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A progress review in wire electrical discharge machining process

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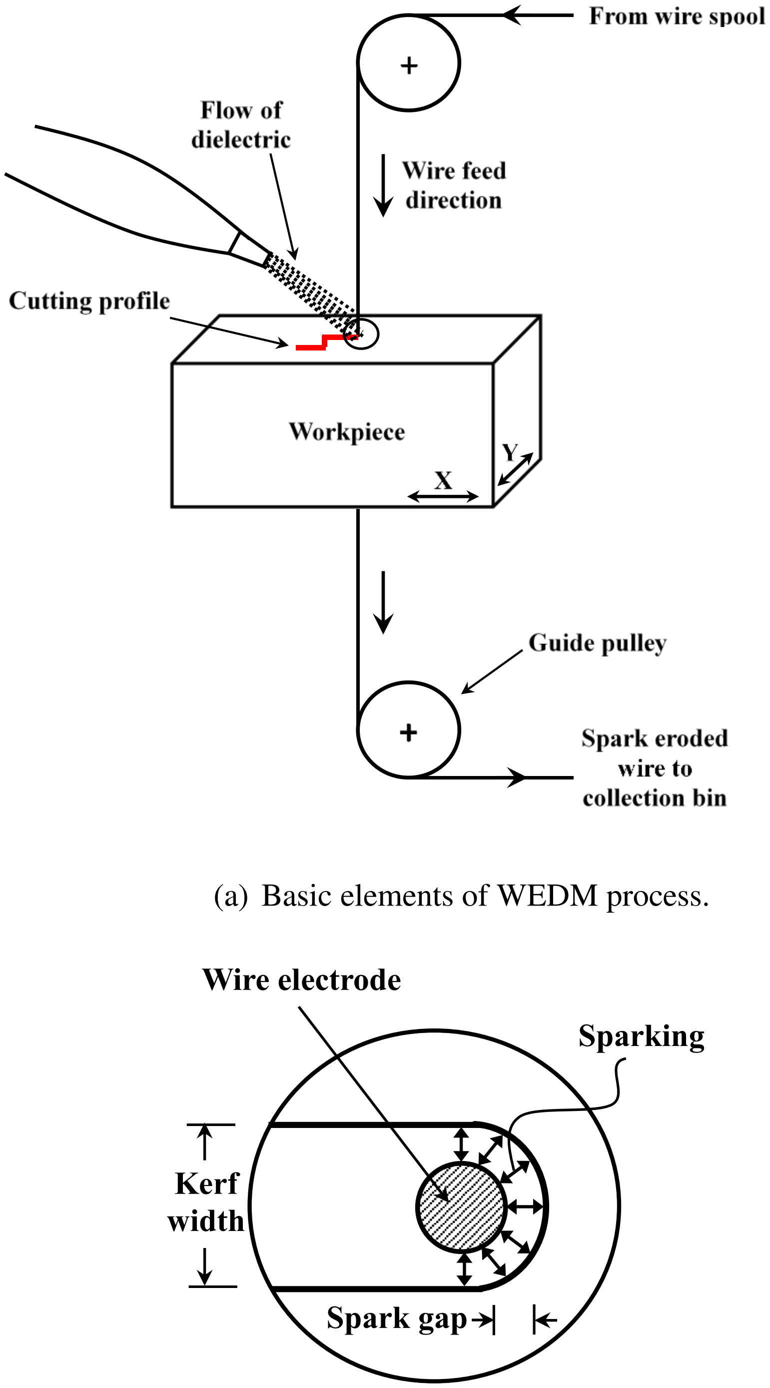
ABSTRACT

Wire Electrical Discharge Machining (WEDM) is an electrothermal non-traditional machining process used for machining electrically conductive materials that are difficult to machine. Material removal in WEDM is by means of spark erosion. WEDM is proven to be the alternative for producing complex parts with higher degree of dimensional accuracy and better surface finish. Over the years, a significant amount of research was globally carried out to explore the WEDM process capability. This paper aims to explore the research work carried on parametric influence of WEDM process variables on various output performance measures. The paper also highlights various modelling techniques to predict optimal machining conditions and explore the feasibility of applying WEDM process to machine advanced materials. Combined technology that benefits from the virtues of WEDM and conventional method is also highlighted in this paper. The final section discusses the development and possible research trend in WEDM process.

Keywords: Wire electrical discharge machining; surface roughness; material removal rate; optimisation.

INTRODUCTION

Materials with unique metallurgical properties are difficult to machine with conventional methods. Machining these materials results in high temperature rise, undesirable residual stress built up in workpiece, rapid tool wear, and increased machining cost. The need for non-traditional machining process arises to meet the above requirements [1-3]. Based on the source of energy involved in material removal, non-traditional machining process can be categorised into electrochemical process (metal removal by chemical dissolution), mechanical process (low amplitude and high frequency of abrasives impacting the workpiece), and electrothermal process (metal removal by melting and vaporisation) [4-7]. In electrothermal process, the material removal mechanism is by means of spark erosion. The application of electrical spark (electrical discharge) generates heat, which melts and vaporises the material from the workpiece surface. Wire Electrical Discharge Machining (WEDM) is one of the non-traditional machining process, which works on the principle of spark erosion [8-10]. WEDM is widely used for manufacturing complex two-dimensional (2D) and three-dimensional (3D) shapes with electrically conductive workpiece by using a wire electrode of diameter that varies from 0.05–0.3 mm. WEDM is a non-traditional machining process used for machining electrically conductive materials that are difficult to machine use conventional methods. Material removal in WEDM is by means of spark erosion that involves melting, vaporisation, and rapid cooling of molten metal. Metal erosion in WEDM is by means of rapid repetitive spark discharges from a pulsating direct current power supply with dielectric flow between the workpiece and tool electrode [11, 12]. The schematic representation of WEDM process is given in Figure 1.



(a) Basic elements of WEDM process.

(b) Enlarged view of the marked region.

Figure 1. Schematic illustration of WEDM process.

The material removal in WEDM is by a series of repetitive spark discharges that occurs between the tool (wire electrode) and workpiece immersed in a liquid dielectric separated by a distance called spark gap. During pulse-on time, when an appropriate voltage is applied, the dielectric breaks down and an electrical spark is established between the tool and workpiece. The electrical energy is transmitted into heat energy by thermal conduction through formation of discharge column. The tool and workpiece starts melting due to high-energy plasma formation. As the discharge continues, tool, workpiece, and dielectric starts vaporising that results in the formation of a compressed vapour bubble, which expands until the pulse-ontime. At the beginning of pulse-off time the discharge ceases, results in a violent collapse of plasma channel and compressed vapour bubble causing the super-heated and molten liquid to explode into dielectric. The expelled materials re-solidify into tiny spheres and are flushed away by the dielectric. This resulted in the formation of a small cavity or crater on workpiece surface. As the successive number of discharge take place, the required amount of material is removed from the workpiece surface [13, 14].

