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State of the art in wire electrical discharge machining (WEDM)

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Abstract

Wire electrical discharge machining (WEDM) is a specialised thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. This practical technology of the WEDM process is based on the conventional EDM sparking phenomenon utilising the widely accepted non-contact technique of material removal. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality.

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 optimising 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 optimisation of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. The paper also highlights the adaptive monitoring and control of the process investigating the feasibility of the different control strategies of obtaining the optimal machining conditions. A wide range of WEDM industrial applications are reported together with the development of the hybrid machining processes. The final part of the paper discusses these developments and outlines the possible trends for future WEDM research.

Keywords: Wire electrical discharge machining (WEDM); Hybrid machining process; Process optimisation; Cutting rate; Matenal removal rate; Surface finish

1. Introduction

Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. It is considered as a unique adaptation of the conventional EDM process, which uses an electrode to initialise the sparking process. However, WEDM utilises a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05–0.3 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the workpiece and the wire, eliminating the mechanical stresses during machining. In addition, the WEDM process is able to machine exotic and high strength and temperature resistive (HSTR) materials and eliminate the geometrical changes occurring in the machining of heat-treated steels.

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. In 1974, D.H. Dulebohn applied the optical-line follower system to

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automatically control the shape of the component to be machined by the WEDM process [1]. By 1975, its popularity was rapidly increasing, as the process and its capabilities were better understood by the industry [2]. It was only towards the end of the 1970s, when 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 for any through-hole machining owing to the wire, which has to pass through the part to be machined. The common applications of WEDM include the fabrication of the stamping and extrusion tools and dies, fixtures and gauges, prototypes, aircraft and medical parts, and grinding wheel form tools.

This paper provides a review on the various academic research areas involving the WEDM process, and is the sister paper to a review by Ho and Newman [3] on die-sinking EDM. It first presents the process overview based on the widely accepted principle of thermal conduction and highlights some of its applications. The main section of the paper focuses on the major WEDM research activities, which include the WEDM process optimisation together with the WEDM process monitoring and control. The final part of the paper discusses these topics and suggests the future WEDM research direction.

2. WEDM

This section provides the basic principle of the WEDM process and the variations of the process combining other material removal techniques.

2.1. WEDM process

The material removal mechanism of WEDM is very similar to the conventional EDM process involving the erosion effect produced by the electrical discharges (sparks). In WEDM, 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 [4]. However, today's WEDM process is commonly conducted on workpieces that are totally submerged in a tank filled with dielectric fluid. Such a submerged method of WEDM promotes temperature stabilisation and efficient flushing especially in cases where the workpiece has varying thickness. The WEDM process makes use of electrical energy generating a channel of plasma between the cathode and anode [5], and turns it into thermal energy [6] at a temperature in the range of 8000–12,000 $^{\circ}$C [7] or as high as 20,000 $^{\circ}$C [8] initialising a substantial amount of heating and melting of material on the surface of each pole. When the pulsating direct current power supply occurring between 20,000 and 30,000 Hz [9] is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten particles from the pole surfaces in the form of microscopic debris.

While the material removal mechanisms of EDM and WEDM are similar, their functional characteristics are not identical. WEDM uses a thin wire continuously feeding through the workpiece by a microprocessor, which enable parts of complex shapes to be machined with exceptional high accuracy. A varying degree of taper ranging from 15° for a 100 mm thick to 30° for a 400 mm thick workpiece can also be obtained on the cut surface. The microprocessor also constantly maintains the gap between the wire and the workpiece, which varies from 0.025 to 0.05 mm [2]. WEDM eliminates the need for elaborate pre-shaped electrodes, which are commonly required in EDM to perform the roughing and finishing operations. In the case of WEDM, the wire has to make several machining passes along the profile to be machined to attain the required dimensional accuracy and surface finish (SF) quality. Kunieda and Furudate [10] tested the feasibility of conducting dry WEDM to improve the accuracy of the finishing operations, which was conducted in a gas atmosphere without using dielectric fluid. The typical WEDM cutting rates (CRs) are 300 mm^2/min for a 50 mm thick D2 tool steel and 750 mm^2/min for a 150 mm thick aluminium [11], and SF quality is as fine as 0.04–0.25 μRa. In addition, WEDM uses deionised water instead of hydrocarbon oil as the dielectric fluid and contains it within the sparking zone. The deionised water is not suitable for conventional EDM as it causes rapid electrode wear, but its low viscosity and rapid cooling rate make it ideal for WEDM [12].

