discharge Machine (WEDM), a non-traditional machining process, is becoming more important in providing a non-contact machining process. It is suitable for machining geometrically complex and hard advanced material which is impossible to machine using the conventional machine. This paper reviewed the experimental results on performance evaluation of machining parameters which affected machining performance which would reflect the machining factors and responses. In addition, the methods in analyzing, modelling, development and tool steel in WEDM were also discussed. Some recommendations and future WEDM research were proposed.

**KEYWORDS**: *Wire Electrical Discharge Machine; Machining Process; Taguchi; ANOVA*

## 1.0 INTRODUCTION

A large and growing body of literature has investigated on the various academic research areas involving the WEDM process. WEDM is basically a controlled machining by sparks which was first introduced by Lazarenko in Russia in 1944. The first British patent was granted to Rudorff in 1950. It was the late 1960s where WEDM was first introduced with a wire that continuously travelled past the surface being machined which would solve the wire breakage problem.

In 1967, a wire-cut EDM machine was produced in the USSR. Literature from the period found that an application of the optical line follower system by Dulebohn results in automatic control of the component shape to be machined by the WEDM process in 1974. Later, in 1975, it became popular as the process and capabilities better understood by the industries. In the late 1970s, computer numerical control (CNC) system was initiated into WEDM that brought about a major evolution of the machining process. As a result, the broad capabilities of the WEDM process were extensively exploited and common applications of WEDM include the fabrication of the stamping and extrusion tools and dies.

The material removal mechanism of WEDM is very similar to the conventional EDM process involving the erosion effect produced by the electrical discharges (sparks). Several studies identified WEDM as a process in which material is eroded from the workpiece by a series of discrete sparks occurring between the workpiece and the wire separated by a stream of dielectric fluid which is continuously fed to the machining zone [1] as shown in Figure 1.

Thus far, however, there has been little discussion about various applications of new analysis method involving new advanced workpiece material of the WEDM process specifically on the collections of a new D2 cold work tool steel with modified or doped alloy. Surprisingly, information related to its behaviour towards the end responses of the material through these unconventional processes is still scarce.

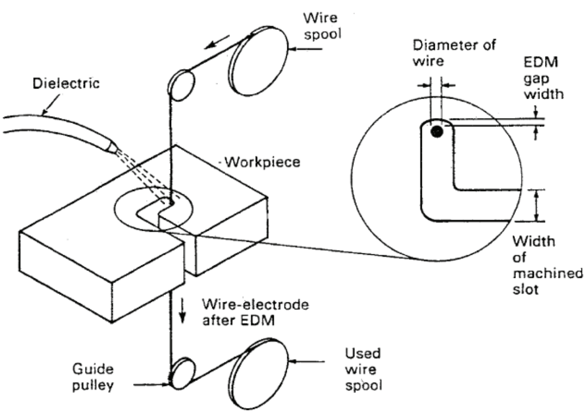


Figure 1: Basic feature of WEDM sets up

## 2.0 WEDM CURRENT RESEARCH TRENDS

This section consists of WEDM factors and responses (F&R), WEDM monitoring and control, and WEDM new development. F&R will include pulse on time ($T_{on}$), peak current ($I_p$), pulse off time ($T_{off}$), servo voltage (SV), flushing pressure (FP), wire speed (WS) and wire tension (WT). The factors to be included are material removal rate (MRR), duty cycle (DC), surface roughness (SR), cutting speed (CS) and kerf width (KW).

### 2.1 WEDM Factors and Responses

Previous research indicates that various WEDM parameters have a significant effect on the performance measures. Voltage is applied for a gap between the workpiece and the electrode during the on time (spark gap) and no voltage occurs during off time. Numerous studies have attempted to explain that machining speed increases while SR decreases with the increase of $T_{on}$ due to the increase of discharge energy. During $T_{on}$, sparks are being generated within certain frequencies and erosion takes place where melting and vaporization of workpiece occur. Longer $T_{on}$ indicates more material being melted and vaporized.

$T_{on}$ and $T_{off}$ are the duration of time where no machining takes place. It has conclusively been shown that discharge energy increases with $I_p$ and the no-load voltage [2]. Gautier et al. [3] have done an analysis on the $T_{on}$, SV and WT which have significant effect towards SR. The low value of $T_{on}$ and WT provide high SR while low SV produces low SR. Ghodsiyeh et al. [4] claimed SV used to control the movement of wire electrode either in advances (toward workpiece) or retraction (away from the workpiece).

The flushing pressure was indicated to give significant effect towards MRR. Within the certain limitation of pressure [5,6] , MRR increases with a certain amount of FP(1.96 bar) and beyond that causes wire deflection and wire vibration which lead to lower MRR. Chinnadurai and Vendan [7] added that more melted drops, globules of debris, craters and cracks are produced from high SR due to arc generation by insufficient flushing.

Wire speed is an important factor in WEDM that carries the speed of the wire in WEDM. The costs of machining increased with increased WS and wire breakage can occur with low CS. Chinnadurai and Vendan [7] revealed the increase of WS which increases MRR. Durairaj et al. [8] claimed that the increase in wire feed will decrease SR and KW.