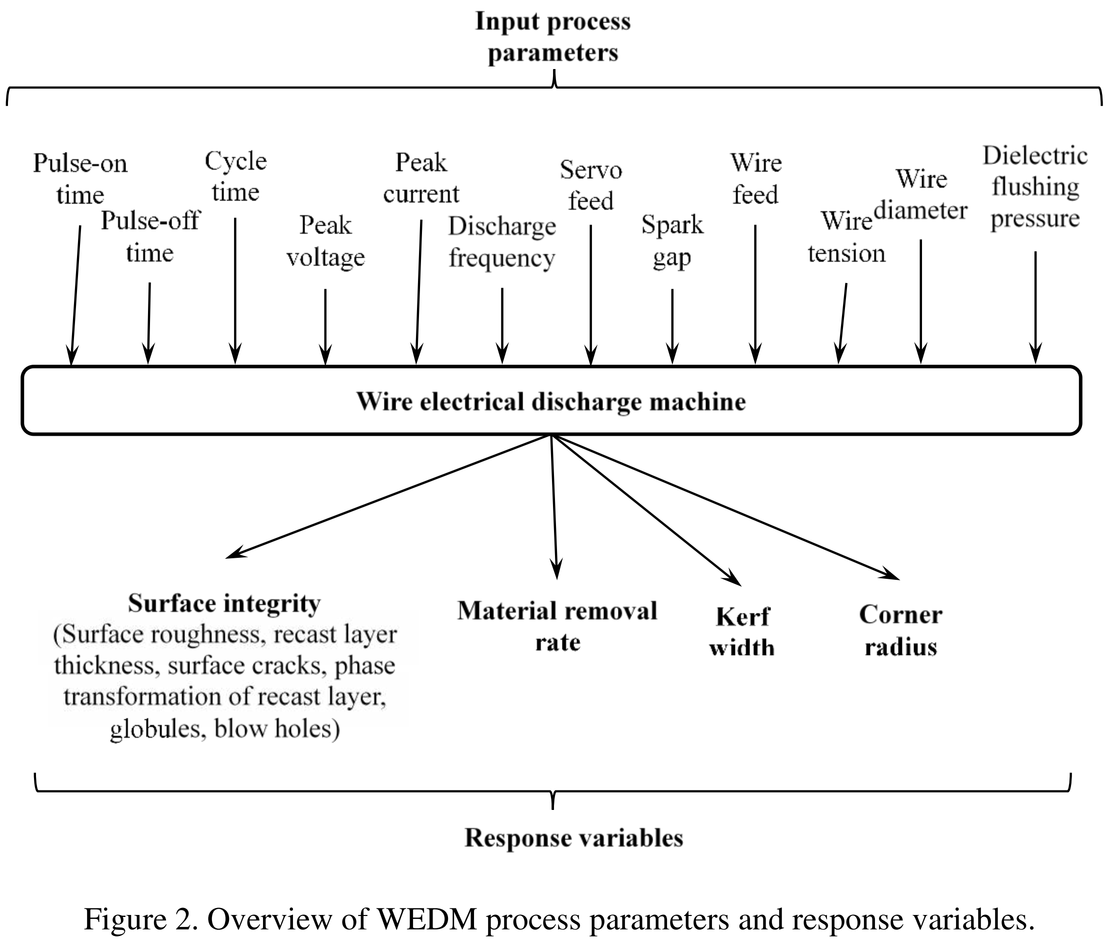


Figure 2. Overview of WEDM process parameters and response variables.

The erosion phenomenon in WEDM is similar to that of electrical discharge machining process, which is transient and stochastic in nature. It involves a combination of several disciplines, such as electric, magnetic, thermal, mechanic, dynamic or hydraulic. Due to the complex erosion phenomena of WEDM process it is quite difficult to understand the relationship between the input process variables and output performance measures. Many research had contributed in investigating the relationship between input process variables, such as pulse-on time, pulse-off time, discharge voltage, discharge current, discharge energy, discharge frequency, servo feed, spark gap, wire feed, wire tension, wire diameter, and dielectric flushing pressure on the response variables, such as surface integrity (surface roughness, recast layer thickness, micro cracks, and chemical composition of recast layer), material removal rate (MRR), cutting speed, kerf width, and corner radius. Figure 2 shows the overview of WEDM process parameters and the response variables. However, the review presented in this paper is on current research trends carried out by various researchers studying the parametric influence on machining characteristics of WEDM process, machining advanced materials by using WEDM and modelling techniques in predicting the performance of WEDM process. WEDM process were developed in many areas, such as machining of advanced materials [15-25] and combining technology of grinding, milling, and turning with WEDM that benefits the virtue of both processes [3-6, 8-10]. The topics are selected due to a growing need for machining advanced materials, novel techniques developed by using WEDM, and understanding the performance of WEDM (machining characteristics and modelling techniques). The activities carried out by each researcher and the development in understanding WEDM process capabilities are presented in each topic. Table 1 shows the contribution from various researchers towards WEDM process capabilities.

EFFECT OF PROCESS PARAMETERS ON MACHINING CHARACTERISTICS

Effect of Process Parameters

WEDM process is mostly used in manufacture of die and mould components, like sheet metal press dies, extrusion dies, etc., prototype, and special form inserts manufacturing where surface roughness plays a significant role. Surface roughness of the WEDM machined components is primarily dependent on the process parameters. Investigation on the influence of process parameters on roughness of WEDM machined components was carried out by several researchers. The influence of process parameters, such as voltage and current on varying thickness of different grades of steel material namely 1040, cold work tool steel (2379), and plastic mould steel (2738) was carried out. It is observed for same process parameter combination, different roughness values are obtained due to change in the material property [26-28]. The effect of process parameters, like pulse duration, pulse-off time, open circuit voltage, servo feed, servo voltage, dielectric flushing pressure, wire feed, and wire tension on surface roughness of Ti6Al4V material [29-31], AISI 4140 steel material [14], and AISI D2 tool steel material [32] were studied. It was found that roughness of Ti6Al4V was significantly affected by servo voltage, wire feed, and wire tension whereas the effect of open circuit voltage was dominant in machining AISI 1040 steel material. As open circuit voltage increased, the electric field becomes stronger and spark discharge takes place in the gap that resulted in a rough surface. As the wire tension was increased, deflection and vibration of wire was reduced, which improved the surface finish. The increase in dielectric flushing pressure leads to reduced roughness of machined components due to better flushing in the gap [32]. The influence of process parameters, such as pulse-on time, pulse-off time, peak current, wire diameter, wire tension, wire feed, and dielectric flushing pressure on machining of Inconel 601 material was determined [33].

Table 1. Progress in WEDM research.

