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THE STATE OF ART: REVOLUTIONARY 5-AXIS CNC WIRE EDM & ITS RECENT DEVELOPMENTS

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Keywords:
WEDM;
Process parameters;
Performance parameters;
Recent developments;
Future scope.

Abstract

5-axis CNC wire EDM is the greatest innovation usually called as the revolutionary machining process affecting the modern machine tool and precision machining industries. WEDM has acquired improvements to the machining industry in product accuracy, quality and profitability. In the early stages, costly conventional processes were frequently used in the production, however, now with the aid of computer numerical controlled WEDM machines, intricate, complex shape and hard materials (Hardened D2, Tungsten Carbides, high carbon tool steel, composites etc.) can be machined automatically and precisely at low costs. Components having superior properties, higher surface finish, precise and close tolerances are the most important requirements in industries and to achieve these requirements, highly precise, non-conventional machining processes are preferred. This paper presents the review of 5-

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axis CNC WEDM, its developments, experimental analysis, literature survey for optimization of WEDM process parameters and its effect on the properties and performance parameters of the materials.

1. Introduction

Non-conventional machining processes are the requirements of the fastest growing industries because of the precision, complex, intricate shapes of work material, higher tolerances and economically. Hard materials and super alloys such as tungsten carbides, hardened D2, high-carbon tool steel generally used in tool industries, automotive, electronics, medical and aerospace industries are very difficult to machine by conventional machining processes, therefore for the ease of metal cutting and machining, non-conventional machining is preferred. WEDM is generally used to produce intricate, complex shapes which are impossible to produce by means of any other conventional and non-conventional machining method. [9]

EDM was introduced in 1940's. WEDM is a variation and development of EDM. In 1969, the Swiss firm Agie developed and delivered the world's initially Wire EDM machine. These machines had machining ability to cut the material about 21mm^2/min per hour. These machines were extremely slow in production rate. After the continuous improvements in the machining ability, the machining speed went up to 64 mm^2/min per hour in early 80's. [6] In the modern era, developing materials with superior properties is vital in the field of Engineering, Automotive, Aerospace, Medical etc. Therefore, the novel materials are the solution for all these needs. A well known un-conventional machining process capable of satisfying the widest machining requirements demanded by manufacturing industries is Wire EDM. Recently developed advanced WEDM are equipped with automatic controlling and monitoring system and have tendency to cut the material 20 times faster than the initial beginning machines. [9] Machining of parts with varying hardness and complex profiles with higher accuracy and precision is possible in WEDM. Therefore, WEDM is revolutionizing machining and can cut all types of electrically conductive materials up to 45 degrees.

2. Wire EDM (Wire-Electric Discharge Machining)

WEDM process is thermal erosion process in which a thin metallic wire electrode introduced into the work piece. The machining part is submerged fully or partially in a dielectric fluid. Wire is held between upper & lower diamond guide and constantly fed from a wire spool through guide pulleys. WEDM is an advanced material removal process and accepted as a standard precision machining process. [7] The schematic view of WEDM is shown in Figure 1.

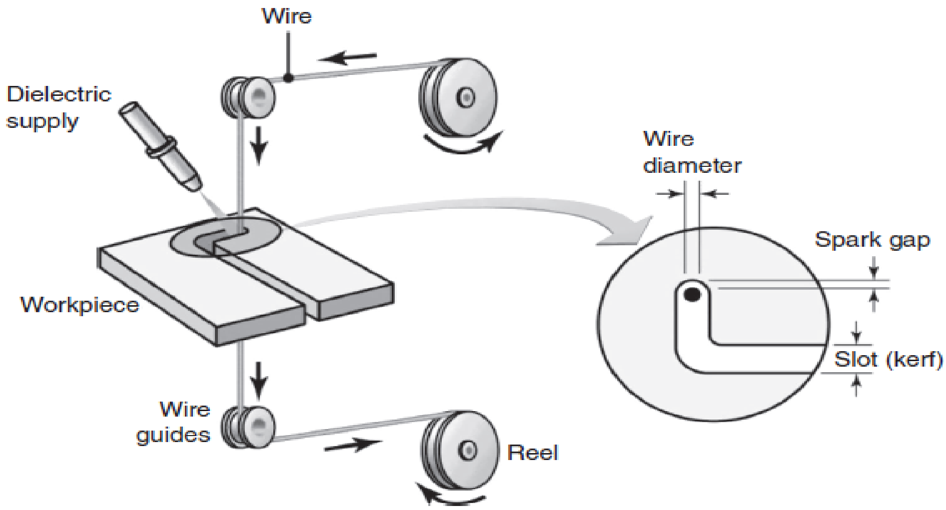

Figure 1. *Schematic diagram of WEDM process*

WEDM is widely used in the manufacture of:

- Hard electrode,
- Forming tools & dies,
- Cutting the hard extrusion dies,
- Aerospace, Medical, Electronics & semiconductor industries,
- Automotive, Nuclear industries,
- In making fixtures, gauges and cams,
- micro-tooling for micro EDM and other micro machining processes and
- The removal of material to produce complex, intricate shapes by means of a series of discrete discharges.

2.1. Working principle of WEDM

WEDM removes material from the wok metal with the use of electricity by means of spark erosion as shown in Figure 1. It is the most important requirement that the work material must be electrically conductive. AC servo motors are used to provide positioning, stability and enhancement of wire tension. A DC or AC servo mechanism maintains the gap (0.051 to 0.076mm) between the electrode and work material and prevents the short circuiting of wire. [7], [9] In this process, the material is submerged in the dielectric medium. 'Dielectric' is the shield between the wire electrode and material. De-ionized water is generally used a dielectric medium because the dielectric medium acts as an insulator. Tap water contains minerals and becomes conductive and cannot be used directly, therefore the tap water is passed through the resin tank to reduce its conductivity. The main function of resin tank is to remove the dissolved particles.