Fard et al. [9] indicated that the increase of the mean value for cutting velocity occurs if WT increases during the WEDM process of metal matrix composite of AL-SiC through intelligent modelling ANFIS and Artificial Bee Colony. Likewise, a study verifies this condition in the evaluation of WEDM machining of Inconel 706 through ANOVA for turbine disk purpose [9]. Using Taguchi L18 full factorial design experiment, an author [10] exposed that MRR increases with the increase of $T_{on}$ and wire speed by referring to process parameter of AISI 4140 work piece. Kumar et al. [10] develop a numerical modelling through the use of numerical simulation ANSYS software and comparison is made and the $T_{on}$ is found to be the most significant factor towards MRR, indicating that the increased $T_{on}$ will increase MRR. Durairaj et al. [8] have confirmed that using ANOVA, $T_{on}$ plays a major role on SR and KW through the processing of stainless steel. The objectives of the study are achieved through Taguchi and GRA by optimizing the SR and KW and validating them through experimental results [8].

In an investigation on MRR of particle reinforced A606 aluminum matrix composite, the most influencing factor over MRR is the DC[11]. Prakash et al. [12] claimed that through an experimental investigation on Aluminium alloy Hybrid Composite with WEDM through Taguchi and ANOVA, MRR is most affected by gap voltage while SR is affected by gap voltage and wire feed. In contrast, the effect of machine feed rate over KW, MRR and SR is examined [13]. The decreasing of machine feed rate produces the smallest value of KW, MRR and high value of SR. A similar study is also conducted [14] to ascertain the best optimal performance to decrease the consumption of electric power, material and time in machining titanium.

In WEDM, the lower SR and higher CS are the indications of better performance. SR value (in μm) can be obtained by measuring the mean absolute deviation. There is a significant positive correlation between SR, $T_{on}$, and $I_p$, in which SR increases with the decreasing of a $T_{on}$ and $I_p$ due to the high energy pulse generated[15]. Higher energy means greater depth of craters. In the case study of WEDM of aluminium based composites, four factors are identified ($I_p$, $T_{on}$, wire feed rate and workpiece material) that influence responses including KW and SR [16]. Kumar et al. [16] also noted that $T_{on}$ is more influencing with a contribution of 96.16%. SR also increases with the increasing of $T_{on}$ due to the development of the larger crater by the increase of spark [16].

SR is found to decrease with the increase of pulse off time [16]. High $T_{off}$ refers to more flushing time and molten material which are driven off through the machining zone and reduce SR. SR is also reduced if the servo voltage increases due to an increase of wide spark gap that reduces the spark intensity and increases the flushing and form microcavities which lead to better surface finish. The increase of wire feed used to decrease SR due to the improved splashing of molten material up to the certain values and beyond those values, SR increases [17]. Zhang [18] investigated the SR through the effect of cutting parameter based on ANFIS and concluded that SR increases as $I_p$ and $T_{on}$ increase while the higher number of power transistors give higher average of SR [2]. It is proven that fine machining produces low roughness whereas medium and coarse machining produce highly rough surface. The EDS analysis showed that the wire electrode material that is molybdenum is found to be on the machined surface. Dongre et al. [19] managed to improve SR where 2-3μm is produced compared with 3-5μm of the conventional methods. Muttamara and Janmanee [20] have completed an experiment of WEDM on SKD 11 steel in finding accurate dimensions and better SR. Surprisingly, the study [20] also succeeded to gain SR and accuracy within the targeted values. Overall, SR was affected by $T_{on}$, $T_{off}$, $I_p$, SV, wire feed, the number of the power transistor and WT during the WEDM process.

CS should be as high as possible to result in the least machine cycle time which leads to increased productivity [21]. The CS is computed by dividing the cutting length by the corresponding cutting time. Selvakumar et al. [15] pointed out that $T_{on}$ and $I_p$ increase the CS through the machining of 5083 Aluminum alloy and verifying through Taguchi method. Dongre et al. [19] discovered highest machining slicing speed which gives overall improvement about 40% -50% over the conventional method for processing a semiconductor resulted in reduced KW, giving a net cost saving of 200% - 300%. Besides, the most significant factors are $I_p$ and pulse width that affect CS, SR and heat affected zone (HAZ) through the use of neuro-fuzzy inference system and Taguchi method[17]. WT affected only SR with minor effect of CS and HAZ.