Machining characteristics			Machining of advanced materials	Modelling and simulation	New techniques using WEDM
Roughness	Surface integrity	Material removal rate			
Gokler and Ozanoozgu [26], [29]; Tosun et al. [14]; Hascalyk and Caydas [32]; Hewidy et al. [33]; Sarkar et al. [34]; Pramanik and Basak [35]; Kanlayasiri and Boonmung [36]; Han et al. [37]; Mahapatra and Patnaik [38]; Yan and Lai [39]; Ramakrishnan and Kaunamoorthy [40]; Newton et al. [41]; Shah et al. [42]; Satishkumar et al. [43]; Alias et al. [30]; Yang et al. [44]; Soo et al. [45]; Amineh et al. [46]; Suresh Kumar et al. [47]; Jangra [48]; Gong et al. [49]	Kuriakose and Shunmugam [11]; Huang et al. [50], Huang et al. [51]; Hascalyk and Caydas [32]; Puri and Bhattacharyya [52]; Han et al. [37]; Newton et al. [41]; Hatami et al. [53]; Li et al. [54]; Welling [55]; Liu et al. [56]; Zhang [57]; Manjaiah et al. [58], Manjaiah et al. [59]; Prasad et al. [60]; Sharma et al. [61]; Wei et al. [62]; Liu et al. [63]; Sireli et al. [64]	Kunieda and Furudate [65]; Tosun et al. [14]; Miller et al. [21]; Mahapatra and Patnaik [38]; Ramakrishnan and Kaunamoorthy [40]; Poros and Zaborski [66]; Shah et al. [42]; Yang et al. [67]; Zhang [57]; Goswami and Kumar [68]; Radhakrishnan et al. [69]; Singh et al. [70]	Rhoney et al. [22]; Badami et al. [15]; Miller et al. [21]; Takino et al. [23], Takino et al. [24]; Yu et al. [71]; Yeh et al. [72]; Lee et al. [20]; Hou et al. [73]; Greer et al. [74]; Cheng et al. [16]; Gupta and Jain [75]; Bae et al. [76]; Bobbili et al. [77], Bobbili et al. [78], Bobbili et al. [79]; Dongree et al. [17]; Ayesta et al. [80]; Gee et al. [18]; Pramanik et al. [81]; Gee et al. [19]; Joshi et al. [82]	***Modelling*** Puri and Bhattacharyya [52]; Tosun et al. [14]; Kuriakose and Shunmugam [83]; Mahapatra and Patnaik [38]; Hewidy et al. [33]; Kanlayasiri and Boonmung [36], [84]; Poros and Zaborski [66]; Ramakrishnan and Kaunamoorthy [40]; Prasad and Gopala Krishna [85]; Gauri and Chakraborthy [86]; Shah et al. [42]; Kumar and Agarwal [87]; Yang et al. [44]; Mukherjee et al. [88]; Khan and Rajput [89]; Boopathi and Sivakumar [90]; Rajyalakshmi and Venkata Ramaiah [91]; Ikram et al. [92].	Masuzawa and Tonshoff [4]; Qu et al. [6]; Uhlmann et al. [12]; Mohammadi et al. [5]; Menzies and Koshy [9]; Janardhan and Samuel [3]; Gotoh et al. [10]; Giridharan and Samuel [1], Giridharan and Samuel [2]; Zhu et al. [8]

Table 1. Continued.

Machining characteristics			Machining of advanced materials	Modelling and simulation	New techniques using WEDM
Roughness	Surface integrity	Material removal rate			
				Modelling Gautier et al. [93]; Aggarwal et al. [94]; Zhang et al. [95]; Prasad and Gopala Krishna [96]; Bobbili et al. [77], [78], Bobbili et al. [79]. Cheng et al. [16]; Pramanik et al. [81]; Samanta et al. [97]; Shakeri et al. [98]; Majumder et al. [99]; Nain et al. [100] ***Simulation*** [37], Han et al. [101], [102];Sanchez et al. [103]; Tomura and Kunieda [104]; Okada et al. [13]; Banerjee and Prasad [105]; Yang et al. [44]; Hada and Kunieda [106]; Okada et al. [13], [107]; Lingling et al. [108]; Yueqin et al. [109]; Shi et al. [110];Werner [111]; Wentai et al. [112]	

For low amplitudes of peak current, no variation in roughness of machined component was observed and with increase in the peak current, drastic increase in roughness of machined component was observed. As the peak current increases, the discharge energy of the spark increases that melts and vaporises more amount of material that resulted in a rough surface. The above mentioned reason was also supported by [36, 84] while machining DC53 cold die steel material. [37] studied the influence of pulse duration and current on roughness of alloy steel and stated identical surface roughness can be obtained for different pulse duration keeping peak current at constant value. Although the roughness value of the machined component appears to be the same, the colour and lustre of the machined surface was different. The formation of shallow and deep crater for short and long pulse durations, respectively, led to a different surface appearance. The effect of discharge current, pulse duration, and dielectric flow rate was dominant as compared to that of pulse frequency, wire feed, and wire tension on roughness of machined D2 tool steel material [38]. It was possible to achieve a fine surface finish by reducing the discharge duration to nanoseconds and using very low peak current amplitudes [39]. Authors attempted to study the influence of pulse-on time, wire feed, ignition current, wire diameter, table feed, and spark cycle time in Inconel 718 machining material and found that the machined component roughness increased with an increase in pulse duration [40] and wire diameter [41]. Authors studied the influence of material thickness, open voltage, pulse-on time, pulse-off time, servo voltage, wire feed, wire tension, and dielectric flushing pressure on tungsten carbide material and pure tungsten material. It was observed that as the pulse-on time increased, a longer and more concentrated discharge took place that caused a highly localised metal erosion, which resulted in increased roughness. Increase in material thickness led to a more highly distributed discharge, which resulted in reduced surface roughness [42, 44]. Sarkar et al. [34] studied the influence of pulse-on time, pulse-off time, peak current, wire tension, servo voltage, and dielectric flushing pressure on γ titanium aluminide alloy and stated that as the parameters were varied, the increase in cutting speed resulted in an increased surface roughness of the machined component. Gong et al. [49] did an experimental study on the influence of break down voltage on kerf and surface roughness of a machined component. Authors stated that increase in the breakdown voltage magnitude would decrease kerf width and increase surface roughness. [45] studied the comparison of fatigue life of titanium alloy (Ti-6Al-2Sn4Zr-6Mo) machined by using WEDM and a conventional milling process. It was observed that at low applied stress levels more favourable residual stress developed in the milled specimen, which resulted in a 12% increased fatigue life of milled component than a WEDM machined specimen. [113] studied the influence of WEDM process parameters on machining of WC-5.3% Co composite material and stated that a better surface finish can be achieved by setting the optimal wire offset value. Amineh et al. [46] improved the surface finish of WEDM surface by removing the recast layer through a magnetic abrasive finishing method. Authors studied the influence of WEDM process parameters on machining of Al-based composites, namely Al6063/SiC_p composite [43], Aluminium metal matrix composite [35]; Boron carbide [81], and Aluminium (6351) alloy reinforced with 54 wt. % Silicon Carbide (SiC) and 0, 5, 10 wt. % of BC [47]. Authors stated that of all the process parameters, pulse-on time was the significant parameter that affected surface roughness. It was observed from literature that various researchers had studied the influence of WEDM process parameters on the surface roughness of different materials used in manufacturing, automotive, and aerospace applications. Due to the stochastic nature of WEDM process, materials machined under identical conditions will result in non-uniform response characteristics. The following section discusses the influence of WEDM process parameters on surface characteristics of machined surface.

Surface Characteristics

In WEDM, as the discharge begins, high temperature is developed, which results in the formation of molten pool at the vicinity of spark. As the discharge ceases, these molten materials are violently expelled and re-solidifies onto the adjacent region of the machined surface due to rapid cooling. This re-solidified material, so-called white layer or recast layer, is neither ejected nor removed by the flushing action of the dielectric. The thickness of white layer formed is dependent on the input process parameters selected. Apart from recast layer, the other surface characteristics include surface cracks, blow holes, globules, and phase transformation of the re-cast layer. Table 2 shows the surface integrity that occur in WEDM process and the instruments used for measurement.

