An overview of major research areas in Wire cut EDM on different materials

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Abstract: *WEDM (Wire electrical discharge machining) is a precision machining method for cutting electrically conductive materials. It is an unconventional machining process that produces precision parts that match the dimensional tolerances of our designs within the range of ±0.0001mm. As the residual stress results in premature failure of parts, the WEDM is preferred for hard to machine materials such as Inconel, Nickel, and other Super alloys. In the present paper, earlier and recent work was reviewed, segregated and evaluated on the effect of wire material, diameter, dielectric fluid, wire wear, pulse on and off times and machining characteristics such as kerf size, machining efficiency, material surface characteristics, etc. This paper also focused on hybrid and ultrasonic-assisted WEDM used for machining of different materials. This paper discussed the major research studies in WEDM.*

Key Words: *WEDM, different materials, process parameters, electrode wire, material surface, machining characteristics, hybrid WEDM, pulse, kerf, dielectric fluid, ultrasonic assisted WEDM, discharging systems, dry WEDM*

1. INTRODUCTION

Machining process plays a major job in manufacturing industries where quality and cost are taken as a benchmark [1]. WEDM is most influential machining processes overall unconventional machining processes for difficult-to-machine materials (like tungsten carbide, graphite, molybdenum, tool steel, titanium, zirconium, copper, aluminum, waspaloy, Inconel, hastelloy, conductive ceramics, polycrystalline diamond compacts, metal matrix composites etc.), which are widely used in manufacturing industries like aeronautics, nuclear reactors, automobiles etc., [2] & [3]. In WEDM, process material removal will take place using generated heat by electrodes made of electrically conductive metals. The machining process takes place without contact between the wire tool and the workpiece, and hence, cutting is done without residual stress, as the workpiece cannot undergo a cutting pressure. This type of advantages makes WEDM an exemplary method for machining of precision parts as well as machining of complex and hard workpieces with complicated profiles and shapes which are difficult to machine materials with conventional machines [4] & [5]. WEDM is a potential thermo-electrical machining technique and this is a contactless machining process, i.e. the wire electrode does not come into contact with the workpiece electrode. This technique was invented for better precision purpose during machining. Material was eroded by a series of controlled sparks between two electrodes. Both electrodes are connected to the DC pulse power supply and immersed in the dielectric fluid; the fluid behaves like an electrical conductor, which acts like electrical insulator until the ionization time. The spark discharges occur at the small gap between the electrodes with the frequency of thousands of sparks per second. At each spark moment, with a period of about 10^{-4}–10^{-6}s, deionization and ionization of the liquid medium is caused. The vicinity of the cutting area heats up to 10,000–20,000ºC and the dielectric medium around this region evaporates, especially when the pressure increases. In addition, little quantity of workpiece and wire materials liquefies and evaporates, which produces minor craters on the workpiece area. When the spark is stopped and the starting moment begins, the pressure drop leads to the condensation of the metal globules, which have been discharged by the flowing dielectric medium.

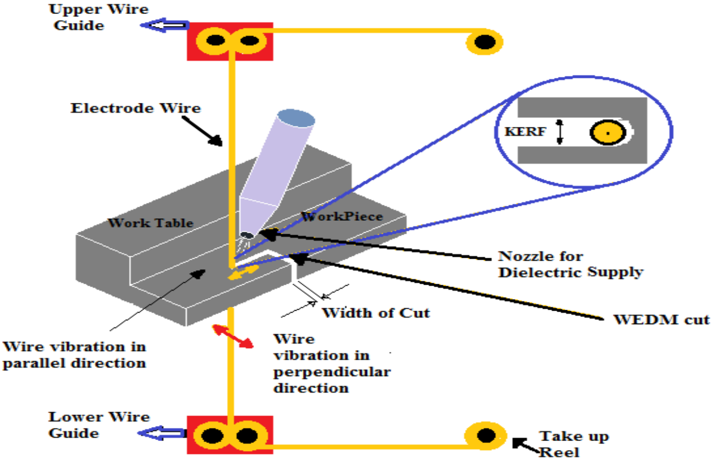

Figure 1: WEDM schematic diagram

A veneer of melted and re-solidified material referred as recast layer can be observed on the surface of the workpiece after processing. The major factors affecting WEDM performance are discharge power, pulse frequency and duration, wire speed and tensions/voltage, dielectric fluid type and fluid slip rate [6] & [7].

2. LITERATURE REVIEW

Literature reviews were categorized based on process parameters, electrode wire, material surface, machining efficiency, hybrid WEDM, pulse, kerf, dielectric fluid, ultrasonic assisted WEDM, discharging systems, dry WEDM and Thermal.