2.2. Hybrid machining processes

There are a number of hybrid machining processes (HMPs) seeking the combined advantage of WEDM with other machining techniques. One such combination is wire electrical discharge grinding (WEDG), which is commonly used for the micro-machining of fine rods utilized in the electronic circuitry. WEDG employs a single wire guide to confine the wire tension within the discharge area between the rod and the front edge of the wire and to minimise the wire vibration. Therefore, it is possible to grind a rod that is as small as 5 μm in diameter [13] with high accuracy, good repeatability and satisfactory straightness [14]. Other advantages of WEDG include the ability to machine a rod with a large aspect ratio, maintaining the concentricity of the rod and providing a wider choice of complex shapes such as tapered and stepped shapes at various sections [15]. Several authors [16–19] have employed the WEDG process in the micro-machining of fine electrodes or pins with a large aspect-ratio, which are difficult to be machined by traditional precision micro-machining methods such as Micro-EDM, LIGA and excimer laser drilling.

Some of the HMPs seek to improve the WEDM performance measures such as the surface integrity and the CR. For example, the ultrasonic vibration is applied to the wire electrode to improve the SF quality together with the CR and to reduce the residual stress on the machined surface [20]. On the other hand, the wire electrochemical grinding (WECG) process replaces the electrical discharge used in WEDG with an electrochemical solution to produce high SF quality part for a wide range of machining condition [15]. Masuzawa et al. [13,15] compared the SF quality obtained from the WECG with WEDG, which is suitable for finishing micro-parts. A rotary axis is also added to WEDM to achieve higher material removal rate (MRR) and to enable the generation of free-form cylindrical geometries [21,22]. The effects of the various process parameters such as part rotational speed, wire feed rate and pulse on-time on the surface integrity and roundness of the part produced have been investigated in the same feasibility study [23].

3. WEDM applications

This section discusses the viability of the WEDM process in the machining of the various materials used particularly in tooling applications.

3.1. Modern tooling applications

WEDM has been gaining wide acceptance in the machining of the various materials used in modern tooling applications. Several authors [24,25] have investigated the machining performance of WEDM in the wafering of silicon and machining of compacting dies made of sintered carbide. The feasibility of using cylindrical WEDM for dressing a rotating metal bond diamond wheel used for the precision form grinding of ceramics has also been studied [22]. The results show that the WEDM process is capable of generating precise and intricate profiles with small corner radii but a high wear rate is observed on the diamond wheel during the first grinding pass. Such an initial high wheel wear rate is due to the over-protruding diamond grains, which do not bond strongly to the wheel after the WEDM process [26]. The WEDM of permanent NdFeB and ‘soft’ MnZn ferrite magnetic materials used in miniature systems, which requires small magnetic parts, was studied by comparing it with the laser-cutting process [27]. It was found that the WEDM process yields better dimensional accuracy and SF quality but has a slow CR, 5.5 mm/min for NdFeB and 0.17 mm/min for MnZn ferrite. A study was also done to investigate the machining performance of micro-WEDM used to machine a high aspect ratio meso-scale part using a variety of metals including stainless steel, nitronic austentic stainless, beryllium copper and titanium [28].

3.2. Advanced ceramic materials

The WEDM process has also evolved as one of the most promising alternatives for the machining of the advanced ceramics. Sanchez et al. [29] provided a literature survey on the EDM of advanced ceramics, which have been commonly machined by diamond grinding and lapping. In the same paper, they studied the feasibility of machining boron carbide (B_4C) and silicon infiltrated silicon carbide (SiSiC) using EDM and WEDM. Cheng et al. [30] also evaluated the possibility of machining ZrB_2 based materials using EDM and WEDM, whereas Matsuo and Oshima [31] examined the effects of conductive carbide content, namely niobium carbide (NbC) and titanium carbide (TiC), on the CR and surface roughness of zirconia ceramics (ZrO_2) during WEDM. Lok and Lee [32] have successfully WEDMed sialon 501 and aluminium oxide–titanium carbide (Al_2O_3–TiC). However, they realised that the MRR is very low as compared to the cutting of metals such as alloy steel SKD-11 and the surface roughness is generally inferior to the one obtained with the EDM process. Dauw et al. [33] explained that the MRR and surface roughness are not only dependent on the machining parameters but also on the material of the part.

An innovative method of overcoming the technological limitation of the EDM and WEDM processes requiring the electrical resistivity of the material with threshold values of approximately 100 Ω/cm [34] or 300 Ω/cm [35] has recently been explored. There are different grades of engineering ceramics, which Konig et al. [34] classified as non-conductor, natural-conductor and conductor, which is a result of doping non-conductors with conductive elements. Mohri et al. [36] brought a new perspective to the traditional EDM phenomenon by using an assisting electrode to facilitate the sparking of highly electrical-resistive ceramics. Both the EDM and WEDM processes have been successfully tested diffusing conductive particles from assisting electrodes onto the surface of sialon ceramics assisting the feeding the electrode through the insulating material. The same technique has also been experimented on other types of insulating ceramic materials including oxide ceramics such as ZrO_2 and Al_2O_3, which have very limiting electrical conductive properties [37].