WEDM is an electrothermal machining process in which a thick oxide layer is formed due to thermal oxidation. These oxide layers are not preferable when the WEDM-machined components are subjected to high temperature applications, especially automotive and aero engine applications. The intensity of this oxide layer can be analysed by using various metallurgical techniques. Kuriakose and Shunmugam [11] analysed the effect of process parameters on the intensity of oxide layer while machining Ti64 material byusing XRD diffraction profiles. The study revealed that among the various WEDM process parameters, pulse duration, pulse-off time, and injection pressure had greater influence on the formation of oxide layer. The longer the pulse duration time, the higher was the discharge energy that generated the increased peak intensity of oxide layer. As the pulse-off time increases, the number of discharges for a given time reduces that result in a non-uniform heating and cooling of the surface. Non-uniform heating and cooling induces higher rate of thermal stresses and results in suppression of peak intensity of oxide layer formation. Increasing the dielectric flushing pressure and rapid cooling of molten material leads to increased thermal stress and peak intensity of oxide layer formation. The elemental composition of the WEDM AISI 440A steel material was studied using energy dispersive X-ray spectrometer (EDX) integrated with micrograph taken using Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM). The specimen was subjected to multiple pass by varying the process parameters, such as discharge duration, pulse-off time, wire feed, and wire tension. The EDX profile of the cut specimen revealed that as the number of passes increased, the rate of deposition of wire electrode material onto the machined surface increased. The SEM and TEM images revealed the formation of fine spherical nodules with multi passes due to reduced surface energy during solidification [50, 51]. The thickness of the recast layer (RCLT) formation, Heat Affected Zone (HAZ), and inter-granular cracking on quenched and tempered AISI 440A was also analysed by using SEM and TEM micrographs. SEM micrograph revealed that quenched steel possessed large RCLT as compared to tempered steel for the same parameter combinations. As the temperature of tempering increased, RCLT was reduced. Adjacent to the recast layer, a distinct lath martensitic structure was detected in HAZ. The inter-granular cracking caused by relieve of residual thermal stress of the quenched workpiece was observed. The phase transformation of the WEDM machined surface, which involved melting and rapid cooling, can be revealed using Micro Hardness Testing Method. Hascalyk and Caydas [32] distinguished the RCLT and HAZ from the parent material using Micro Hardness Testing. The micro hardness test of the cut specimen revealed that the hardness value was high at RCLT due to rapid cooling of molten metal and due to thermal softening whichreduced value of hardness was observed at HAZ. Sireli et al. [64] studied the influence of HAZ on surface integrity of WC-10Co alloy. The WEDMed WC-10Co component was coated with TiN layer to study the adhesion, friction, and wear property. The results were compared with that of the dry blasting process. Coating of TiN directly on WEDMed surface appeared to be rough as compared to that of dry blasted surface. The variation of RCLT or white layer thickness during the first cut and trim cut of die steel were analysed by using SEM micrograph.

During trim cut the wire electrode was allowed to trace the previously executed profile with reduced discharge energy. Moreover, trim cut was employed for finishing operation. During trim cut, the white layer formed in the previous pass will be removed that resulted in a reduced thickness of white layer at the end of trim cut [52]. Reversing the polarity of tool and electrode will have a significant effect on the machined surface. Han et al. [37] studied the influence of normal (workpiece +ve) and reverse polarity (workpiece –ve) by using XRD profile while machining alloy steel (Cr12) material by using brass as wire electrode. As the polarity was reversed more amount of copper got deposited onto the crater of the machined surface. Wire diameter was one of the influencing parameter in RCLT formation. For the same operating conditions, as the wire diameter increased, the energy per spark increased and resulted in increased RCLT [41]. The micro hardness test of Inconel 718 revealed that the hardness value measured at white layer decreases due to thermal softening as compared to that of the hardness measured at HAZ and parent metal [54].

Table 2. Surface integrity of WEDM process and its measuring instruments.

Surface integrity	Measuring instruments
Surface roughness	i. 2D roughness measuring instrument ii. 3D surface profiler
White layer or recast layer	i. Scanning Electron Microscope ii. Transmission Electron Microscope iii. Stereo Microscope
Heat Affected Zone	i. Scanning Electron Microscope ii. Transmission Electron Microscope iii. Micro hardness tester
Blow holes and globules	i. Scanning Electron Microscope
Surface cracks	i. Scanning Electron Microscope ii. Stereo Microscope
Phase transformation	i. Energy dispersive X-ray spectrometer ii. X-ray diffraction

Prasad et al. [60] studied the influence of process parameter on damping property of WEDM machined A356.2 aluminium alloy. Authors stated that the presence of a large number of micro cracks and micropores on the surface of the white layer enhanced the damping property. Authors studied the influence of different sized wire diameter on surface integrity of Inconel 706 material. Small diameter wire produces better surface finish, smaller RCLT, and reduce machining time [61]. The surface burning property of Cr12 steel material was analysed for different machining conditions [62]. Welling [55] compared the fatigue life of components manufactured by using different manufacturing techniques under high cycle fatigue test conditions. Author stated that the failure moments of WEDM machined surface was comparable with the surface generated by using conventional broaching process. This serves as an alternative method for manufacture of fir tree slots instead of conventional broaching technique. Authors studied the surface integrity of advanced materials, such as shape memory alloys (Nitinol SE508) and nano-composite ceramics. The significant thermal softening resulted in reduced micro hardness at the top surface of shape memory alloy as compared to that of the parent material. The machined surface of Nitinol SE508 revealed alternate porous and solid white layers for high and discharge energies, respectively. At low discharge energy, the tensile residual stress was not sufficient to crack the white layer that resulted in solid white layer. The EDS profile of WEDM machined TiN/Si3N4 nano-composite ceramic surface revealed that the material from the wire electrode can transfer to the workpiece and the transfer of wire electrode increased with increase in number of power transistor [56, 57]. Liu et al. [63] compared the thickness of white layer generated by WEDM machining of Nitinol shape memory alloy using different machining process. Authors stated that the white layer produced by WEDM process exhibited a porous and non-uniform bi-layered structure. Manjaiah et al. [58] attempted to study the influence of WEDM process parameters on machining of Ti50Ni45Cu shape memory alloy. Authors also studied the feasibility of machining TiNiCu shape memory alloy by using plain and zinc coated brass wire. The zinc coated brass wire gave better machining characteristics compared to that of plain brass wire Manjaiah et al. [59]. Hatami et al. [53] attempted to study the characterisation of wire electrical discharge machining of powder metallurgical cold work tool steels, namely Vancron 40 and Vanadis 10 by using XRD, SEM, and X-ray photoelectron spectroscopy (XPS). Authors stated that Vancron 40 exhibited a higher cracking tendency due to its low resistance to thermal shock.

The surface characteristics of various materials, such as steel, titanium alloy, Inconel, etc., were presented in the above section. It was observed that each process parameter was having its significance on the white layer thickness, surface cracks, and formation of oxide layer. Irrespective of the materials' property, the formation of oxide layer on the machined surface due to melting, vaporisation, and rapid cooling of molten metal was observed in all the materials. However, variation in the peak intensity of oxide layer was dependent on materials' property. The presence of these surface characteristics was not suitable for components that were subjected to high temperature applications like in aero engines. Hence, these surface characteristics will be removed by finish machining process.