Process parameters: There are four major parameters, which affect the WEDM process.

Table 1. Major parameters considered in WEDM

1. Electrical	2. Electrode	3. Dielectric	4. Workpiece
>Peak Current	>Wire Material	>Flow rate of dielectric	>Material
>Gap Voltage	>Wire Size	>Conductivity of dielectric	>Height
>Servo Feed	>Wire Tension		
>Spark gap set voltage	>Wire Feed rate		
>Pulse on Time			
>Pulse off Time			

Selection of the correct parameters for WEDM to get better performance is an important task.
Peak current: Maximum supplied current for each regular pulse from the generator/power supply.
Gap voltage: A proper gap is necessary to generate sparks between the workpiece and the wire electrode. Therefore, WEDM discharge gap is about 0.005 to 1.0mm.
Servo feed: The servo feed system provide balanced operation even at machine running conditions. (P off time > P on time).
Pulse on time: Metal removal rate is correlative to the amount of power supplied during the pulse on time. The longer the pulse, the more the material will be removed.
Pulse off time: One cycle will finished when required pulse off time maintained prior to starting of the coming cycle. Pulse off time influences the stability and accelerates the cut.

Table 2. Review on electrical parameters

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings/ Discovered
Krishnan and Karuna /2006 [8]	Heat treated tool steel	Taguchi's robust design, MRSN, ANOVA, SEM	Optimization of multi responses	Selected multiple performance characteristics can be improved by the process.
Mahapatra and Amar /2007 [9]	D2 tool steel	Perthometer, Microscope L27 orthogonal array, MINITAB, GA	Process parameters optimization	The tested algorithm used for finding parameters optimization along with different weighting factors of various objectives.
Gauri and Chakraborty /2009 [10]	Y-titanium aluminide alloy	Taguchi's design, MRSN, Principal component analysis (PCA), ANOVA	Optimization of multi-response process	Based on MRSN and PCA approaches, the predicted overall quality is almost equivalent.
Gauri and Chakraborty /2010 [11]	-	MRSN, Grey relational analysis, ANOVA, VIKOR, L27 Taguchi	Optimization of multi-response parameters performance	No method can give superior overall quality than the results derived using the weighted signal-to-noise ratio method.
Yang et al./2012 [12]	Tungsten	RSM, BPNN, SA, Taguchi L18, SEM, ANOVA	Process parameters optimization	Finest reproducibility conclusions of the experiment.
Rajyalakshmi and Ramaiah /2013 [13]	Inconel 825	Taguchi L36 orthogonal array, Grey relation analysis, ANOVA	Optimization of multi process parameters	Suggested method is suitable and ideal for the process parameters optimization, when employed characteristics such as Ra, MRR and spark gap.
Babu and Krishna /2014 [14]	Al7075/SiCp MMC	RSM, L27 Orthogonal array, GA, ANOVA, SEM	Optimal process parameters selection	Manufacturers can choose the optimal WEDM conditions based on the machined design component quality indicators.
Vivek et al./2015 [15]	Inconel 718	RSM, CCD, ANOVA,	Parameters modeling and optimization	From developed models with experimental results, the prediction errors are less than ±5%.
Zhang et al./2016 [16]	Tungsten tool YG15	ANN, LWPA, BPNN, CCD	Parameter optimization integrated with ANN-LWPA	The suggested approach has obtained non-dominated results.
Abbasi et al./2017 [17]	HSLA steel	Factorial design of experiments, SEM, ANOVA	Parameters effect on surface roughness	By decreasing the wire speed, power and on time pulse, the surface finish can improve.
Venkata et al./2017 [18]	High speed steel	ANN, Supporting vector machines	Parameters prediction and optimization	Developed models predict optimum power and discharge current for required Ra for any plate regardless its thickness.
Shihab /2018 [19]	Friction stir welded alloy	Box-Behnken design, Ra tester, ANOVA	Process parameters optimization	The selected parameters significantly affect the Ra, MRR and kerf width.

Somvir et al./2018 [20]	Udimet-L605 alloy	Taguchi design, XRD, M5P tree approaches, SEM	Performance evaluation	Machining performance was evaluated by using different techniques.
Pramanik et al./2019 [21]	Al 6061 alloy	RSM, surface texture measuring, Minitab, ANOVA, SEM	Parameters effect on MRR and Ra	Maximum MRR and minimum Ra achieved by varying the process parameters.
Sahoo et al./2019 [22]	HCHCr D3 grade	MOORA, ANOVA	Multi objective optimization	MRR, Ra and Kerf width values more with long pulse on time and servo voltage and less with short pulse off time.
Ezeddini et al./2019 [23]	Recycled Ti-17	RSM, ANOVA, SEM	Parameters optimization	Small kerf width from higher servo voltage, greater MRR from high speeds.