When the voltage is applied, the electrical pulses are generated, fluid ionizes and a spark generates between the electrode wire and work material, the controlled spark precisely erodes the metal from the work material causing it to melt and vaporize. Pressurized Dielectric fluid flows continuously. It cools the vaporize material and carry away the particles from cutting section. The dielectric passes through the filter to remove suspended particles and used continuously. Chillers are used to maintain the temperature of dielectric fluids for higher machine efficiency and accuracy. In WEDM the wire electrode never comes in contact with the work piece, therefore this process is stress free cutting operation. [32]

Recently developed materials with superior properties, especially composite materials and alloys are challenging the viability of the Wire EDM process. [2] Therefore, continuous improvement is required in order to best utilize its machining capacity. The major components of WEDM are dielectric filter and deionization system, wire transportation system, automatic wire cutting and threading system, slug removal system, workpiece table, axis control (X, Y, U, V and Z axis) and CNC control with spark generator.

Table 1. Mechanism of WEDM

Mechanics of Materials	Melting and Evaporation
Medium	Dielectric (De-ionized water, kerosene oil, W*EDM oil, Kerosene and water with Glycol, silicon-based oil* etc.)

Tool Material	Copper, Brass, Cu-W alloy, Ag-W alloy, Graphite
Gap	10-125 µm
Material Application	All conducting metals and alloys
Shape Application	Intricate complex shapes, sharp corners, micro taper holes for nozzles, Blind complex cavities
Limitation	Not applicable for non-conducting materials.

2.2. Independent Axis of WEDM

Independent five axis of WEDM (i.e. X, Y, Z and U, V) allow the machine to cut different profiles on the top and bottom surface of the work piece.

- X & Y axis controls the movement of the work material in the direction of X and Y axis.
- Z axis are the perpendicular axis and controls the upper diamond wire guide movement along vertically up and down.
- U axis is the movement of the upper wire guide in the direction of the X-axis (for taper cutting).
- V axis is the movement of the upper wire guide in the direction of Y-axis (for taper cutting).

2.3. Categories of WEDM

As per the industrial requirement and precision, WEDM is generally categorized into three types:

(a) Submerged type WEDM: In this type of WEDM the wire electrode and work material are submerged in dielectric fluid during the material cutting. These machines are preferred for longer workpieces, larger taper angle up to 45 degrees and for the temperature stability requirements in the cutting zone.

(b) Non-submerged (co-axial flushing) type WEDM: In this type of WEDM, the cutting zone around the wire electrode is submerged in the dielectric fluid. The dielectric fluid flushes from the top and bottom nozzles. Therefore, this type of machining is called the coaxial flushing process. These types of machines are preferred to cut the longer workpieces for greater flexibility and taper cutting angle up to 10 degrees.

(c) Dry and near-dry WEDM: In this type of WEDM, the dielectric is replaced with the minimum quantity of gaseous atmosphere. The main advantages of this type are lower gap distance and no-corrosion for material during machining which improves the accuracy and surface finish of the material. The major drawbacks are lower MRR and the generation of streaks.

With the recent developments, WEDM have the capability to switch automatically from large diameter wire to small diameter wire for rough cut and finish cut simultaneously. The other advancement is the modern CNC-integrated expert system which allows the machine to cut material without breakage of the wire. [5] In-process inspection, multi-sided and multi axis capability and use of dielectric oil are the recent advancements in WEDM industries.

2.4. Process parameters in WEDM

These are input controllable machining parameters which specify the machining condition and directly affect the machining productivity and performance parameters. The various important process parameters of WEDM are shown by Ishikawa cause and effect diagram in Figure 2.

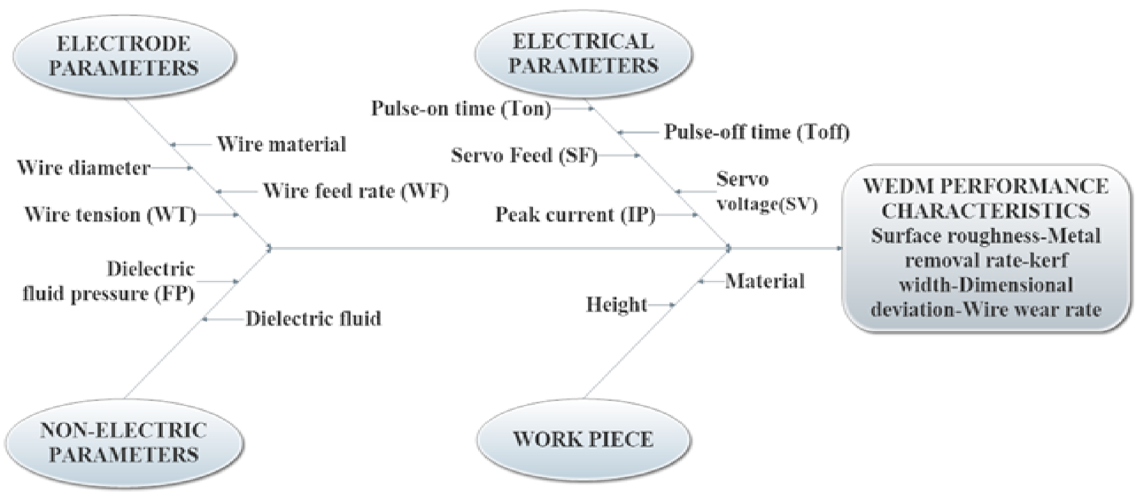

Figure 2. *Ishikawa cause and effect diagram for WEDM*

(i) Peak Current (I_p): It is the maximum amount of current passes through wire electrode for given pulse. As the Ip increases, it increases the discharge energy which expands the cutting speed and cutting rates.