Material Removal Rate

Material removal rate is one of the important parameters that influence the productivity of any machining process. Many authors studied the significance of WEDM process parameters on MRR. Kunieda and Furudate [65] compared MRR of dry and conventional WEDM processes. Dry WEDM possessed the advantages of corrosion free surface, better straightness, gap length, and accuracy in corner-cut. However, conventional WEDM proved to be suitable in terms of MRR. Tosun et al. [14] studied the influence of process parameters on MRR and kerf while machining AISI 4140 steel material. Among the WEDM process parameters, pulse duration and open voltage proved to be significant parameters that affect MRR and kerf width, whereas the effect of wire feed and dielectric flushing pressure seemed to be insignificant. The influence of dielectric flushing pressure was insignificant on MRR [38]. As the effect of pulse-on time and ignition currents increased, there were more number of discharge in the gap that resulted in increased MRR, whereas the increase in delay time resulted in a reduced number of discharges for a given time that led to reduced MRR while machining Inconel 718 material Ramakrishnan and Kaunamoorthy [40]. Poros and Zaborski [66] studied the performance of uncoated, zinc coated, and brass coated wire electrode on MRR of cemented carbide and Ti6Al4V material. In both materials for a given process parameter combination, brass coated wire proved to give a higher MRR due to improved electrical conductivity as compared to that of the other two wire electrode types. The MRR of tungsten carbide decreased with increase in material thickness due to inadequate flushing because of the longer kerf area [42]. With an increase in pulse-on time, the discharge energy developed in the gap increased, which removed more material and hence resulted in increased MRR while machining tungsten material [44]. Miller et al. [21] proposed a process envelope for selecting suitable machining parameter combinations while machining advanced materials like porous metal foams, metal bond diamond grinding wheels, sintered Nd-Fe-B magnets and carbon–carbon bipolar plates. Zhang [57] studied the influence of pulse-off time and number of power transmitters used while machining nano-composite ceramic material and stated that the machining speed increased with increase in number of power transistors used and decreased with increase in pulse-off time. Goswami and Kumar [68] studied the influence of trim cut on machining characteristics of Nimonic 80A material using WEDM process. Radhakrishnan et al. [69] studied the influence of lateral wire vibration on MRR of Ti6Al4V material and proposed that low frequency wire vibration will enhance MRR. The influence of WEDM process parameters on machinability of multi-walled carbon nanotubes filled alumina composites of varying composition was studied. Authors observed that MRR increased with increase in volume fraction of carbon nanotubes in the composite matrix [70]. The influence of WEDM process parameters on MRR of different materials was presented in the above section. Due to the transient erosion phenomena of WEDM process, materials machined under identical conditions did not produce similar results.

WEDM OF ADVANCED MATERIALS

Many researchers have studied machining of electrically conductive and electrically resistive advanced materials [7, 114, 115]. The overview of WEDM process used for machining of advanced materials was given in Table 3. Few researchers have attempted to study the feasibility of machining advanced materials by using WEDM process. Rhoney et al. [22] demonstrated the feasibility of WEDM process applied for truing of metal bonded diamond grinding wheels for precise grinding of ceramics and compared it with wheel trued by using single point diamond. The WEDM trued grinding wheel exhibits 20%–40% lower grinding force and wear faster as compared to that of the wheel trued by using single point diamond. The WEDM trued grinding wheel possessed a higher wheel wear rate during first pass and became lower and stabilised during subsequent passes. However, the wear rate of grinding wheel varied for different cutting conditions.

Badami et al. [15] demonstrated the feasibility of WEDM process applied to generate fine pitch threads on Superinvar material. High quality 40 TPI threads were produced; however, 20%–25% of the screws produced had defects, which include asymmetry and distortion in the thread profile and significant deviations from the nominal thread angle. Authors stated that the quality of threads produced by WEDM was superior to threads produced by single point cutting tool. Gupta and Jain [75] studied the feasibility of applying WEDM process for manufacture of a miniature spur gear having a total profile deviation of 13.20 μm, total lead deviation of 5.40 μm, and average surface roughness of 1.00 μm. The geometrical variations were observed in gears due to wire lag and high discharge energy pulses. An attempt was made in generating fine grooves by using WEDM process on AISI 304 stainless steel, to test the hydrophobic and oleophilic properties of the grooved surface. Authors demonstrated a super superior hydrophobic property of WEDM machined grooves of different depth and stated that increasing the depth of groove will likely prevent water droplet from wetting the groove [76]. Ayesta et al. [80] compared the fatigue behaviour of Inconel 718 material machined byusing WEDM process and compared it with components manufactured through a grinding process. Authors proposed that at high fatigue cycles, the components machined through

WEDM process exhibited 10% lesser fatigue strength than that of the grounded component. Takino et al. [23] attempted to study the machinability of polished single crystal silicon using water and oil as dielectric medium. The surface cut by water is more degraded such as formation of silicon dioxide and roughed whereas the surface cut by oil appeared to be smoothened. The authors suggested that by using water as dielectric medium for rough cutting and oil for finish cutting while contouring polished single crystal silicon plates. The surface of gears appears to have chips sized 60 μm and between 40–60 μm when machining by using water and oil, respectively [24, 25]. Comparison of machining feasibility of poly crystalline silicon material with auxilliary pulse supply and conventional-pulse voltage supply mode was attempted by [71]. It was observed that the auxilliary pulse supply effectively broke the polysilicon insulation and avoided delay in electrical discharge that contributed to effectiveness. Increasing the wire tension significantly decreases the groove width due to reduced wire vibration.

However, increasing the wire tension led to machining instability. Dongree et al. [17] proposed a hypothesis of by using WEDM process as an alternative for conventional methods for silicon wafer slicing. Gee et al. [18] studied the variation in thickness of deterioration layer of monocrystalline silicon under different machining conditions. Authors studied the surface damage of mono-crystalline silicon for different machining conditions. Authors had proposed two modes of material removal, such as normal removal method (removal by melting and gasification) and compound removal or thermal spalling removal. The depth of damage decreased when the removal took place by melting and gasification whereas thermal spalling removal increased the depth of damage [19]. The thickness of deterioration layer increases with increase in n-pulse width. Joshi et al. [82] explored the possibility of using WEDM process to produce ultra-thin silicon wafer slicing sized 140.5 μm at a rate of 0.96 mm/min. Yeh et al. [72] attempted to study the performance of phosphorus dielectric while machining polycrystalline silicon and stated that the cutting speed increased by 1.48 times as compared to that of water as dielectric medium. Hou et al. [73] attempted to study the influence of open voltage on machining speed, machining gap, surface roughness, and surface micro topography while machining zirconia and stated as the open voltage value increases surface finish degrades. An attempt was made to investigate the machining possibilities of advanced materials like porous metal foams, metal bond diamond grinding wheels, sintered Nd-Fe-B magnets, and carbon–carbon bipolar plates.

A feasible envelope of process parameters was proposed to select process parameters for achieving a higher MRR and for machining micro features [21]. Greer et al. [74] attempted to study the influence of WEDM process parameters on magnetic property of NdFeB permanent magnets material and stated the magnetic property does not influence any of the process characteristics. Lee et al. [20] studied the machining feasibility of n-type high purity germanium (HP Ge) by deposition of conductive metals on outer surface. The metal coating improved the cutting rate and generation of crack surface machined surface. Cheng et al. [16] demonstrated the feasibility of by using WEDM process for generation of micro helical profiles on tools used in micro machining applications. Bobbili et al. [77] studied the influence of WEDM process parameters on machining characteristics of hot pressed boron carbide material and stated the surface finish of machined component was significantly affected by increasing pulse-on time. This section explored the attempts made by various researchers to highlight the possibilities of applying WEDM process for machining advanced materials, like metal bonded diamond grinding wheels, superinvar, single crystal silicon, poly crystal silicon, porous metal foams, sintered Nd-Fe-B magnets, carbon-carbon bipolar plates, high purity germanium materials, and hot-pressed boron carbide. WEDM process also proved to be an economical process for the generation of precise form on poor machinability materials.