Electrode wire (vibration, Wire lag, Wire breakage, Wire feeding and Wire tension): The WEDM process depends on an amalgamation of properties of the electrode wire.

For high precision machining and high-speed cutting, any of the wire electrodes must have properties like more electrical conductivity, melting point, straightness, tensile strength and elongation along with geometrical properties of the wire like coating layer structure, shape, and diameter.

The diameters of wires ranging from 0.02-0.36mm are readily available on the market for WEDM [24].

Table 3. Types of wire materials used in WEDM [36]

Plain wires	Coated wires	Diffusion-annealed coated wires	Steel wires	Special wires
>Copper >Brass >Aluminum-brass	>Single-layer >Double-layer >Multi-layer	>Alpha phase >Beta phase >Gamma phase >Epsilon phase	>Molybdenum >Tungsten >Moly Carb >Steel core	>Abrasive -assisted >Hot dip galvanized >Porous electrode

The wire factors that affect the process of WEDM are mentioned below.

Wire vibration: Vibration wire during machining is one of the main drawback, which affects the products surface finishing and accuracy. Wire moves between Upper & Lower guides (vertically) and may vibrate in parallel and perpendicular directions with the wire moving direction as exhibited in figure 1.

Reducing the wire vibration is a very important factor to get greater efficient machining and better shape accuracy [25] & [26].

Wire lag: Most of the researches have studied vibration in the wire; less research has been carried on the wire lag phenomenon, which is also an important factor for precision machining. Such a study requires an investigation of the deflection or deformation of the wire in detail [27].

Wire breakage: Everybody knows that the WEDM machine is running around the clock even without an instructor. If the wire breaks while doing machining for any cause, it is not possible to rearrange the wire at the exact place. Therefore, the accuracy and efficiency of the machining process may decrease.

In fact, breakage of wire has a great influence on the machining productivity, but skilled technician can avoid breakage of wire and keep their machine running effectively and efficiently with expert skills about the WEDM process [28] & [29].

Wire feed: During the machining process, the wire is fed into the machining area by wire supply reel, after being discharged from the machining area, the wire is unused. However, in some special cases the wire electrode can be used repeatedly based on requirements.

Wire tension: To solve the above trouble the wire will be tensioned at each ends. This may cause a short circuit, which in turn can have an influence on the quality of cutting surface and machining accuracy of a workpiece. For this reason, it is imperative to locate some advantageous strategies to resolve the un-even wire tension problem to improve the cutting balance and precision of the workpiece [30], [31] & [32].

Table 4. Review on wire electrode parameters

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings / Discovered
Puri & Bhattachary/ 2003 [33]	Die steel plate	Taguchi design, Ra instrument, contour measuring instrument	Inaccuracy in workpiece due to wire lag phenomenon	For getting geometrical accuracy, the trim and rough-cut values set as more as possible up to getting the better surface finish.
Okada et al./2010 [34]	SKD 11	Digital high-speed camera, acrylic tank, oscilloscope	Wire vibration and spark distribution	Spark distribution becomes uniform when pulse interval time are long, servo voltage is high, and wire running speed is low.
Okada et al./2015 [35]	SKD 11	CFD, nozzle jet flushing with high flow rate	Deflection and breakage of wire	Deflection of wire becomes greater due to jet flushing and the debris deposited easily in the kerf length, causes wire breakage.
Prasad and Krishna /2015 [36]	AISI-D3	RSM, Harmony search algorithm, CCD, ANOVA	Modeling and optimization of WWR and kerf	From the proposed methodology, either the minimization of the wear ratio of the wires or the minimization of the strip width could be achieved.
Conde et al./2016 [37]	AISI D2 steel	MATLAB, 1&3 concatenated circular interpolation	Wire-lag influence in WEDM	Workpiece effected with concavity is a function of machined radius, the concavity increases, the accuracy is less while the radius decreases.
Pramanik et al./2016 [38]	Metal matrix composite (Al-based SiC)	SEM, EDX	Wire electrode degradation during machining of MMC	The cutting side of the wire face involves in removal of material, the left and right faces smoothen the kerf wall, and the back face minimizes the chance of wire fail.
Zhidong et al./2017 [39]	Solar-grade polycrystalline silicon	Two-direction projection of light on wire deflection detection and control system	Detection of wire deflection	The self-made signal control system, can help and control the uniformity of wire deflection, thereby contributing to the improvement of cutting stability and ensuring shape cutting precision.
Ciwen et al./2018 [40]	Cr12	Reciprocated ultra-long wire WEDM, tensile dual reels	A study on feeding of wire	The quality of the surface in the frequent change of direction of the wire has been significantly reduced.
Shather and Mohammed /2018 [41]	AISI 1012 steel	ANOVA, ANN	Parameters effect on MRR, Ra and wire wear ratio	Coated wire: MRR-16.1, Ra-1.34, WWR-1.8; Brass wire: MRR-7.4, Ra-1.44, WWR-0.9
Ramamurthy and lingam/ 2019 [42]	Ti-6Al-4V	Brass wire, zinc diffused coated wire, ANOVA, Histogram	Machinability analysis	Regular brass wire gives greater MRR and zinc diffused coated wire gives low surface roughness.
Bisaria and Shandilya /2019 [43]	Nickel-titanium alloy	Optical microscope	Corner error	The corner error was mostly/largely affected due to wire in tension by the effect of wire vibration and deflection in cutting the angular profiles.