(ii) Pulse on time (T_{on}): It is the duration of time in µs (microseconds) in which the current flows in each cycle. Voltage is applied between the electrode and work material during this time. As the duration time (T_{on}) increases, the discharge energy also increases, which may tend to the electrode wire breakage.

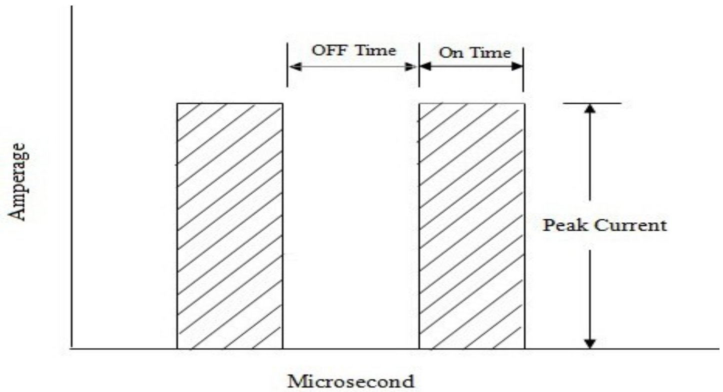

Figure 3. *Peak current, pulse on time and pulse off time*

(iii) Pulse off time (T_{off}): It is the duration of time in µs (microseconds) when the voltage is not supplied in the cycle. It represents the duration of time between two simultaneous sparks. The lower value of T_{off} increases the cutting rate, whereas the very lower values may damage the wire electrode.

(iv) Servo Voltage or Spark gap voltage (SV): It is the set reference voltage for the actual gap between the wire electrode and work material while cutting.

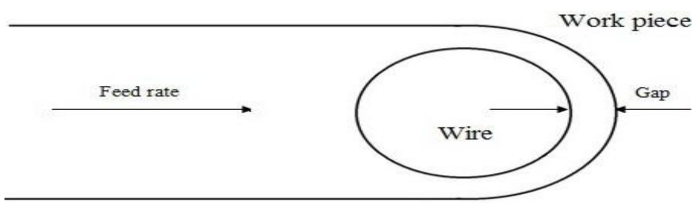

Figure 4. *Wire feed rate and gap size*

(v) Wire Feed Rate (WF): It is the rate at which wire electrode passes alongside the guide ways and wire is fed continuously for machining.

(vi) Wire Tension (WT): The wire is kept straight between the upper and lower guide during machining. WT determines the tension of wire and it greatly affects the machining accuracy and cutting speed.

(vii) Dielectric flow rate: It is the rate at which dielectric fluid enters into the machining zone. For higher values of pulse rate, higher flow rate is preferred whereas; low flow rate is preferred for thin workpieces and for trim cut operations.

(viii) Wire Electrode: The wire electrode material and diameter of the wire electrode plays an important role for the effective machining. The cutting speed is mostly influenced by the diameter of wire because larger wire diameter can handle more energy. Therefore, MRR will be higher and cutting speed will increase. The cutting speed is also influenced by the type of material to be cut and properties of the material.

2.5. Performance parameters of WEDM

The performance of the machining is measured by various performance parameters, such as;

(a) MRR (material removal rate)

It is the major performance parameter of WEDM which ensures the highest productivity and cutting efficiency. Many researchers have tried to maximize the MRR and measured the influence of various parameters. Dian Thomos et al (2011) concluded that T_{on}, peak current and T_{off} has the major influence on MRR while they worked on EN31 steel using RSM methodology. [11] Aqeel Shah et al. (2011) concluded that the work piece thickness has also significance for MRR. (Kashid D V. et al 2014, Vishal Prashar et al. 2014) optimized the parameters for MRR. Pratik A. Patil 2014 et al concluded that MRR increases with the increase of I_p and WT (wire tension) also plays a significant role in MRR. [19] Singh H. et al (2014) reported that MRR decrease with increase in SV (servo voltage) and T_{off}. Rajendra S. et al (2012) concluded that MRR is directly proportional to T_{on} whereas; inversely proportional to WT (wire tension).

(b) SR (surface roughness)

Minimization of surface roughness means the higher value of surface finish. Many researchers reported their work to minimize the surface roughness. Giovanna Gautier et al (2015) concluded that the value of SR increases with the lower values of T_{off}, T_{on} and WT. [14] Shinde V. D. et al (2014) concluded that the wire speed and T_{on} has the strongest correlation with SR as compared to current and T_{off}. Singh H. et al (2009) reported that SR increases with the increase in I_p and T_{on} whereas, SR decreases with increase in T_{off} and SV (servo voltage). Abdul Kareem S. et al

(2011) concluded that wet WEDM gives higher surface integrity compared to the dry WEDM. Miller P. J. et al (2015) reported that the gap voltage has the most influence on SR.