Table 3. Machining of advanced materials using WEDM process.

References	Inference
Rhoney et al. [22]	Truing of metal bonded diamond grinding wheel
Badami et al. [15]	Fine pitch threads generated on superinvar material 40 TPI threads were produced
Miller et al. [21]	Machining of porous metal foams, metal bonded diamond grinding wheel, sintered Nd-Fe-B magnets, and carbon-carbon bipolar plates
Miller et al. [21], [23-25]	Machining of polished single crystal silicon (oil and water as dielectric medium); contouring of polished single crystal silicon plates
Yu et al. [71]	Machining of poly-crystalline silicon using auxiliary pulse supply
Lee et al. [20]	Machining of n-type high purity germanium (HP Ge)
Yeh et al. [72]	Machining of polycrystalline silicon using phosphorous as dielectric medium
Cheng et al. [16]	Generation of helical profiles on ultra-hard materials
Gupta and Jain [75]	Manufacture a miniature spur gear having total profile deviation of 13.20 µm, total lead deviation of 5.40 µm, and average surface roughness of 1.00 µm
Greer et al. [74]	Parametric study on magnetic property of NdFeB permanent magnets material
Hou et al. [73]	Parametric study on machining of zirconia
Bae et al. [76]	Manufacture deep grooves of different depth to enhance super superior hydrophobic property
Bobbili et al. [77]	Machinability of hot pressed boron carbide material
Dongree et al. [17]	Silicon wafer slicing
Gee et al. [18], Gee et al. [19]	Studied the variation in thickness of deterioration layer of monocrystalline silicon
Ayesta et al. [80]	Compared the fatigue life of WEDMed Inconel 718 material with that of ground specimen
Joshi et al. [82]	Manufacture of ultra-thin silicon wafer with 140.5 µm slicing size at the rate of 0.96 mm/min

MODELLING AND SIMULATION TECHNIQUES

Many researchers had predicted the performance measures of WEDM process by using regression models [116, 117]. WEDM was a transient erosion process in which the relationship between the process parameters and the response variables were difficult to predict accurately. Modelling of WEDM process was necessary for achieving higher productivity with desired accuracy and surface finish. Puri and Bhattacharyya [52] proposed an optimal process parameter combination for achieving an improved dimensional accuracy of machined surface by reducing the wire lag phenomena. Hewidy et al. [33] proposed a regression equation to predict roughness and material removal by using response surface methodology. Authors stated that peak current and dielectric flushing pressure were response parameters that affected MRR, whereas wire tension and duty factor were response factors that affected roughness. A model was proposed to predict the thickness of white layer by using RSM and the response variable that affected white layer thickness were pulse-on time and wire tool offset Puri and Bhattacharyya [52]. A regression equation was proposed to predict the surface roughness of the DC 53 die steel through ANOVA technique and showed that pulse-on time and peak current were the significant variables that affected roughness of machined components [36]. Shah et al. [42] proposed a model to predict surface roughness, MRR, and kerf width considering material thickness. Authors stated material thickness had least effected MRR and kerf width. However, it had significant effect on surface roughness. Poros and Zaborski [66] proposed a semi-empirical model to predict efficiency of WEDM process based on workpiece material properties. Authors stated that as the thermal conductivity and specific heat capacity of workpiece material increased efficiency of WEDM process decreased. Rajyalakshmi and Venkata Ramaiah [91] predicted that the optimum process parameter combination for obtaining increased MRR and better surface finish by using grey relational analysis. Ikram et al. [92] proposed a linear regression equation to identify the influencing process parameters on kerf, MRR, and surface roughness by using statistical analysis tools, such as ANOVA and S/N ratio. Gautier et al. [93] proposed a regression model to predict surface roughness and dimensional deviation through RSM technique and found that both response parameters were least affected by pulse-off time. Aggarwal et al. [94] attempted to predict the optimal process parameter combination for obtaining better surface finish and increased cutting speed using response surface methodology while machining Inconel 718 material. Highest cutting speed of 2.55 mm/min with surface roughness of 2.54 μm ws achieved. Authors proposed a mathematical model using Buckingham pi theorem and grey relational analysis to understand the relationship between machining variables and performance measures (MRR and surface roughness) on armour materials, such as Al 7017 an Al-Mg-Zn based alloy and RHA steel materials. Authors stated that for similar process parameter combinations higher MRR was obtained for Al 7017 due to low melting point, larger heat capacity and thermal conductivity as compared to that of RHA steel material [77-79]. Cheng et al. [16] proposed a three-dimensional multi-physics coupling model to predict wire vibration and improve the corner accuracy while cutting thin plate by using WEDM process. Samanta et al. [97] proposed a model by using regression analysis to predict cutting speed, surface finish, and kerf width while machining die steel material. Authors studied the effect of WEDM process variables on machining capabilities of Inconel 800 material and Udimet L605 alloy. Furthermore, authors proposed models by using grey relational analysis and hybrid PCA grey relational analysis to predict surface roughness of the machined component [99, 100].

WEDM process involves many process parameters and is needed to optimise the process parameter combinations for achieving a desired cutting performance. Optimisation of single parameter was not economical as far as WEDM process is concerned. Researchers have attempted to optimise the process by adopting various multi-objective optimisation techniques for achieving increased MRR and better surface finish with minimum kerf width. Tosun et al. [14] proposed a model by using ANOVA to minimise kerf together with maximum MRR. Kuriakose and Shunmugam [83] proposed a Non-Dominated Sorting Genetic Algorithm for obtaining a non-dominated process parameter combination for achieving an improved cutting velocity and better surface roughness of Ti6Al4V workpiece material. A multi-objective, multi-variable, non-linear optimisation was proposed to maximise MRR and SF and minimise kerf [38]. Ramakrishnan and Kaunamoorthy [40] proposed an Artificial Neural Network (ANN) model to maximise MRR and SF and minimise kerf by using multi-response signal-to-noise (MRSN) ratio. Authors stated that MRSN with Taguchi's parameter design was a simple, systematic, reliable, and more efficient tool for optimising multiple performance characteristics of WEDM process parameters. Prasad and Gopala Krishna [85] proposed an empirical relation by using RSM and NDSGA for achieving a higher MRR and better surface roughness of the machined component. Researchers attempted to obtain optimal parameter combinations by using various hybrid optimisation techniques. Grey Relational Analysis (GRA), MRSN, Weighted Signal-to-Noise (WSN) ratio and VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje in Serbian) methods were employed to determine optimal process parameter combination for achieving a higher productivity during WEDM process [86]. A hybrid method including response surface methodology (RSM) and back-propagation neural network (BPNN) integrated simulated annealing algorithm (SAA) were proposed to determine an optimal parameter setting for MRR, surface roughness, and corner deviation [67]. A comparison of different non-traditional optimisation algorithms, such as genetic algorithm, particle swarm optimisation, sheep flock algorithm, colony optimisation, artificial bee colony, and biogeography-based optimisation for single and multi-objective optimisation of WEDM have been attempted to arrive at near optimal solution Mukherjee et al. [88]. Authors stated that biogeography-based algorithm converges quickly towards the optimal solution and has minimum dispersion for its obtained optimum values. Authors proposed a linear regression model and feed forward back propagation neural network for achieving better surface finish and improved MRR while machining HCHCr [89] and cementation alloy steel 1.7131 [98]. Authors stated that among the various optimisation techniques, neural network is the most robust technique for WEDM process. Boopathi and Sivakumar [90] proposed a multi-objective optimisation technique for predicting optimal cutting parameters for rough and finish cut using Pareto-front using the multi-objective evolutionary algorithm (MOEA). Zhang et al. [95] attempted to predict optimal process parameter combination for achieving better surface integrity using back propagation neural network combined with genetic algorithm (BPNN-GA) and Non-dominated Sorting Genetic Algorithm-II [87]. Prasad and Gopala Krishna [96] described the benefit of using harmony search algorithm for achieving minimum kerf and wire wear ratio. Pramanik et al. [81] proposed a hypothesis by using grey relational analysis to predict optimum process parameter combination to achieve higher machining speed and better surface finish while machining boron carbide material.