Material surface:

Surface integrity: Condition of a workpiece surface after modification by a machining process known as surface integrity. The surface integrity of a product or workpiece changes the material properties [44].

Surface finish: It is the nature of a workpiece surfaces depending on three aspects like lay, waviness and roughness of the surface. Each machining process makes some texture on surface [45].

Surface analysis: A surface analysis method is a technique for discovering the chemical structure of thin and an extremely shallow area called the surface number atomic layer of the solid matter [46].

Table 5. Review on workpiece electrode

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings / Discovered
Kapil and Neelesh /2014 [47]	Brass	Elcam software, Smart CNC machine, SEM, Micro hardness	Surface integrity in miniature spur gears	The suggested work said that the WEDM is better for fine gear manufacturing.
Xu et al.2015 [48]	Ti-6Al-4V	Laser confocal microscopy, JR3A dielectric fluid	Analyze the properties of workpiece	Friction coefficient of the workpiece surface is twice lower than the previous non-colored one.
Pramanik and Littlefair /2016 [49]	MMCs (with varying particle size)	SEM, other analysis techniques	Kerf formation, Ra and MRR	Kerf formed, surface having defects and material removal rate is low due to high reinforced particles.
Azam et al./2016 [50]	30CrMnSiA (HSLA steel)	Hardness testing, Spark emission, SEM, EDS, ANOVA	Recast layer formation analysis	Pulse-on time is the greatest controlling parameter to overcome asymmetry in the machining process.
Bisaria & Shandilya/ 2017 [51]	NiTi alloy	Differential scanning calorimetry, SEM, EDS, XRD	Cutting rate average and Ra	Machined surface having many voids, craters, bulges of debris, recast layer and micro cracks with compounds formation.
Sujeet and Neelesh /2017 [52]	SS 304	Meso bevel gear, Meso helical gear	Surface quality	WED machined meso gears do not require post-processing treatments.
Manikandan et al./2018 [53]	Ti-6Al-4V grade 5	Texturing process	WEDM textured tool influence	Machining of textured tools is better performed than that of the non-textured tools
Mussada et al./2018 [54]	Die steel	Spark emission spectroscopy, SEM	Surface hardenability	Workpiece surface hardness is slowly reduced to beneath surface from the recast layer.
Priyadarshini et al. /2019 [55]	AISI P20 tool steel	Optical microscope, SEM, Micro-hardness tester, ANOVA	Machinability and Surface morphology	Compared to parent metal the sub-cooled metal has smaller deposits and spherical globules.
Roy and Mandal /2019 [56]	Nitinol-60 shape memory alloy	ANOVA, RSM, SEM, Monte- Carlo analysis,	Surface integrity	Surface cracks and the recast layer thickness was increased with the increase in flow rate; these defects are eliminated by setting the optimal values.
Adam Khan et al./2019 [57]	Titanium based human implant materials	DOE software, ANOVA, SEM, EDS	Surface quality	From the output, it can be noticed low surface roughness and coarse structure from high voltage and low voltages, respectively.

Machining characteristics: In WEDM, the parameters considered are: the component geometry, workpiece materials, dielectric liquids, machining characteristics, setting of machining and related parameters. Make mild adjustments in the parameters will have an effect on the overall performance of a machining characteristics such as asymmetry, MRR and Ra features [58] & [59].