3.3. Modern composite materials

Among the different material removal processes, WEDM is considered as an effective and economical tool in the machining of modern composite materials. Several comparative studies [38,39] have been made between WEDM and laser cutting in the processing of metal matrix composites (MMC), carbon fibre and reinforced liquid crystal polymer composites. These studies showed that WEDM yields better cutting edge quality and has better control of the process parameters with fewer workpiece surface damages. However, it has a slower MRR for all the tested composite materials. Gadalla and Tsai [40] compared WEDM with conventional diamond sawing and discovered that it produces a roughness and hardness that is comparable to a low speed diamond saw but with a higher MRR. Yan et al. [41] surveyed the various machining processes performed on the MMC and experimented with the machining of $Al_2O_3/6061Al$ composite using rotary EDM coupled with a disk-like electrode. Other studies [42,43] have been conducted on the WEDM of Al_2O_3 particulate reinforced composites investigating the effect of the process parameters on the WEDM performance measures. It was found that the process parameters have little influence on the surface roughness but have an adverse effect on CR.

4. Major areas of WEDM research

The authors have organised the various WEDM research into two major areas namely WEDM process optimisation together with WEDM process monitoring and control.

4.1. WEDM process optimisation

Today, 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. This section provides a study on the numerous machining strategies involving the design of the process parameter and the modelling of the process.

4.1.1. Process parameters design

The settings for the various process parameters required in the WEDM process play 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 CR, MRR and SF.

4.1.1.1. 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 CR, which are two of the most significant aspects of the WEDM operation [44]. Suziki and Kishi [45] studied the reduction of discharge energy to yield a better surface roughness, while Luo [46] discovered the additional need for a high-energy efficiency to maintain a high machining rate without damaging the wire. Several authors [47] have also studied the evolution of the wire tool performance affecting the machining accuracy, costs and performance measures.

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 CR, MRR and SF. 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 [48] demonstrated that the parameter settings given by the manufacturers are only applicable for the common steel grades. The settings for machining new materials such as advanced ceramics and MMCs have to be further optimised experimentally.

4.1.1.2. Effects of the process parameters on the cutting rate. Many different types of problem-solving quality tools have been used to investigate the significant factors and its inter-relationships with the other variables in obtaining an optimal WEDM CR. Konda et al. [49] classified 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 design of experiments (DOE) technique to study and optimise the possible effects of variables during process design and development, and validated the experimental results using noise-to-signal (S/N) ratio analysis. Tarng et al. [50] employed a neural network system with the application of a simulated annealing algorithm for solving the multi-response optimisation problem. It was found that the machining parameters such as the pulse on/off duration, peak current, open circuit voltage, servo reference voltage, electrical capacitance and table speed are the critical parameters for the estimation of the CR and SF. Huang et al. [51] argued that several published works [50,52,53] are concerned mostly with the optimisation of parameters for the roughing cutting operations and proposed a practical strategy of process planning from roughing to finishing operations. The experimental results showed that the pulse on-time and the distance between the wire periphery and the workpiece surface affect the CR and SF significantly. The effects of the discharge energy on the CR and SF of a MMC have also been investigated [54].

4.1.1.3. Effects of the machining parameters on the material removal rate. The effects of the machining parameters on the volumetric MRR have also been considered as a measure of the machining performance. Scott et al. [52] used a factorial design requiring a number of experiments to determine the most favourable combination of the WEDM parameter. They found that the discharge current, pulse duration and pulse frequency are the significant control factors affecting the MRR and SF, while the wire speed, wire tension and dielectric flow rate have the least effect. Liao et al. [53] proposed an approach of determining the parameter settings based on the Taguchi quality design method and the analysis of variance. The results showed that the MRR and SF are easily influenced by the table feed rate and pulse on-time, which can also be used to control the discharging frequency for the prevention of wire breakage. Huang and Liao [55] 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. An experimental study to determine the MRR and SF for varying machining parameters has also been conducted [56]. The results have been used with a thermal model to analyse the wire breakage phenomena.