Table 2. Performance parameters

Sr. No.	**Performance Parameter**	**Definition**	**Formula**
1.	Surface Roughness (SR)	The closely spaced irregular deviations on a scale and smaller than the waviness.	$Ra = \frac{1}{L}\int_0^L Z(x)dx$ *(I)*
2.	Material Removal Rate (MRR)	The rate of Volume of the material removed or Rate of erosion of the work piece.	$MRR = V_c * b * h$ *(II)* *(mm^3/min.)*
3.	Wire Wear Rate (WWR)	Quantity of electrode material removed per unit time.	$WWR = \frac{WWL}{IWL}$ *(III)* WWL – Weight loss after Machining IWL- Initial Wire Weight
4.	Wear Ratio (WR)	It is the ratio of Wire Wear Rate for the Material Removal Rate.	$WR = \frac{WWR}{MRR}$ *(IV)*
5.	Recast Layer Thickness	Recast layer locates above the HAZ. It is the region of resolidified molten material occurred at the topmost layer of the machined surface.	$Sparking\ Gap\ (mm) = \left(\frac{Avg.\ of\ kerf\ width - Dia.of\ wire}{2}\right)$ *(V)*
6.	Kerf Width	It is the quantity of material wasted during	Kerf width = 2* Sparking gap + Wire DIA.

		machining.	*(VI)*
7.	Dimensional Deviation	It is the inaccuracy or the geometric error of the work material after cutting.	$Dimensional\ deviation = \frac{Observed\ value - Actual\ value}{Actual\ value} \times 100$ *(VII)*
8.	Heat Affected Zone (HAZ)	It is the un-melted region of a material during machining which experiences a phase transformation because of high temperature.	It is measured with the help of SEM and X-ray microscopy.

(c) Wire Electrode Wear Rate (EWR/WWR)

Most of the researchers tried to minimize the WWR to decrease the wire rupture phenomena. Manoj Malik et al (2012) concluded that I_p has the most influence on EWR whereas; the duty factor has least influence. Hewidy M.S. et al (2005) reported that WWR increases with the increase of peak current.

(d) Kerf width and sparking gap

It measures the quantity of material wasted during cutting. It is the major factor in dimensional accuracy of the components. Abinash K. S. et al (2012) concluded that the voltage has the most significance on kerf width. The authors conducted the experiments on tungsten carbide to measure the kerf width using brass wire. Adeel Ikram et al (2013) concluded that T_{on} is the most significant factor for kerf width. Aqeel S. et al (2011) reported that kerf width is influenced by material thickness. Saurav Datta et al (2010) found that discharge current, pulse duration and wire speed has the major influence on kerf width. [38] Probir S. et al (2013) reported that the increase of gap voltage increases the kerf width.

(e) Wire lag, Wire offset and Inaccuracy at corner

Some researchers tried to minimize the wire lag because wire lag leads to the geometrical inaccuracy of the complex profiles. Daniel G. et al (2013) optimized the WEDM parameters such as T_{on}, T_{off}, I_p and SV on wire lag using RSM. Sarkar et al. (2005) concluded that the surface quality decreases as the cutting speed increases. [34]

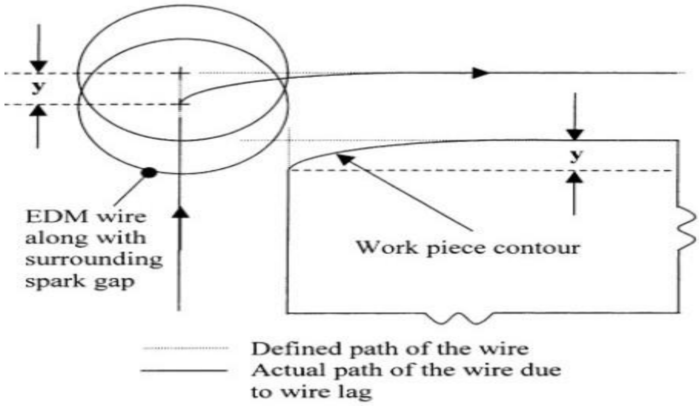

Figure 5. *Wire lag phenomena*

(f) Cutting speed (CS)

The cutting speed is mostly influenced by the diameter of wire because the large diameter wire can handle more energy. Therefore, with a larger diameter of wire, MRR and cutting speed will increase. The cutting speed is also influenced by the type of material to be cut and the properties of the material mainly density and melting point of the material. Work piece height also affects the Cutting speed. The influence of material thickness on different height of workpieces is shown in Figure 6.

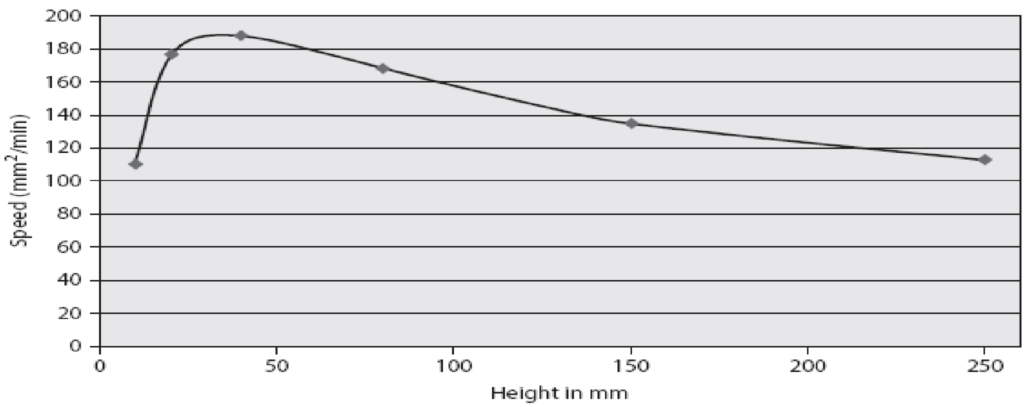

Figure 6. *Influence of material height on cutting speed*

2.6. Methods of application of cutting fluid in WEDM

Dielectric fluid such as de-ionized water, Kerosene, etc. is applied in the form of fine jet or nozzle under pressure up to 4 MPa. Better cutting performances and surface finish is obtained consequently with jet application. The primary function of cutting fluid in material cutting is to control the total heat generated during cutting. [25] In the Deionization process, total dissolved solids are removed from water through ion exchange. De-ionization Process uses cationic (-ve) and anionic (+ve) two resins that are opposite in charge. Cations attract the positively charged ions (Ca++, Mg++, Na++, etc.) and release an equivalent amount of hydrogen (H+) ions. Other functions of dielectric fluids are;