Table 6. Review on machining performance

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings / Discovered
Ozdemir and Ozek /2006 [60]	GGG40 nodular cast iron	Regression analysis, Optical micrograph,	Machinability investigation	Results show that the input machining parameters have a major effect on the efficiency of machining nodular cast iron.

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Han et al./ 2007 [61]	Cr12	SEM, X-ray determination	Machining parameters influence on Ra in finish cut	From the experimentation, it can be noticed that high peak value with a short pulse duration can generate better surface roughness, which a long pulse cannot do.
Saha et al./ 2008 [62]	Composite	BPNN, SEM, ANOVA, ANN, MINITAB, EDX	Surface roughness and Cutting speed	Peak capacity and current increases lead to roughness of the workpiece.
Patil et al./ 2010 [63]	Al/SiCp composites	RSM, Buckingham's π theorem, SEM, ANOVA	Finding of MRR by dimensional analysis	The MRR decreased to almost 12% with a 10% increase in ceramic reinforcements.
Kamal et al./ 2011 [64]	Carbide material	Graph approach, Digraph, Matrix	Performance evaluation	The proposed method assists in judging the impact of different influence elements and their sub-elements on die performance.
Somashekhar et al./2012 [65]	Aluminum	Simulated annealing, SURFPAK software	Machining parameters optimization	Machining process of μ-WEDM can conspicuously improve while attaining optimum process parameters.
Ravindranadh et al./2015 [66]	Hot-pressed boron carbide	Taguchi L16 orthogonal array, Signal/Noise ratio, ANOVA, SEM	Experimental study	Because of high discharge energy, pulse on time and peak current leads to the creation of debris, craters, and micro-cracks on the workpiece surface.
Kamal /2015 [67]	WC-5.3% Co composite	MINITTAB 15, ANOVA, signal-to-noise	Multi-pass cutting operation study	Multi-pass cutting process of materials, to achieve appreciative machining performance.
Samanta et al./2016 [68]	Die steel	Volume removal rate, Specific energy consumption, Regression analysis	Different control strategies influence by job height varying	This study is very useful in finding the proper control strategy during machining of varying job heights and understanding the WEDM gap characteristics.
Shakeri et al./2016 [69]	Cementation alloy steel 1.7131	ANN, BPNN, Regression model	MRR and Ra	A neural network has a better accuracy with a more robust than using the regression model.
Anjali et al./2017 [70]	Inconel-718 and Ti64Al4V	Taguchi design and ANOVA	Optimize the process energy consumption	Almost 67% of the energy saved.
Vikram et al./2017 [71]	AISI D2 steel	Taguchi technique, RSM, ANOVA, Signal-to-noise ratio	Parameters experimental investigation	The major significant parameters that change the machining process are the pulse on and off times and the servo voltage.
Conde et al./2018 [72]	AISI D2 tool steel	ANN, ELRNN, SA	Predict the accuracy of components	The proposed system is very efficient where the deformation of wire is high.
Smirnov et al./2018 [73]	3Y-TZP/Ta ceramic-metal composites	SEM, SPS, XRD, Universal testing machine	Machining characteristics, electrical properties and bending study	The results reveal that the machined workpieces have a better accuracy also without change in mechanical strength.
Mouralova et al./2018 [74]	X210Cr12 alloy steel	SEM, 3D noncontact profilometer, 3D opto-digital microscope, EDX	Cutting direction influence on the occurrence of cracks in semi product	Avoid the components production that will only have a small limited lifetime.

Kumar et al./2018 [75]	Aluminum metal matrix composite	Acoustic emission	Machining performance monitoring	Amplitude and energy during machining of the MMC show passing of the cutting wire through various phases of the workpiece.
Pramanik et al./2019 [76]	Titanium alloy	Taguchi DoE, ANOVA, CMM	Dimensional accuracy	Dimensional accuracy mainly depends on flushing pressure and wire tension.
Ishfaq and Ahmed /2019 [77]	Mild steel and Stainless steel	Taguchi DoE, CMM, ANOVA, SEM	Cut quality issues and MRR	Mild steel layer thickness plays a major role in identifying the MRR.

Hybrid WEDM: Hybrid WEDM is also known as abrasive WEDM process that has an embedded wire with electrically non-conducting abrasives. Removal of material is similar to that of the general WEDM process, but the abrasive action improves electrical erosion rate through the removal of recast/molten workpiece material. Almost no recast-layered products were produced from this processing. The main problem of abrasives is the graphitization because of which the performance highly decreases [78].

