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Optimization Studies in CNC Wire Cut EDM: A Review

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ABSTRACT

CNC Wire cut electrical discharge machining (WEDM) has become an important non-traditional machining process which is used to manufacture intricate shapes with great accuracy and good surface roughness. Due to large number of process parameters and response characteristics, lots of researchers have attempted to model and optimize the process. This paper reviews the research trends in relation between different process parameters and different performance measures including Surface roughness (Ra),material removal rate (MRR), Dimensional deviation (DD), kerf width (KW) and wire wear ratio (WWR). In addition, this paper highlights different optimization methods and discusses their role in CNC WEDM process.

Introduction

In recent times, industries which manufacture tools, dies, molds and metal-workings, are in need of materials which as high resistance, high wear and tear, hardness, strength and toughness. Hence development of new materials like titanium, Inconel, ceramics, zirconium, stainless steel, hastalloy, carbides, nitralloy and many other high strength temperature resistant alloys are widely used in automobile, aerospace, medical, defense, tool and die manufacturing industries. For such materials, machining by conventional process is difficult and sometimes impossible. Thus, non-conventional processes are applied instead of traditional methods for extremely hard and brittle materials. Non-traditional manufacturing processes are classified by their distinct machining mechanisms. One such non-conventional process is Wire cut electrical discharge machining (WEDM).

WEDM is a thermo-electrical process in which material is eroded by series of sparks between work piece and the wire electrode (tool). A continuously travelling wire electrode made thin copper, brass or tungsten of diameter 0.05-0.30 mm. Wire path is programmed by the user and controlled by the NC machine.

This paper mainly focuses on the major WEDM research activities, which include the process optimization governed by the various process parameters such as Pulse ON Time, Pulse OFF Time, Peak current, Wire tension, Wire feed rate, Servo voltage, dielectric fluid and Flushing Pressure. These process parameters have most influence on the performance measures like Material removal rate, Surface roughness, Wire wear rate, Kerf width and Dimensional deviation.

2. Process Parameter of WEDM

Figure 1 shows the Ishikawa cause and effect diagram to identify the process parameters that may affect the machining performance of WEDM machined parts.

2.1 Pulse on time (T_{ON})

The pulse on time (T_{ON}) represents the duration of time in micro seconds, µs. During this time, Electrical discharge occurs between workpiece and the electrode wire. During this time the voltage (VP), is applied across the electrodes. For getting long discharge, large value of ON time to be selected.

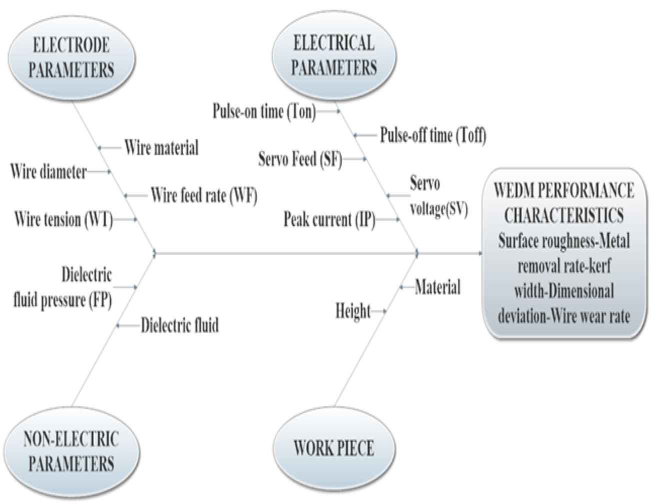

Figure 1. Ishikawa Cause and Effect Diagram for WEDM Process.

2.2 Pulse off time (T_{OFF})

The pulse off time (T_{OFF}) represents the duration of time in Micro Seconds, µs. During this time no voltage is applied consequently no electric discharge between the workpiece and wire electrode takes place. Low value of discharge leads to wire breakage and due to this cutting efficiency also reduces.

2.3 Peak Current (IP)

The peak current is represented by IP and it is the maximum amount of current flowing through the circuit during pulse on time. It is measured in amperage. This parameter actually reveals how much power is used in WEDM. Higher value of peak current is required for roughing operations and cutting rate also increases with increase in peak current.

2.4 Servo voltage (SV)

This parameter actually controls the wire movement i.e. (advancing and retracting). So if SV is applied more, than gap between wire electrode and workpiece will be wider and hence

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electric spark will be less and machining rate will be low. If SV is less, less gap is found, so electric sparks are more then automatically machining/cutting rate will be more.

2.5 Wire Tension (WT)

Wire tension controls how much the wire is to be stretched between upper and lower wire guides. This is a gram-equivalent load with which the continuously wire feed is kept under tension so that it remains straight between the wire guides. More the thickness of job more is the tension required. Improper setting of tension may result in the job inaccuracies as well as wire breakage.

2.6 Wire feed (WF)

Wire feed is the amount at which the wire-electrode travels along the wire guide path and it fed continuously between the wire guides.

2.7 Dielectric fluid

Dielectric fluid is indispensable parameter of WEDM. It is used to cool the wire and flush off the debris from the gap. Distilled water is the commonly used dielectric fluid for WEDM.

2.8 Flushing Pressure

Flushing Pressure is a selection of flushing input pressure of the dielectric. The flushing pressure range on this machine is either 1 (High) or 0 (low). High input pressure of water dielectric is necessary for cutting with higher values of pulse power and also while cutting the work piece of more thickness. Low input pressure is used for thin work piece and in trim cuts.