- To cool the wire electrode and workpiece
- To protect the work against rusting
- To improve surface finish
- To prevent short circuiting
- To carry away, eroded particles from the cutting zone.
- The dielectric medium helps in initiating discharge and acts as a conducting medium. [9]

2.7. Benefits and advantages of WEDM

- The tool material can be machined in as hard condition, it enables high accuracy.
- Highly delicate sections, intricate, complex profiles can be cut without distortion of material.
- Irrespective of strength and hardness of material, any conductive material can be machined by this process.
- It takes less machining time rather than conventional machining processes.
- Close tolerances can be achieved without additional costs.
- Any contour and varying tapers sections can be machined precisely.
- Extremely thin sections can be machined without distortion by eliminating the cutting stresses on work material and electrode.
- Higher surface finish and accuracy up to 0.025 mm can be produced.
- WEDM eliminates the extra machining processes on work material.
- Perfectly straight and burr free machining can be achieved.
- Hardness of the work material doesn’t affect the machining ability.
- Electrode wear doesn’t exist.
- Semi skilled craftsperson can work on the machine.
- WEDM can machine thin sections precisely with micro finishes.

3. Research trends and Optimization techniques in WEDM

The authors reported their work to optimize the various machining parameters using traditional, non-traditional, Hybrid and AI (artificial intelligence) techniques to improve the productivity, effectiveness and efficiency of the WEDM process. The use of various optimization techniques in WEDM is discussed in the literature review. The classification of major CNC WEDM research areas is illustrated in Figure 7.

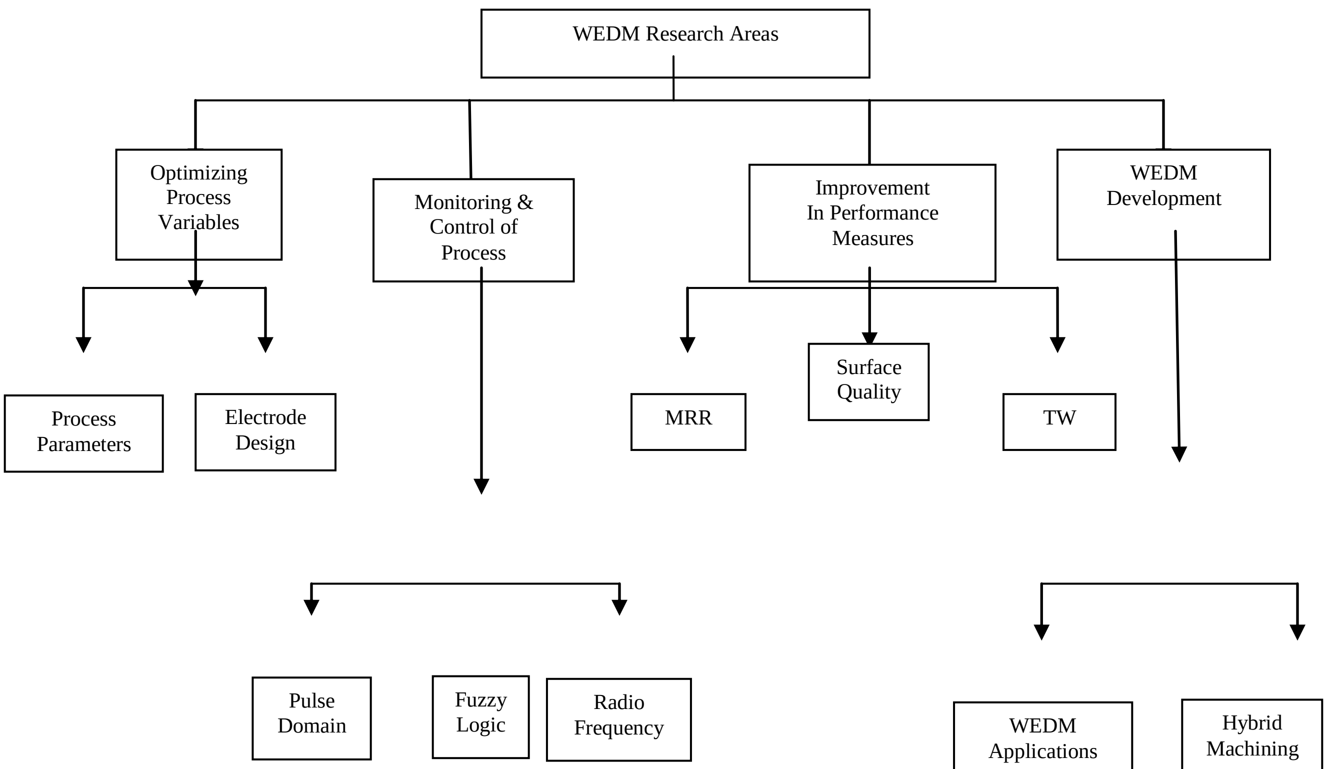

Figure 7. *Classification of Major CNC WEDM research area*

4. Literature review

As an attempt for the WEDM development and to use the WEDM process effectively, some researchers reported the influence of various parameters on the machining performance and productivity using various traditional, non-traditional, hybrid and artificial intelligence (AI) optimization approaches. Y. S. Liao et. al (1997) reported the effect of machine process parameters such as On time, Off time and feed on the behavior of pulse trains i.e. short ratio, Arc ratio, normal ration and gap width. Experiments were conducted on SKD 11 tool steel. The authors concluded that on time was a significant factor for arc ratio. Short on time, along off time and a large feed decreased the normal ratio and Ignition delay time. [49]