Table 7. Review on hybrid machining

Author(s)/ Year	**Workpiece material(s)**	**Technique(s)/ Equipment's**	**Objective(s)**	**Findings / Discovered**
Xiaoyu and Shujuan/ 2018 [79]	Silicon ingot	3D microscope, SEM, EDX, contact angle, EDS	Comparison of WEDM, hybrid and abrasive wire saw's	Hybrid machining efficiency is 160% higher than the WEDM efficiency and 6% greater than the abrasive wire saw.
Sanjay et al./ 2018 [80]	HCHCr D2 tool steel	Portable X-ray residual stress, Ultrasonic generator, ANOVA	Effect of hybrid WEDM conditions	Compared to vibration conditions, the residual stresses are low in without vibration conditions.

Pulse: In WEDM, electrical power needed to result in spark and removal of metal in workpiece principally happens due to the electrical power of the spark known as a pulse. Pulses are four classes: arc, open circuit, short circuit and normal discharge [81].

Table 8. Review on pulses

Author(s)/ Year	**Workpiece material(s)**	**Technique(s)/ Equipment's**	**Objective(s)**	**Findings / Discovered**
Kai et al./2018 [82]	1.4571 stainless steel	High speed WEDM, USB-Oscilloscope,	Automated analysis of pulse types	Breakdown fields only occur when excessive gas formed due to passivation.
Qiu et al./2019 [83]	P type monocrystalline silicon	Proportional-integral-derivative	Discharge probability	Proposed continuous discharge probability power source gives stable and automatic semiconductor processing

Kerf: Kerf is an effective width of cut in the WEDM processes. Kerfs of the machined slots are mainly dependent on regulate parameters, such as the electrode feed rate, input capacitance, open voltage, air injection pressure, between the two pulses time, pulse current ignition, wire speed and tensions. Increasing in Kerf width by increasing in pulse on time and decreasing in pulse off time caused by higher discharge power [84] & [85].

Table 9. Review on width of cut (Kerf)

Author(s)/ Year	**Workpiece material(s)**	**Technique(s)/ Equipment's**	**Objective(s)**	**Findings/ Discovered**
Suhas et al./ 2017 [86]	p-type polycrystalline silicon ingot	Response surface methodology, ANOVA, SEM	Slicing rate maximize and minimizing the loss of kerf	A higher practical 150µm of wafer thickness can got at 1.05 mm/min of great slicing rate and with 121µm of minimal kerf loss.

Okamoto et al./2018 [87]	Monocrystal line silicon	Multi-WEDM slicing of ingot with circular section	Kerf width control	The sliced wafer almost uniform thickness can be obtained by properly controlling the feed rate of the workpiece depending on the cutting width.

Dielectric fluid: In most of the WEDM processes, a dielectric fluid submerges the workpiece. The dielectric liquid major features are to ensure the deionization of small space between the electrodes, to move out the removed metal particles at some point of erosion from the working region and to maintain the working area temperatures.

Deionized water has low conductivity. Researchers changed the regular dielectric fluid with steam water mist, pure water with sodium pyrophosphate powder and Nano powder mixed EDM oil etc., [88] & [89].

Table 10. Review on dielectric liquid

Author(s)/ Year	**Workpiece material(s)**	**Technique(s)/ Equipment's**	**Objective(s)**	**Findings/ Discovered**
Liu et al./ 2017 [90]	Cr12	Pulse discharge probability, Field-programmable gate array, SEM, EDS, XRD	Lifespan detection of dielectric fluid	Reduction in the chip removal efficiency of the dielectric fluid is the central cause of the inter-electrode discharge state deterioration, finally causing decreases in cutting efficiency and pulse discharge probability.
Ebisu et al./ 2018 [91]	-	CFD, Lagrangian method, ANSYS	Jet flushing influence on accuracy of corner shapes	While corner machining due to pressure, dielectric flow around the wire by jet flushing changes cutting direction to the corner.

Ultrasonic assisted WEDM:

1. WEDM assisted with ultrasonic vibration given to wire electrode ultrasonically activates the wire with a frequency and vibration amplitude through ultrasonic activator during machining process [92] & [93].
2. WEDM assisted with ultrasonic vibration given to workpiece as shown in figure 5; ultrasonically activated the workpiece with a frequency and vibration amplitude through ultrasonic activator during the machining process [94] & [95].
3. WEDM assisted with ultrasonic vibration to dielectric medium ultrasonically activates the fluid takes place. Because of the erosive motion of some particles and debris in dielectric fluid will remove with the influence of an ultrasonic zone [96].