Models based on process parameter, such as RSM, regression model, ANOVA, and semi-empirical model were utilised to predict surface roughness and MRR. However, modelling of single parameter was not feasible for WEDM process. In WEDM process, it was desired to achieve maximum MRR and better surface finish with minimum kerf. Therefore, multi-objective optimisation techniques, such as NDSGA, multi-variable non-linear optimisation, ANN, MRSN, GRA, WSN, VIKOR, BPNN, and SAA were employed. However, it is observed no method can give better optimal process parameter combinations due to the complex erosion mechanism of the WEDM process. Authors simulated the WEDM process by using different techniques. Han et al. [101] simulated the WEDM process by using parametric programming for discharge location, workpiece erosion, and wire vibration. A thermo-analysis was carried out by using Finite Element Method (FEM) to understand the change in surface morphology while varying pulse duration [118]. Han et al. [119] proposed a corner error simulation considering the reaction forces due to wire vibration during WEDM of right-angle machining, sharp-angle machining, obtuse-angle machining, and compared it with experimental results. An FEM model was proposed to describe the behaviour of soft wire while taper cutting [103]. Han et al. [102] proposed a thermal model to predict the temperature distribution in wire electrode at normal discharge and short circuit conditions. The flow field and movement of debris in kerf was simulated using Computational Fluid Dynamics (CFD) software and validated the simulation using high speed imaging technique [13]. Tomura and Kunieda [104] proposed a 2D FEM to investigate the electromagnetic field that occurred around the wire. Banerjee and Prasad (2010) proposed a numerical model to study the behaviour of wire electrode under random pulse and cluster of pulse conditions. Yang et al. [44] proposed a moving heat source model to predict the temperature field under different machining conditions. Hada and Kunieda [106] proposed a hypothesis to predict the impedance of wire and workpiece by using electromagnetic field generated by FEM. Habib and Okada [120], [121, 122] attempted to model the movement of wire electrode and wire vibration using high speed imaging technique and proposed that wire vibration was mainly dependent on wire tension. Maximum wire vibration was observed at upper and lower surfaces of workpiece due to the pressure of dielectric fluid flow. Increasing the wire offset value will lead to reduced wire vibrating amplitudes. Okada et al. [107] proposed a hypothesis through simulation to predict wire breakage and wire oscillation during WEDM process and stated that the debris stagnation in kerf and wire deflection were the causes for wire breakage during machining. Authors attempted to simulate the wire tension during WEDM process while cutting different heights of the workpiece material [108, 110, 112].Yu et al. [71] attempted to model leakage energy in the gap discharge phenomena of WEDM process during multi- pass cutting of Cr12 steel material. Werner (2016) proposed a model to improve the machining performance of WEDM processed by reducing the curvilinear error. Literature revealed that various simulation softwares, such as FEM, CFD, etc., were used to simulate WEDM process phenomena. However, there is scope for better simulation of WEDM process by proper understanding of discharge phenomena.

ON-LINE MONITORING OF WEDM PROCESS

Many researchers have attempted to improve the performance of WEDM process by monitoring the process on-line. Yan [123] proposed a real time wire tension improvement strategy to get improved accuracy of the machined components. Lautre [124] proposed a diagnosis system to predict the wire breakage. Cabanes [125] proposed a hypothesis that prevents wire from rupture by using virtual instrumentation system and the diagnostic system that detects low quality cutting regimes and predicts wire breakage. Liao [126] proposed an on-line pulse train system that could predict the causality of ignition delay time. Portillo et al. [127] proposed a real time monitoring system to detect the wire breakage. Okada et al. [13] attempted to capture the wire movement using high speed imaging technique. Liao [126] proposed a hypothesis that detects the height of workpiece and subsequently give input to the servo feed control. Literature reveals that researchers propose different strategies, such as fault diagnosis system, virtual instrumentation systems, and real-time monitoring systems to predict wire rupture ahead of failure. High speed imaging proved to be a feasible technique for predicting the discharge location.

IMPROVEMENT IN WEDM PROCESS

WEDM is one of the most important processes applied for generating precise form on the materials used in aerospace application. By integrating two or more process with WEDM (hybrid machining), complex form geometries can be machined easily. The following section discusses about the new techniques developed by making/adding slight modifications to the existing WEDM process. Figure 3 shows the new techniques developed in WEDM process.

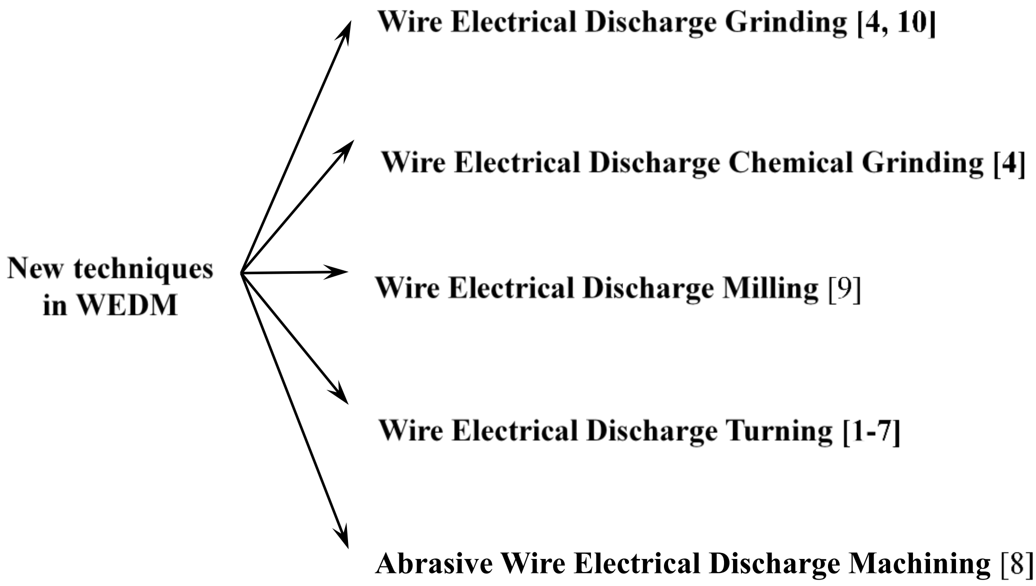


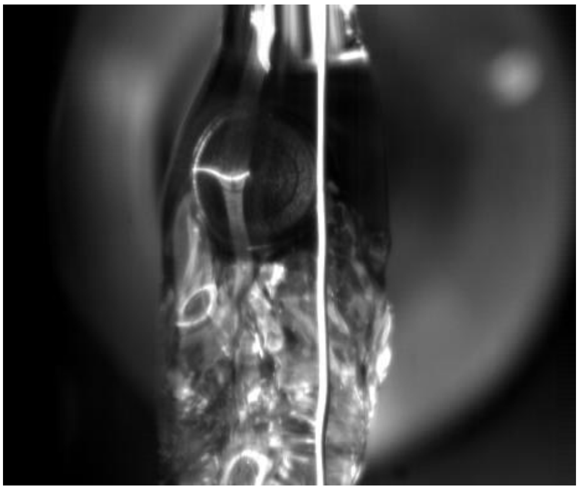
Figure 3. New techniques in WEDM process.