N. Tosun et. al (2003) presented the impact of pulse duration, open circuit voltage, wire speed & dielectric flush pressure on AISI 4140 steel material to measure the crater size of electrode. The experiments were conducted on Sodick A320D/EX21 WEDM. Brass wire having DIA. 0.25mm was used. The researchers resulted that the crater size increased with pulse duration, open circuit voltage & wire speed whereas crater size decreased with dielectric flushing pressure. [27] Scott F. Miller et. al (2004) demonstrated the capability of WEDM to machine advanced materials such as porous metal foams, diamond grinding wheels, sintered Nd-Fe-B magnets, etc. Author examined the effect of spark on time duration & spark on time ratio on Surface roughness and Material Removal Rate by using Brother HS-5100 WEDM. [39] Aman Aggarwal, et. al (2004) comprehensively reviewed the various optimization techniques and concluded that the Fuzzy Logic, Genetic Algorithm (GA), Taguchi Technique and Response Surface Methodology (RSM) are most recent optimization techniques and being applied to optimization of performance parameters in Industrial applications.

S.S. Mahapatra et. al (2004) optimized the WEDM performance parameters such as Material Removal Rate, SR & kerf width by using Taguchi method. ROBOFIL100 5-axis CNC WEDM was used for experimental work. Experiments were conducted on D2 tool steel by using zinc-coated copper wire having 0.25 mm diameter. De-ionized water is used as Dielectric medium. The author concluded that Discharge current, pulse duration and the dielectric flow rate had the significant effect on the performance parameters. Ulas Caydas et. al (2009) worked on the impact of Pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on white layer thickness and Surface roughness. Author developed the ANFIS model for the prediction of performance parameters. SODICK A320D WEDM was used for experimentation work & AISI D5 tool steel was used as a work material. [44] Vamsi Krishna Pasam et. al (2010) investigated the effect of Ignition pulse current, short pulse duration, wire speed and wire tension on Surface roughness by using Genetic Algorithm (GA). The experiments were conducted on ROBOFIL 310 5-axis CNC WEDM machine. Zinc coated brass wire (0.25 mm DIA.) was used as electrodes. [45] M.T. Antar et. al (2011) concluded the increase in productivity and surface roughness of Udimet 720 (nickel based super alloy) & T6246 (Titanium alloy) by replacement of standard uncoated brass wire with diffused annealed coated wires. The experiments were conducted on Agie Charmilles Robofil 240 CC & Cu coated wires and Zn rich brass wires were used. [22]

Anish Kumar et. al (2012) demonstrated the effect of pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension on the machined work surface roughness. The author concluded that pulse on time, pulse off time, peak current and spark voltage had higher impact on surface roughness. The experiments were conducted on 4-axis CNC (ELECTRONICA Sprint-cut 734) on pure titanium grade-2 material. [4] S.V. Subrahmanyam et. al (2013) concluded that the Gray Rational method is the most appropriate method for multi-parametric performance optimization. Author worked on the effect of T_{on}, T_{off}, IV, SV, WT, WF on Material removal rate and Surface roughness. Experiments were performed on the Sprint - cut (AU) With Pulse Generator ELPULS 40A DLX WEDM by using brass wire (0.25mm DIA.) and de-ionized water as a dielectric fluid. [35] Sushil Kumar et. al (2014) comprehensively reviewed the previous research works of WEDM, current research techniques, trend in WEDM and studied the literature in this area. [41] A.V.S. Ram Prasad et. al (2014) reported that the Peak current & pulse on time were significant parameters to maximize the Material Removal Rate and Surface Roughness after they studied the effect of Peak current, Pulse on time, Servo voltage on Ti-6Al-4V alloy. The experiments were conducted on Maxi-cut Electronica & brass wire having DIA. (0.25) was used as electrodes. [3]

Pujari Srinivasa Rao et. al (2016) analyzed the effect of pulse on time, peak current and spark gap voltage on residual stresses in the Aluminium alloy work material. Ultra Cut 843/f2 CNC WEDM was used for experimental work and zinc coated brass wire with de-ionized water was used. The author resulted that cutting speed affects the residual stress and Surface roughness. T_{on}, I_P and SV were significant parameters which affect the performance parameters. [29], [30] Somvir Singh et. al (2016) conducted the experimental work on Udimet L-605 materials to optimize the parameters such as MRR, Surface roughness, recast layer and white layer. Experiments were conducted on Electronica Sprint cut 40A DLX with brass wire (0.25 mm

DIA.). The author concluded that the white layer increased with the increase in pulse on time. For surface roughness and material Removal Rate, pulse on time, spark gap voltage and pulse of time were momentous parameters. [40] D. Devara Siddappa et. al (2016) developed the Artificial Neural Network (ANN) model for the optimization of surface roughness. The experiments were conducted on Electronica Sprint Cut 734 CNC WEDM. Inconel 825 aerospace work pieces were machined by zinc coated brass wire. The author concluded that the Surface roughness can be predicted at low levels of Pulse on time and servo voltage. [10]