Table 11. Review on ultrasonic assisted machining

Author(s)/ Year	**Workpiece material(s)**	**Technique(s)/ Equipment's**	**Objective(s)**	**Findings/ Discovered**
Unune and Harlal /2017 [95]	Inconel 718	High-speed diamond cutter, vibration device, FESEM, Digital Microscope	Improve machining rate	Increase in machining rate Improves the overall performance of the process with vibration assistance conditions.
Wang et al./ 2018 [96]	TiNi-01 shape memory alloy	Ultrasonic vibration, Magnetic field, Taguchi technique, Acoustic emission	Mechanism of complex assisted WEDM system	Assisted WEDM can improve the pulse discharge states, surface quality and machining efficiency simultaneously, reducing Ra.

Discharging systems: More than 75 decades ago, the Russian scientists Natalya Lazarenko and Boris investigated the impact of electrical discharges on the removal of metal from the workpiece. However, the removal mechanism and the gap discharge characteristics were not clearly understood because of the randomness of the discharge position and the complexity of the WEDM process [97].

Table 12. Review on discharging systems

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings/ Discovered
Yan et al./ 2016 [98]	SKD 11 tool steel	Mechatronic system approach, Pulse train analysis	Part straightness	The suggested mechatronic system can further stabilize the wire, due to the fact that the rectification of the part in the WEDM process improves by 61% after a rough cut.
Liu et al./2017 [99]	Cr12 die steel	Discharge probability detection	Process efficiency increasing of HSWEDM	Suggested servo system can improve performance and accuracy of servo control and reduce the workpiece surface burning under large cutting energy.

Dry WEDM: As electrolytic power flows through dielectric water, it creates corrosion in WEDM process.

To eliminate the corrosion and geometrical errors, liquid dielectric is replaced by gaseous medium, known as dry WEDM [100] & [101].

Table 13. Review on WEDM with gaseous medium as a dielectric medium

Author(s)/ Year	Workpiece material(s)	Technique(s)/ Equipment's	Objective(s)	Findings/ Discovered
Khatri et al./ 2017 [102]	Ti-6Al-4 V	Rapid prototyping machine, Ultrasonic horn	Concentric flow dielectric dry WEDM agitated with ultrasonically	From the experiments it results, that overall performance is better compared to conventional one.

3. SUMMARY OF LITERATURE SURVEY

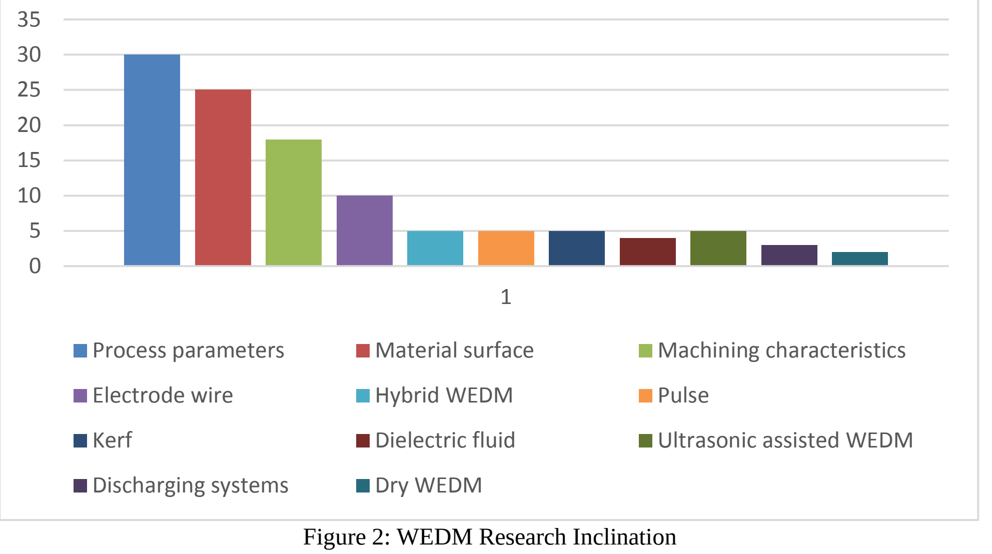

Figure 2: WEDM Research Inclination

Figure 2 shows the summary of the literature survey. Most authors concentrated on influence of the parameters in the process, modeling of machining characteristics and evaluation of product quality and machining efficiency.

For better surface finishing, precision machining, close tolerances and economic machining of complexed parts, the WEDM will be used.