Wire Electrical Discharge Grinding (WED-Grinding)

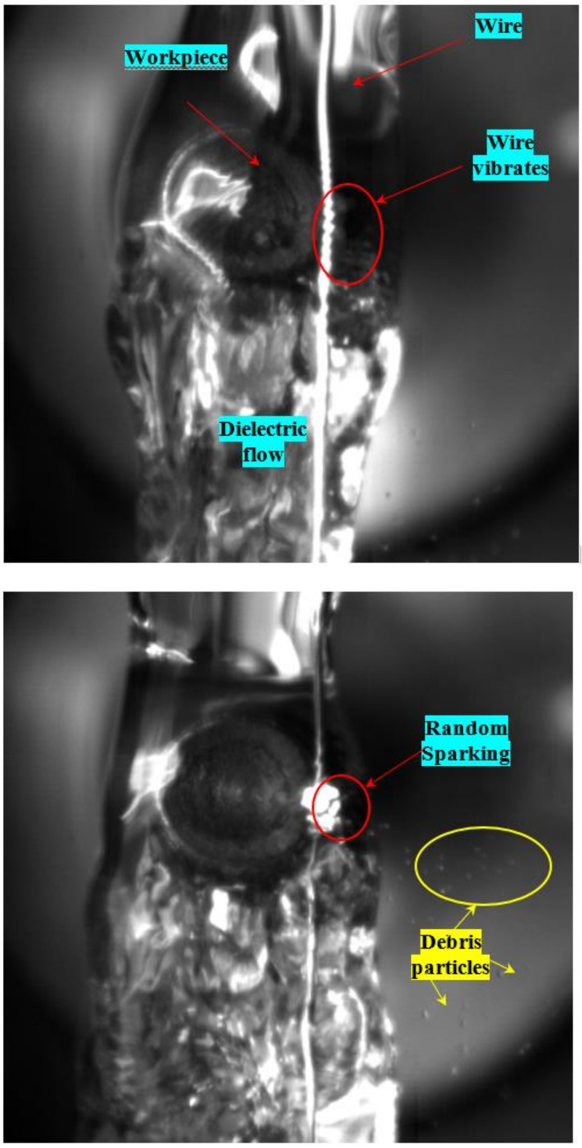
The concept of WEDG was first proposed by Masuzawa and Tonshoff [4] by adding an additional rotary axis to the workpiece. Authors proved that by using WEDG, manufacture of micro pins of diameter of 5 μm is feasible by using WEDM process, which can be used as a micro tool for micro machining applications. Uhlmann et al. [12] attempted to study the influence of process parameters during WEDG and achieved a fine surface finish of 0.38 μm while machining micro axi-symmetric components.

Wire Electro Chemical Grinding (WECG)

The credit goes to Masuzawa and Tonshoff [4] for development of this WECG concept process. The disadvantages of electrochemical process were overcome by this technique. The unit removal in this process was very low, which produced a smooth and disturbance-free surface and makes this process an alternative for finish machining of micro-components.



(a) No spark.



(b) Wire vibration and random spark generation.

Figure 4. High speed images of wire vibration taken at 130000 frames per second.

Wire Electrical Discharge Milling (WED-Milling)

To overcome the problems in conventional milling process, such as tool wear and built-up edge, the concept of WED-Milling was developed. It is simply the combined effect of electrical discharge milling and wire electrical discharge grinding. The concept of WEDM is explained as a bar-shaped wire guide is reciprocated in a rotary manner to generate a 3D form on any conductive material Gotoh et al. [10].

Wire Electrical Discharge Turning (WED Turning)

Turning by WEDM was first proposed by Masuzawa and Tonshoff [4]. The characteristics of WEDG and WEDT process variants are the relative motion between the electrodes (tool and workpiece) and the feed. In WEDT and WEDG, the erosion mechanism is the same as that of the WEDM process; the difference is that in WEDT, the workpiece is fed horizontally, whereas in WEDG, the workpiece is fed in the longitudinal direction. The geometric accuracy of the machined workpiece was affected by wire deflection and direction of axial feed motion (as in WEDG), the workpiece was prone to deflect more due to gravity as compared to that of longitudinal feed as in WEDT process. Similar to WEDG, WEDT makes it possible to generate precise cylindrical forms, micro pins, micro shafts, and any axisymmetric form on conductive materials, regardless of their hardness [1, 2]. Very few attempts were made to study the influence of process parameters on WEDT process by researchers [3, 5, 6]. Apart from the parametric influence study of WEDT process, focus is made in understanding the gap phenomena of WEDT process by using high speed imaging technique. An attempt was made to study the spark gap phenomena under various cutting conditions during WEDT process byusing high speed imaging technique. Figure 4 shows the influence of discharge energy on wire vibration recorded at 130000 frames per second [2]. Component with high aspect ratio was fabricated byusing wire EDM process [8].

Abrasive WEDM (AWEDM)

In a typical WEDM process, high material removal rate and better surface finish are the deciding factors in which one is dependent on the other. An attempt was made to achieve higher MRR and better surface quality by incorporating abrasive grains into the wire core. The mechanism of material removal in AWEDM was as follows, electrical spark that occurs between the wire core and workpiece remove material by spark erosion, while the abrasives simultaneously abrades the surface [9].

CONCLUSIONS

Wire Electrical Discharge Machining is an economical non-conventional machining process used for manufacture of micro tools used in micro machining applications. The surveying of WEDM process revealed that numerous process variables were involved in the process and each process parameter had its significance on response variables. Modelling of machining characteristics, such as roughness and MRR helped to understand the WEDM process but it was not feasible to optimise one parameter and supress the other. Therefore, multi-objective optimisation was performed by using different optimisation techniques for achieving high MRR and better surface finish with minimum kerf width. Attempts were made to understand the process phenomena of WEDM by using various simulation techniques. WEDM process is employed for machining advanced materials such as porous metal foams, metal bond diamond grinding wheels, sintered Nd-Fe-B magnets, and carbon-carbon bipolar plates. Various on-line monitoring strategies were adopted to prevent wire breakage. High speed imaging technique helps to understand spark distribution in WEDM process. New areas for development of WEDM process (hybrid machining), such as WED-Grinding, WECG, WED-Milling, and WEDT extends the possibility of WEDM process applied for manufacture of micro and axi-symmetric components used in automotive and aerospace applications. The review of WEDM process capabilities and its performance measures were presented in detail. However, there is a scope to use WEDM to machine advanced composite materials and ceramics used in aerospace industry. Further on-line monitoring of WEDM process helps in deeper understanding of WEDM process and development of hybrid machining processes.

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