Gaurav Kumar et. al (2016) concluded that the Surface roughness increases with the increase in peak current because peak current increases the discharge energy. They conducted the experimental work on Tungsten Carbide with brass wire (0.125 mm DIA.). Feed, flushing pressure & current were the significant parameters for Surface roughness. [13] Vladimir Simna (2016) reported that the greater height of work material increase the wire breakage probability. The experiments were conducted on high speed molybdenum-vanadium steel (H56-52C) with CuZn37 wire (0.25 mm DIA.). De-ionized water was used as a dielectric fluid. [47] Sameh Habib et. al (2017) worked on the effect of wire tension, wire running speed, flow rate and servo voltage on Kerf width & Material Removal Rate. Experiments were conducted using Sodick AP200L WEDM machine on SKD11 (alloy tool steel). Tungsten electrode was used to find the significant effect. The author resulted that the wire tension, wire running speed, flow rate & servo voltage greatly affected the kerf width and Material Removal Rate and kerf width decreased with the increase of wire tension and wire speed. [36]

Satish Kumar et. al (2017) investigated the impact of current, pulse on time, pulse off time and tool material on Material Removal Rate and Tool wear rate. Experiments were conducted on WEDM OSCAR MAXS645 on Inconel-600. Three wire electrodes as Copper, copper-chromium and graphite were used. The author resulted that the current, Pulse on time & tool material were decisive factors for MRR and tool wear. [37] Hulas Raj Tonday et al (2017) demonstrated the effect of spark voltage, pulse on time, wire tension and dielectric pressure on the WEDM performance parameters such as Material Removal Rate and Surface roughness on Inconel 718. AGIECUT 100 CNC WEDM was used with brass wire (0.25 mm DIA.) & de-ionized water was used as a Dielectric fluid. The author resulted that the spark voltage was the most significant parameter which has a higher impact on Material Removal Rate & Surface Roughness. [17] T. Vijaya Babu et al (2017) concluded that the peak current was a significant parameter for surface roughness after they studied the effect of Pulse on time, pulse off time and peak current on Inconel 625. Copper wire electrode was used for machining with de-ionized water dielectric fluid. [42] A. Maniappan et al (2017) reported the influence of peak current on Kerf width. The experiments were conducted on Al 6061 alloy (Al hybrid) with zinc coated brass wire electrode material. [2]

Tompe S. V. et al (2017) investigated the effect of the Current, pulse on time, pulse off time and wire tension on Surface roughness and Material Removal Rate on graphite plate. The author concluded that the Material removal rate increased with increase in pulse off time. [43] Y. Chandra Sekhar et. al (2017) examined the behavior of WEDM process parameters such as pulse on time, pulse off time & pulse current on SS317 to measure the effect on Material Removal Rate and Surface Roughness. ELECTRONICA Maxi cut WEDM was used to conduct the experimentation and brass wire having 0.25 mm DIA. was used as electrodes. Distilled water was used as dielectric medium. The researcher concluded the pulse on time as a significant parameter. [48] Dain Thomas et al (2015) reported the effect of input machining parameters, namely Ton, T_{off}, WT (wire tension) and I_p (peak current) on MRR using RSM (response surface methodology). EN31 steel was used as a work material and experiments were conducted on SPRINTCUT WEDM with zinc coated brass wire. The authors resulted that T_{on} and T_{off} had the major influence on MRR. [11]

Giovanna Gautier (2015) optimized the machining parameters, namely T_{on}, WT (wire tension) and servo voltage using ANOVA with RSM methodology and measured the influence of parameters on SR (surface roughness). Experiments were conducted on γ- titanium alloy and standard brass wire was used as tool electrode. The authors resulted that the lower value of input parameters contributes for the higher SR. [14] Mohammad Shahir Kasim et al (2015) worked on the impact of SV (servo voltage), wire feed rate and current on SR (surface roughness). Experiments were performed on Incolnel-718 using Mitsubishi RA 90 series CNC WEDM with standard brass wire and RSM methodology was adopted. The authors obtained the best SR (horizontal and vertical) at 42 V of SV, WF= 1.44 mm/min. and 6 amps of current. [24] Baljit

Singh et al (2014) investigated the effect of I_p, T_{off}, WT and T_{on} on MRR (material removal rate) using the Taguchi approach. The experiments were conducted on the ECO-cut, CNC WEDM on titanium alloys using molybdenum wire. The authors obtained the higher values of MRR at T_{on} = 120 µs, T_{off}= 55 µs, WT= 1300g, SV= 80 V, WF= 15 mm/min. and current= 6 Amps. [6] Brajesh Kumar Lodhi et al (2014) demonstrated the effect of I_P, T_{off}, WT and T_{on} on SR using the Taguchi approach. Experiments were conducted on Electronica Supercut 734 WEDM using brass wire and AISI D3 steel was used as work material. [8]

Kashid DV et al (2014) concluded that T_{on} and T_{off} are most influencing parameters for MRR (material removal rate). The authors worked on the effect of $T_{on,}$ T_{off} and wire feed rate on MRR. Experiments were performed on the Sprintcut 40 A Dlx using brass wire and EN 9 steel as work material. [19] Kumar K. et al (2014) investigated the effect of T_{on}, T_{off}, WS (wire speed) and WF (wire feed) on SR (surface roughness) using Taguchi method. The experiments were performed on aluminium metal matrix composites (ALSiC) with molybdenum wire. Sprintcut 734 CNC WEDM machine was used for experimentation. The authors optimized the parameters for minimum SR as Ton= 104 µs, T_{off}= 42µs and WF= 0.5 m/min. [20] A. Conde et al (2016) reported the effect of wire lag and concavity on AISI D2 steel. Experiments were performed on ONA AX3 WEDM with brass wire of 0.25 mm diameter. Zeiss 850 CNC CMM (coordinate measurement machine) was used for coordinating measurements. The authors resulted that concavity is a function of machined radius and wire lag effect must be taken into consideration only when the circle of radii is lesser than 3 mm. [1]