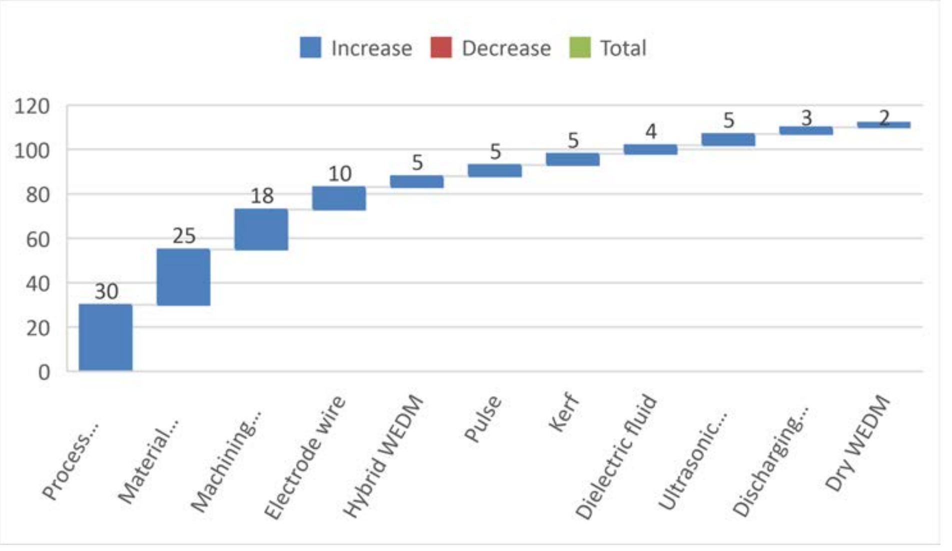

Figure 3: Exponential Growth of WEDEM

Because of the above reasons from figure 3: the WEDM has become commonplace in most of the industries. The techniques used to optimize machining conditions to get good surface roughness are the following: design of experiment, hybrid, fuzzy logic, gray rational analysis, artificial intelligence etc. Presently, WEDM is widely used for machining of precision parts with accuracy; high productivity, surface finish and tolerances are required. The understanding of the WEDM process parameters and their relation on the performance parameters are still limited and yet to be studied.

4. RESEARCH GAPS AND FUTURE SCOPES

1. Experimentally study on newly developed Materials by changing the process parameters, optimization of parameters and using different wires for cutting material to address the performance parameters for effective use of precision WEDM machining.
2. Wire lag effect by changing the parameters and Thermal distribution effects, Concavity and Tolerance analysis of machined parts while cutting the material by using different wires.
3. Analysis on Dry WEDM by using different gases, changing the gas supply nozzle position and correlate the effect of different gases on different wires while cutting.
4. Work on assisted WEDM like Ultrasonic vibration given to workpiece, wire or dielectric fluid and combined with Magnetic field, Auxiliary electrode, Coated materials etc.,
5. Study on Hybrid WEDM by using abrasives coated wire as electrode to investigate surface characteristics, MRR, thermal distribution of abrasives on workpiece, wire rupture etc.,
6. Adopting the Mechatronic system approach like discharge pulse probability, adaptive control systems etc., to get better cutting speed with good accuracy.
7. Use different dielectric fluids like mix-deionized water with any liquid, powder, any subsequent fluid and changing the supply system like workpiece dipped in to dielectric or nozzle supply while cutting different materials to find better one.
8. Changing the electrode wire with different diameters, different materials with coated also and varying its tension, varying length of the wire guides while cutting to find suitable one.

9. Adopting artificial intelligence into WEDM to make better machining than at present.
10. The applications of new techniques for Modeling and Optimization of WEDM like TLBO, AHP, TOPSIS, BWM, COCOSO etc., may get right decision of process parameters.

5. CONCLUSIONS

WEDM is an unconventional machining method that is generally used to cut variety of shapes with good accuracy. Low cutting speed is a drawback of the technique compared to the other cutting techniques. However, the primary goal of the WEDM method is to obtain accuracy with efficiency in cutting. Hence, several researchers have made different studies to enhance the performances in WEDM technique. It was observed that the wire condition has more significance on the performance of machining. This performance concerns an accuracy of the cutting. Good wire condition need to be maintained by monitoring machining parameters such as peak current, pulse on time, open circuit voltage, wire feed rate, dielectric flow rate etc. Hence, it is required to investigate the effect of the process parameters on machining characteristics in order to select the optimum process parameters for high performance in machining.

The most important goal of this article is to spotlight predominant research observations on WEDM. Precursory lookup research targeted on procedure modeling, dielectric fluid, setting the best process parameters, workpiece/tool electrode materials etc. The modern evaluation review stated that WEDM modeling procedure was regarded as key goal.

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