4.1.1.4. Effects of the process parameters on the surface finish. There are also a number of published works that solely study the effects of the machining parameters on the WEDMed surface. Gökler and Ozanözgü [57] studied the selection of the most suitable cutting and offset parameter combination to get a desired surface roughness for a constant wire speed and dielectric flushing pressure. Tosun et al. [58] investigated the effect of the pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the WEDMed workpiece surface roughness. It was found that the increasing pulse duration, open circuit voltage and wire speed increases with the surface roughness, whereas the increasing dielectric fluid pressure decreases the surface roughness. Anand [59] used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and surface roughness. Spedding and Wang [60] optimised the process parameter settings by using artificial neural network modelling to characterise the WEDMed workpiece surfaces, while Williams and Rajurkar [61] presented the results of the current investigations into the characteristics of WEDM generated surfaces.

4.1.2. Process modelling

In addition, the modelling of the WEDM process by means of mathematical techniques has also been applied to effectively relate the large number of process variables to the different performance of the process. Spedding and Wang [62] developed the modelling techniques using the response surface methodology and artificial neural network technology to predict the process performance such as CR, SF and surface waviness within a reasonable large range of input factor levels. Liu and Esterling [63] proposed a solid modelling method, which can precisely represent the geometry cut by the WEDM process, whereas Hsue et al. [64] developed a model to estimate the MRR during geometrical cutting by considering wire deflection with transformed exponential trajectory of the wire centre. Spur and Schönbeck [65] designed a theoretical model studying the influence of the workpiece material and the pulse-type properties on the WEDM of a workpiece with an anodic polarity. Han et al. [66] developed a simulation system, which accurately reproduces the discharge phenomena of WEDM. The system also applies an adaptive control, which automatically generates an optimal machining condition for high precision WEDM.

4.2. WEDM process monitoring and control

The application of the adaptive control systems to the WEDM is vital for the monitoring and control of the process. This section investigates the advanced monitoring and control systems including the fuzzy, the wire breakage and the self-tuning adaptive control systems used in the WEDM process.

4.2.1. Fuzzy control system

The proportional controllers have traditionally been used in the servo feed control system to monitor and evaluate the gap condition during the WEDM process. However, the performance of the controllers was limited by the machining conditions, which considerably vary with the parameters settings. Kinoshita et al. [67] investigated the effects of wire feed rate, wire winding speed, wire tension and electrical parameters on the gap conditions during WEDM. As a result, many conventional control algorithms based on explicit mathematical and statistical models have been developed for EDM or WEDM operations [68–72]. Several authors [73,74] have also developed a pulse discrimination system providing a means of analysing and monitoring the pulse trains under the various WEDM conditions quantitatively. Although these types of control systems can be applied to a wide range of machining conditions, it cannot respond to the gap condition when there is an unexpected disturbance [75].

In recent years, the fuzzy control system has been applied to WEDM process to achieve optimum and highly efficient machining. Several authors claimed that the fuzzy logic control system implements a control strategy, which captures the expert's knowledge or operator's experience in maintaining the desired machining operation [76]. In addition, the fuzzy logic controller does not require any comprehensive mathematical models adapting to the dynamic behaviour of the WEDM operation [77]. Several authors [75,78] proposed the sparking frequency monitoring and adaptive control systems based on the fuzzy logic control and the adjusting strategies, which can be applied to a wide range of machining conditions. Liao and Woo [79] also designed a fuzzy controller with an online pulse monitoring system isolating the discharging noise and discriminating the ignition delay time of each pulse. EDM pulses can be classified into open, spark, arc, off or short, which are dependent on the ignition delay time, and have a direct influence on the MRR, SF, electrode wear and accuracy of the part [80,81].

4.2.2. *Wire inaccuracy adaptive control systems*

The occurrence of wire breakage during WEDM is one of the most undesirable machining characteristics greatly affecting the machining accuracy and performance together with the quality of the part produced. Many attempts have made to develop an adaptive control system providing an online identification of any abnormal machining condition and a control strategy preventing the wire from breaking without compromising the various WEDM performance measures. This section reports research from a collection of published work involving the adaptive control of wire breakage, wire lag and wire vibration.

4.2.2.1. Wire breakage. A wide variety of the control strategies preventing the wire from breaking are built on the knowledge of the characteristics of wire breakage. Kinoshita et al. [82] observed the rapid rise in pulse frequency of the gap voltage, which continues for about 5–40 ms before the wire breaks. They developed a monitoring and control system that switches off the pulse generator and servo system preventing the wire from breaking but it affects the machining efficiency. Several authors [83,84] also suggested that the concentration of electrical discharges at a certain point of the wire, which causes an increase in the localised temperature resulting in the breakage of the wire. However, the adaptive control system concentrating on the detection of the sparking location and the reduction of the discharge energy was developed without making any considerations to the MRR. The breakage of the wire has also been linked to the rise in the number of short-circuit pulses lasting for more than 30 ms until the wire broke [85].