Saurav Datta et al (2010) presented the impact of input parameters, namely discharge current, pulse duration, pulse frequency, WS, WT and dielectric flow rate on MRR, SR and kerf width using RSM and GRA (grey relational analysis). Experiments were performed on Robofil 100 5-axis CNC WEDM with standard brass wire and D2 steel was used as work material. The authors concluded that pulse duration and wire speed has the most influence on response parameters. [38] Murat Kiyak (2018) comprehensively reviewed the applications of various cutting fluids along with their properties on machining, environment and worker's health. Author concluded that soluble oils are a good alternative of mineral oils for higher cooling capacity and the synthetic lubricants are superior for machining purposes. [25] G. Selva Kumar et al (2012-13) reported the influence of controllable parameters, namely, WT, T_{on}, pulse frequency, peak current and servo voltage and non controllable parameters such as material thickness and nozzle height on MRR, SR and corner radius using Taguchi and Pareto approach. Experiments were performed on Electra Supercut 734 series WEDM with Monel-400 and Al-5083 Mg-based aluminium alloy using brass wire of 0.25 mm diameter. Corner errors were measured with OLYMPUS STM 6. The authors resulted that the T_{on} and I_p (peak current) are the most influencing parameters for MRR and SR, whereas the accuracy of corner decreases with increase in material thickness and nozzle height. [12]

R. K. Garg et al (2010) comprehensively reviewed the research work in EDM and WEDM on MMCs (metal matrix composites). [32] Milan Kumar Das et al conducted a study of WEDM parameters, namely I_p, voltage, T_{on} and T_{off} on MRR and SR using weighted PCA (principal component analysis). Experiments were performed on ELEKTRA Maxi cut 434 EDM with zinc coated brass wire of 0.25 mm diameter. The experimental work was carried on EN 31 steel. The author resulted that the peak current and T_{on} are the most influencing parameters for MRR and SR. [23] S. Sarkar et al (2008) reported the influence of T_{on}, T_{off}, I_p, WT, feed rate and wire offset on SR, dimensional shift and machining speed using RSM and Pareto multi-objective optimization. The authors developed a second order mathematical model for output responses. Experiments were conducted on Super cut 734 WEDM with γ-titanium aluminide material and standard brass wire of 0.25 mm DIA. was used as tool electrode. [34] Kaushik Kumar et al (2014) reported the effect of discharge current, voltage, T_{on} and T_{off} on SR using RSM and an artificial bee colony algorithm. Experiments were conducted on ELEKTRA Maxi cut 434 5-axis CNC WEDM with EN 31 steel and standard brass wire of 0.25 mm diameter was used as tool electrode.

Hargobind Soni et al (2017) reported the influence of T_{on}, T_{off}, servo voltage, servo feed and wire speed on SR and MRR. Experiments were performed on ELPULS 15 CNC WEDM with unique class of smart material, namely, TiNiCO shape memory alloy and brass wire of 0.25 mm diameter was used as tool electrode. The authors concluded that T_{on}, T_{off} and servo voltages are the most influential parameters for SR and MRR. Himadri Majumdar et al (2018) investigated the effect of T_{on}, current, WF (wire feed), wire tension and flushing pressure on SR and micro-hardness using MOORA-Fuzzy approach. Experiments were performed on AGIE cut progress-2 WEDM with Nitinol material and standard brass wire was used as tool electrode. The author recorded the micrographs of machined materials and concluded the influence of input parameters on surface topography on Nitinol material. [15] Himanshu Bisaria et al (2018) concluded that SR and cutting efficiency is mostly influenced by T_{on}, T_{off} and spark gap voltage whereas wire tension and wire speed has less influence while machining NiTi shape memory alloy. Experiments were conducted on Electronica Ultra cut 834 WEDM with standard brass wire. [16]

4.1. Summary of Literature

The summary of the literature indicates that most of the research work is concentrated in the area of optimization of process performance parameters, machining condition measurement, product quality analysis, tool condition monitoring and the development of hybrid mathematical model in the revolutionary precision WEDM process. In gathering a good surface finish, close tolerances, economically and for precision machining, Computer controlled WEDM is used. Because of the precision, higher productivity, close tolerances and dimensional accuracy obtained by CNC WEDM, interchangeable manufacture has become commonplace in most industries. Julie, 2007 stated that through theoretical analysis, it is very difficult to calculate the value of surface roughness, therefore the other optimization method like Design of Experiment (DOE), Gray rational Analysis, Fuzzy logic, hybrid, AI (artificial intelligence) etc. models have been using for the analysis. Wire EDM eliminates the need of conventional machining. A new development of non conventional machines, the rough part is often finished in single operation can reduce the need for other machining. Nowadays, WEDM is applied extensively to productions of precision parts where high productivity, accuracy, close tolerances and surface finish are required. The understanding of the WEDM process parameters and their relation to the performance parameters, are still limited and yet to be studied. The factors that have been outlined in the literature have considered, exploring the changes on the selected responses in WEDM.

5. Future scope and directions

(1) Most researchers have been investigated on optimization of performance parameters such as Surface roughness, Material Removal rate, Kerf width, White layer, but very rare literatures

were found on thermal distribution effect, wire lag and concavity and tolerance analysis of machined parts.

(2) More experimental studies required for the newly developed material to address the performance parameters for effective use of precision WEDM machining.

(3) The experimental analysis of the effect of WEDM process parameters as wire breakage, gaseous dielectric medium (near-dry WEDM) has been done by very few researchers. More experimental investigation is required for better understanding of WEDM process.

(4) The applications of artificial intelligent techniques (AI) for WEDM optimization and modeling may add the advancement in the process.

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