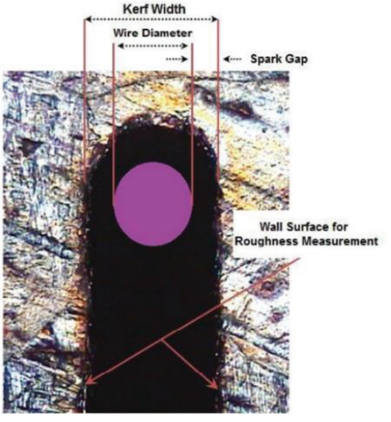


Figure 2: Measurement of kerf width and surface roughness

KW can be defined as the slot or opening produced by the wire cut electrode as it machines the workpiece and greatly influences the machining precision [22] (Figure 2). Lusi et al. [23] have conducted an analysis based on Taguchi based Grey Relational Analysis and discovered the most influential factors which are $T_{on}$ for KW and SR for Aluminium HE30, SKD 61 and stainless steel SS 304. Another researcher focuses on corner control of WEDM through experimental measurement of KW and deflection of wire electrode in achieving effective accuracy. An experiment is implemented [25] to determine KW that is influenced by the capacitance with a gap voltage in micro WEDM. The study showed that KW is obviously affected by $T_{on}$, lateral vibration of the wire, wire radius and breakdown distance [25].

SV and $I_{on}$ are found to have a significant effect on the form of microvoids and micro globules on the machined surface [26]. Low $T_{on}$ and high value of SV will decrease the SR due to the absences of microvoids and micro globules. Chinnadurai and Vendan [7] countered that poor surface finish from the usage of uncoated wire forms a recast layer due to the improper cooling and insufficient flushing during $T_{on}$.

Microstructure investigation implemented by Goswami and Kumar [6] revealed the impact of high energy input towards surface quality. High energy input inherits rougher surface quality with a lot of builds edge layers and better surface quality which occur under low energy input. Even the recast layer is doubled with greater energy input. Huijun et al. [27] investigated the occurrence of small holes in mono-crystalline silicon cut by WEDM. He also discovered that small holes occur after the discharge power density achieves a certain limit [27]. These small holes also resulted in thermal stress damage and crack propagation. Alias et al. [13] spotted low machine feed rate which produces bigger crater compared with high feed rate during the machining of Titanium Ti-6Al-4V.

## 2.2 WEDM Monitoring and Control

There have been a number of longitudinal studies involving wire lag, breakage and vibration. Wire breakage phenomena have also been revealed [28-31]. Several literatures on WEDM monitoring and control are now dealing with wire breakage, lagging and vibration. A recent study [32] has declared that an amplitude of wire tool vibration can be reduced in redesigning the wire winding system by developing and analyzing a mathematical model and simulation or experiment are the main factors that influence tension change are friction of wire electrode at the lower guide wheel, length of wire electrode between the two upper and lower guide wheel and length of wire electrode between wire winding cylinder and lower guide wheel. The system is reliable because it can effectively control non-even wire tension. Shi et al. [32] presented a new winding system account through simulation based on each parameter on wire tension while Chen et al. [33] improved the wire transportation system with the aim to keep wire speed and tension in a constant condition through the use of tension sensor and dynamic absorbers.

Liao et al. [34] successfully developed an online system for the cause of ignition delay time with the capability of detecting short circuit discharges and diagnosis tool for detecting quality electric discharges. Likewise, Habib and Okada [35] have highlighted the relevance of using a digital high-speed camera system in investigating the movement of tungsten wire electrode from the rear and the side. Wire tension influenced vibration amplitude and frequency which can be decreased with the increase of wire tension as well as wire deflection. These results can be practiced to avoid wire breakage, precise shape accuracy, and low surface roughness. However, an author [36] is more concerned with the monitoring of zero defect manufacturing based on advanced sensor signal processing by leading the process condition of WEDM. Liao et al. [34] highlighted the controlling of wire vibration through the analysis of the thermal model, electromagnetic field and structured model and concluded that the evaluation of KW width should include the amplitude of lateral vibration of the wire, wire radius and breakdown distance.

## 2.3 WEDM New Development

Zhang et al. [2] focused on washing away machined debris in the gap through the hybrid technique of WEDM assisted ultrasonic vibration and magnetic field during the machining process. Optimum machining performance is gained with balance machining efficiency and surface roughness for $Ti_6Al_4V$ of aerospace airframes and engine component. Another hybrid technique [37] is a combination of electrochemical process and rotary WEDM in developing a diamond wheel tool array with stable wire tension and without heat distortion of the workpiece. The first accuracy taper cutting research is introduced [38]. Currently, a new lower arm of WEDM taper machine with a lower mass is designed [39]. In contrast, Zhang and Shi [40] proposed a development of NC wire cutting automatic programming system. Some researchers focus more on a study on debris movement in machined kerf in obtaining a stable machining performance through observation using a high-speed video camera [40].

## 3.0 COLD WORK TOOL STEEL IN WEDM

Surprisingly, literature on quantitative analysis of WEDM process on cold work steel tool is scarce. Lately, there are experiments which analyze data of machining tool and die steel with WEDM and most findings assert that to achieve a low SR on the tool and die steel, either SR or die steel should increase the $T_{off}$ and gap voltage.

The surface roughness is also found to decrease with the decreasing of a $T_{on}$ and high flush rate resulted in improving SR at optimal MRR.

## 4.0 CONCLUSION

Relatively, one may suppose that WEDM always lead and perform better in processing a hard to machine and advanced material with precise and better surface quality.

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