Other authors [86] argued that the wire breakage is correlated to the sudden increase in sparking frequency. It was also found that their proposed monitoring and control system based on the online analysis of the sparking frequency and the real-time regulation of the pulse off-time affects the MRR. Liao et al. [87] remedied the problem by relating the MRR to the machining parameters and using a new computer-aided pulse discrimination system based on the pulse train analysis to improve the machining speed. Whereas Yan and Liao [88,89] applied a self-learning fuzzy control strategy not only to control the sparking frequency but also to maintain a high MRR by adjusting in real time the off-time pulse under a constant feed-rate machining condition.

The breaking of the wire is also due to the excessive thermal load producing unwarranted heat on the wire electrode. Most of the thermal energy generated during the WEDM process is transferred to the wire while the rest is lost to the flushing fluid or radiation [86]. However, when the instantaneous energy rate exceeds a certain limit depending on the thermal properties of the wire material, the wire will break. Several authors [90–92] investigated the influence of the various machining parameters on the thermal load of the wire and developed a thermal model simulating the WEDM process. In addition to the sparking characteristics or the temperature distribution, the mechanical strength of the wire also has a significant effect on the occurrence of the wire breakage. Luo [93] claimed that the wire material yielding and fracture contribute to the wire breakage, whilst an increase in temperature aggravates the failure process.

4.2.2.2. Wire lag and wire vibration. The main factors contributing to the geometrical inaccuracy of the WEDMed part are the various process forces acting on the wire causing it to depart for the programmed path. These forces include the mechanical forces produced by the pressure from the gas bubbles formed by the plasma of the erosion mechanism, axial forces applied to straighten the wire, the hydraulic forces induced by the flushing, the electro-static forces acting on the wire and the electro-dynamic forces inherent to the spark generation [94,95].

As a result, the static deflection in the form of a lag effect of the wire is critically studied in order to produce an accurate cutting tool path. Several authors [93,96,97] performed a parametric study on the geometrical inaccuracy of the part caused by the wire lag and attempted to model WEDM process mathematically. Whereas Beltrami and Dauw [98] monitored and controlled the wire position online by means of an optical sensor with a control algorithm enabling virtually any contour to be cut at a relatively high cutting speed. A number of geometric tool motion compensation methods, which increase the machining gap and prevent gauging or wire breakages when cutting areas with high curvatures such as corners with small radii have also been developed [99,100]. Lin et al. [101] developed a control strategy based on the fuzzy logic to improve the machining accuracy and concentrated sparking at corner parts without affecting the cutting feed rates.

In addition, the dynamic behaviour of the wire during WEDM is also restrained to avoid cutting inaccuracies. There are a few discussions on the design and development of a monitoring and control system for compensating the behaviour of the wire vibration [86,102]. Dauw et al. [103] also reported that the vibration of the wire can be substantially reduced when the wire and the wire guides are completely submerged in the working tank filled with deionised water. Several authors [104] derived a mathematical model analysing the transient response of the wire vibration based on the force acting on the tool wire in a single discharge process. A number of authors [105,106] reviewed the research and development of the various advanced monitoring and control systems used in EDM and WEDM processes.

4.2.3. Self-tuning adaptive control systems

In recent years, the WEDM research and development has explored control strategies adjusting to the variation in the power density required in machining a workpiece with varying thickness. Several authors [82,85] found out that a change in the workpiece thickness during machining leads to an increase in the wire thermal density and an eventual breaking of the wire. Rajurkar et al. [107,108] proposed an adaptive control system with a multiple input model that monitors and controls the sparking frequency according to the online identified workpiece height. Other authors [72] developed a system that involves an explicit mathematical model requiring a number of experiments and statistical techniques. Yan et al. [109] used the neural networks to estimate the workpiece height and the fuzzy control logic to suppress the wire breakage when a workpiece with variable height is machined.

The application of a knowledge-based control system to control the adverse WEDM conditions has also been experimented. Snoeys et al. [110] proposed a knowledge-based system, which comprises of three modules, namely work preparation, process control and operator assistance or fault diagnosis, enabling the monitoring and control of the WEDM process. The work preparation module determines the optimal machining parameter settings, while the operator assistance and fault diagnostics databases advise the operators and diagnose the machining errors. Thus, the capabilities of these modules increase the amount of autonomy given to the WEDM machine. Huang and Liao [111] have also indicated the importance of the operator assistance and fault diagnostics systems for the WEDM process. They proposed a prototype artificial neural network-based expert system for the maintenance schedule and fault diagnosis of the WEDM. Dekeyser et al. [112] developed a thermal model integrated with an expert system for predicting and controlling the thermal overload experienced on the wire. Although the model increases the level of machine autonomy, it requires a large amount of computation, which slows down the processing speed and undermines the online control performance.

5. Discussion and future research directions

The authors have classified the wide range of published works relating to the WEDM process into three major areas, namely optimising the process variables, monitoring and control the process, and WEDM developments. This section discusses the classified WEDM research areas and the possible future research directions, illustrated in Fig. 1.

5.1. Optimising the process variables

The optimisation of the WEDM process often proves to be a difficult task owing to the many regulating machining variables. A single parameter change will influence the process in a complex way [52]. Thus, the various factors affecting the process has to be understood in order to determine the trends of the process variation, as discussed in Section 4.1.1. The selection of the best combination of the process parameters for an optimal machining performance involves analytical and statistical methods. However, it is very complicated to relate the input process parameter with the output performance measures and derive an optimal result using a simulated algorithm. The CR, MRR and SF are usually opted as the measures of the process performance. Nevertheless, these methods provide an effective means of identifying the variables affecting the machining performance.

In addition, the modelling of the process is also an effective way of solving the tedious problem of relating the process parameters to the performance measures. As mentioned in Section 4.1.2, several attempts have been carried out to model the process investigating into the influence of the machining parameters on WEDM performance and identifying the optimal machining condition from the infinite number of combinations. As a result, it provides an accurate dimensional inspection and verification of the process yielding a better stability and higher productivity for the WEDM process. How-

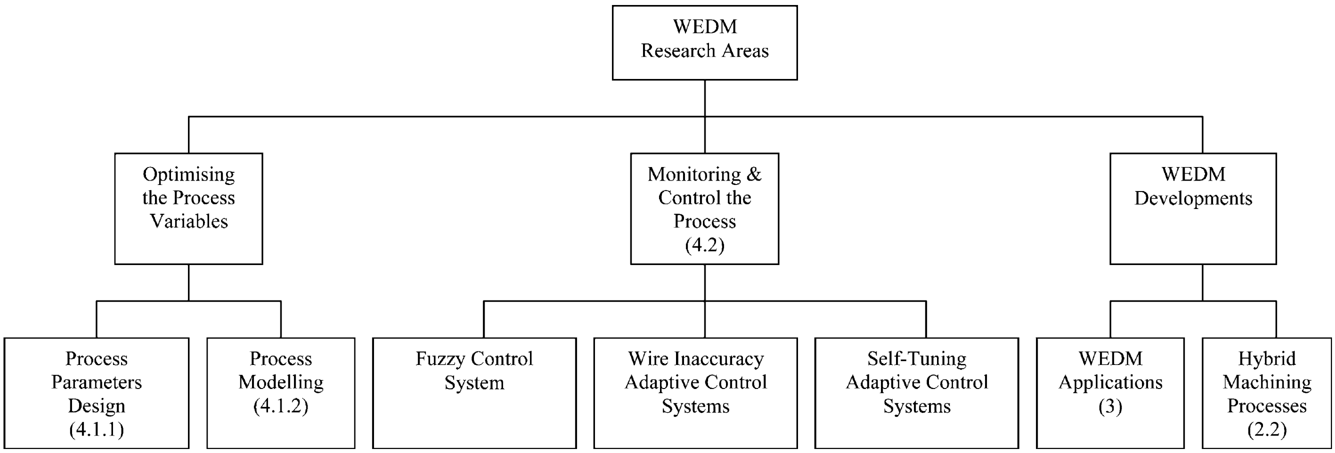

Fig. 1. Classification of major WEDM research areas (corresponding section numbers are in brackets).

ever, the complex and random nature of the erosion process in WEDM requires the application of deterministic as well as stochastic techniques [61]. Therefore, the optimisation of the WEDM process will remain a key research area matching the numerous process parameters with the performance measures.

5.2. Monitoring and control the process

Over the years, the monitoring and control systems have made an important contribution in minimising the effect of disturbances on the WEDM performance. The multi-parameter machining settings have made it difficult to clearly understand and obtain the optimal machining conditions. It requires a control algorithm that is often based on explicit mathematical and statistical models to cope with the machining process. However, the application of the fuzzy control logic has brought about a drastic change to the conventional way of monitoring and controlling the WEDM process. The fuzzy control logic is able to consider several machining variables, weigh the significant factors affecting the process and make changes to the machining conditions without applying the detailed mathematical model, as mentioned in Section 4.2.1. In addition, the feasibility of applying the expert system capable of giving advice and solving problems has also been explored [110]. Such a system would greatly appeal to the shop floor operational needs demanding unattended WEDM operation.

The risk of the wire breakage and the bending of the wire have also limited the efficiency and accuracy of the WEDM process. The occurrence of the wire breakage directly reduces the already low machining speed affecting the overall productivity of the machining process. Although, the control strategies reported in Section 4.2.2 are designed to solve the problems of wire breakage, it solely relies on the indication of the possible occurrence and generates inadequate results investigating the root cause of the wire breakage phenomenon. These strategies may therefore be deemed to be a setback when machining a workpiece with variable heights requiring a drastic change in the machining conditions.

In addition, the wire vibrational behaviour and static deflection easily influence the geometric accuracy of the part produced. The typical solutions to these problems are often very conservative in nature by increasing the machining gap or reducing the discharge energy, which is regarded to be a main drawback for the WEDM process efficiency. Fig. 2 shows the huge amount of research work concentrating on the improvement of

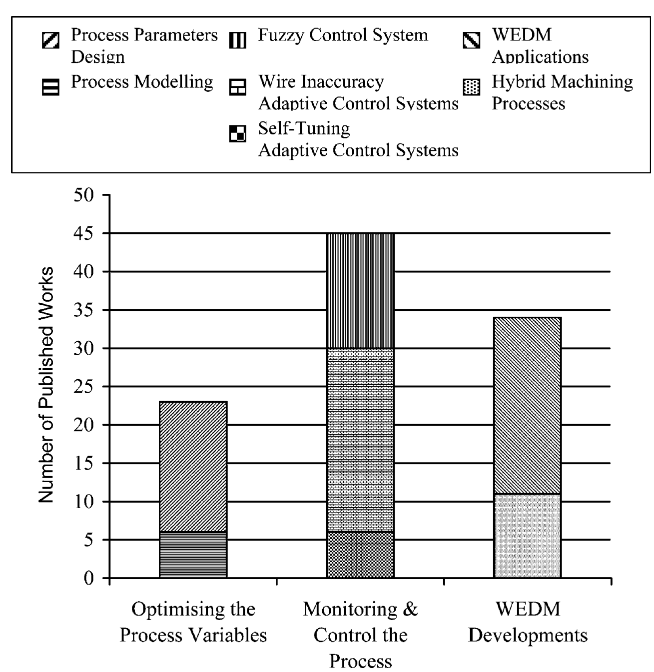

Fig. 2. Distribution of the collection WEDM research publications.

the inaccuracy caused by the wire through the application of an adaptive control system. Jennes and Snoey [113] believed that the traditional research purpose was not to improve machining efficiency, but to prevent from wire rupture during the machining process. Hence, one possible new WEDM challenge and future work area will be steered towards attaining higher machining efficiency by acquiring a higher CR and MRR with a low wire consumption and frequency of wire breakage.

5.3. WEDM developments

The WEDM process is a suitable machining option in meeting the demands of today's modern applications. It has been commonly used in the automotive, aerospace, mould, tool and die making industries. WEDM applications can also be found in the medical, optical, dental, jewellery industries, and in the automotive and aerospace R&D areas [114]. Its large pool of applications, as shown in Fig. 2, is largely owed to the machining technique, which is not restricted by the hardness, strength or toughness of the workpiece material. As mentioned in Section 3, the WEDM of the HSTR, modern composite and advanced ceramic materials, which is showing a growing tend in many engineering applications, has also been experimented. It has replaced the conventional means of machining ceramics, namely the ultrasonic machining and laser beam machining, which are not only costly to machine but damage the surface integrity of the ceramic component. However, with the introduction of over 20 non-traditional machining processes in the past 50 years and the rapid growth in the development of harder, tougher and stronger workpiece materials [115], the WEDM process inevitably has to be constantly rejuvenated in order to compete and satisfy the future crucial machining requirements.

In addition, the WEDM process has sought the benefits of combining with other material removal methods to further expand its applications and improve the machining characteristics. The authors have classified the WEDM machine into the various physical characteristics, which clearly distinguishes the different types of machine features affecting the performance measures, machining capacity and auxiliary facilities, as shown in Fig. 3. One of the most practical and precision HMP arrangements is the WEDG process used mainly to produce small size and complicated shape thin rod, which can be easily bent or broken by the lateral force when using conventional grinding process. The precision of the CNC system is also partly responsible for the accuracy of the WEDG [116]. Therefore, the HMP processes, in particular the WEDG process, will continue to receive intense research attention

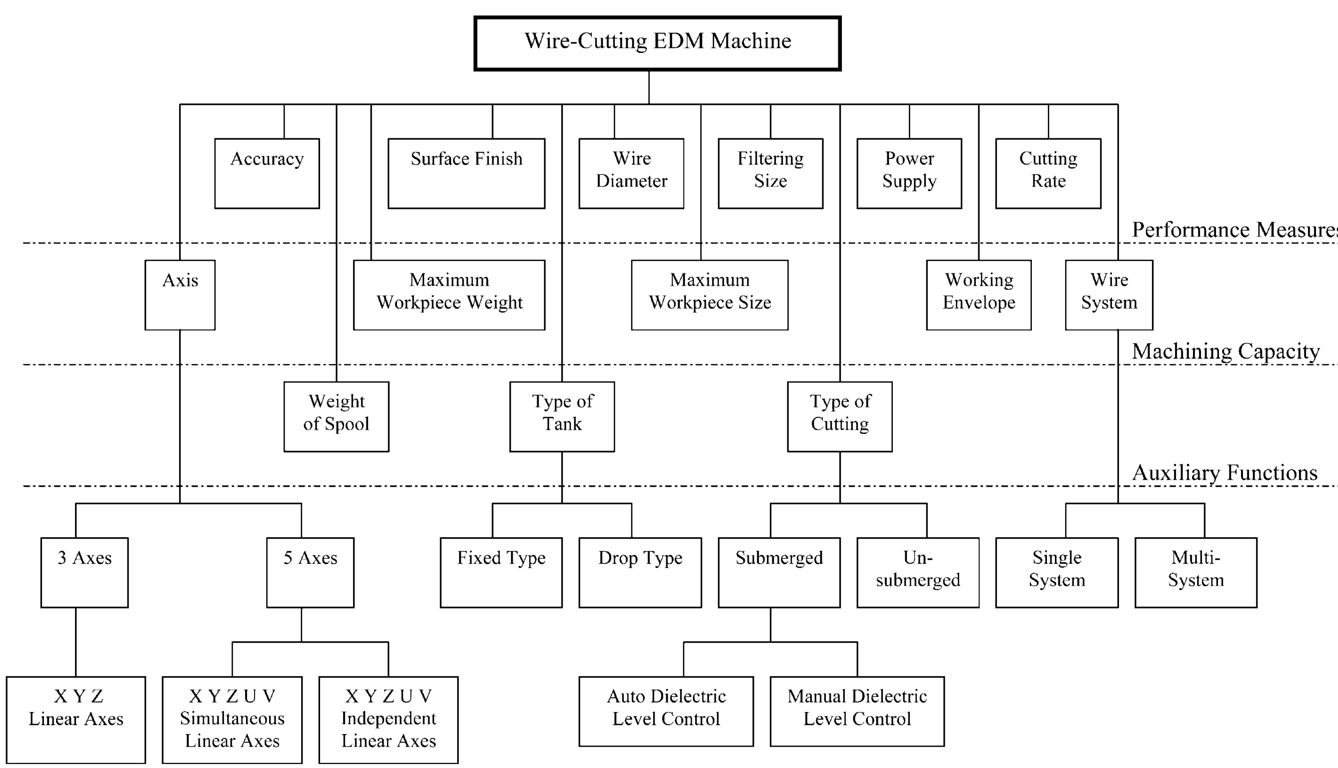

Fig. 3. Classification of wire-cutting EDM machine.

especially in the growing field of micro-electronics circuitry manufacturing.

There is also a major push toward an unattended WEDM operation attaining a machining performance level that can be only achieved by a skilled operator. Such a goal has been partly fulfilled through the application of the CNC to control the machining strategies, to prevent the wire breakage and to automate the self-threading systems. An environmentally friendly and high-capacity dielectric regeneration system, which autonomously maintains the quality of the dielectric circulating within the WEDM machine, has also been experimented [117]. However, due consideration still has to be given to improve the WEDM performance and enhance the level of automation for future integration of the EDM and WEDM processes within the CIM environment [118]. It would then be able to reasonably meet the shortage of highly skilled EDM/WEDM operators and achieve a more cost efficient and cost effective machining operation.

6. Concluding remarks

WEDM is a well-established non-conventional material removal process capable of meeting the diverse machining requirements posed by the demanding metal cutting industries. It has been commonly applied for the machining and micro-machining of parts with intricate shapes and varying hardness requiring high profile accuracy and tight dimensional tolerances. However the main disadvantage of the process is the relatively low machining speed, as compared to the other non-traditional machining processes such as the laser-cutting process, largely due to its thermal machining technique. In addition, the development of newer and more exotic materials has challenged the viability of the WEDM process in the future manufacturing environment. Hence, continuous improvement needs to be made to the current WEDM traits in order to extend the machining capability and increase the machining productivity and efficiency.

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 behaviour 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 vibrational behaviour 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 toolroom manufacturing arena. Though the authors 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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