3. Performance measures of WEDM

Lot of researchers experimentally attempted to use the above different combinations of WEDM process parameters to enhance the performance measures (Material removal rate, Surface roughness, Spark gap, Kerf width, wire wear ratio, Dimensional deviation) of WEDM Hence selection of optimal machining parameters plays an important role for obtaining higher cutting speed, maximum material removal rate, minimum kerf width, lower dimensional deviation and minimum surface roughness.

3.1 Material Removal rate (MRR)

Material removal rate is a very important parameter which influences productivity of any process. As MRR increases, the economic benefits of using WEDM will be worthy for any firm. This factor depends upon number of input parameters which are related with WEDM. Lot of research had been done in past to maximize the MRR by different models and approaches. MRR is generally can be calculated using following equation:

$$\mathbf{MRR = V_C \times b \times h \quad m^3/sec}$$

Where,

V_C - cutting speed in m/sec

b -width of the cut in m

h -height of the workpiece in m

3.2 Surface Roughness (Ra)

Surface roughness is also the very important parameter whose value is required to be minimized. To obtain good surface roughness, certain factors need to be controlled and these are electrical parameters, dielectric fluid, work piece material. Researchers suggest that with increase of discharge energy, roughness of machined surfaces also increases. As larger discharge energy will produce larger crater & hence larger value of surface roughness on the workpiece would be formed.

3.3 Kerf width (KW)

Kerf width represents the amount of material removed or wasted during machining. Dimensional accuracy of finished part is decided by kerf. It is calculated using the following relation:

Kerf width = 2{Sparking gap} + wire diameter

3.4 Dimensional deviation (DD)

Dimensional deviation is the geometrical error done in the machined workpiece. Researches had been done in past to minimize the dimensional deviation. Dimensional deviation is obtained by following equation:

$$DD = \frac{\text{Observed value} - \text{Actual value}}{\text{Actual value}} \times 100$$

3.5 Wire wear rate (WWR)

Researchers tried to minimize the wire wear ratio by different approaches, because this factor can help to decrease the wire rupture. Wire wear rate is obtained by following equation:

$$WWR = \frac{FWW - IWW}{IWW}$$

Where,

FWW= Final wire wear

IWW= Initial wire wear

4. Taxanomy of Optimization in Wire Cut Edm Process

The general goal of the optimization is to find a solution that represents the global maximum or minimum of a fitness function. Most of the problems in engineering, industry, and many other fields, involve the simultaneous optimization of several objectives.

4.1 Traditional Approach

Traditional methods are used to find the optimum solution of continuous & differentiable functions. These methods are analytical and provide a good understanding of the properties of the minimum & maximum points in a function. Some of the traditional methods are Taguchi orthogonal array, Response surface methodology and mathematical formulation.

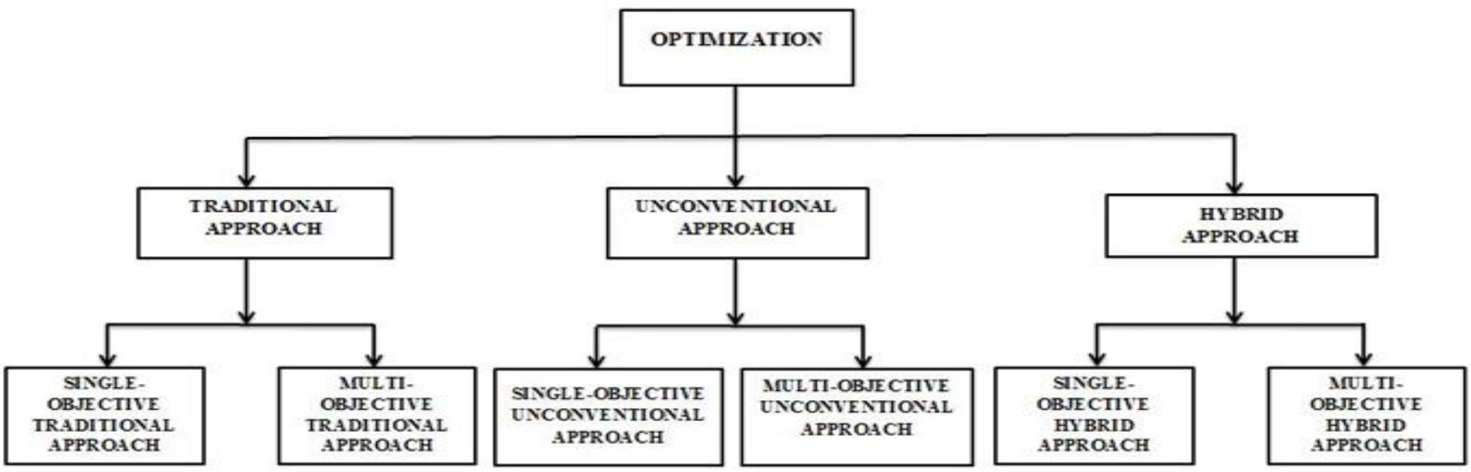

Figure 2. Taxonomy of optimization in Wire cut EDM process.

4.2 Unconventional Approach

The unconventional approaches had been recognized as a prominent technique. Now a day's it is used to solve the problem of combinational issues of process parameters. Based on the literature in history, it is observed that unconventional techniques are used in literature by more in number such as Simulated Annealing algorithm (SAA), Tabu Search (TS), Particle Swarm Optimization (PSO), Sheep Flock Heredity Algorithm (SFHA), Music Based Harmony Algorithm (MBHA), Ant Colony Algorithm (ACO) and Glow Warm Algorithm (GWA).

4.3 Hybrid Approach

Hybrid methods attempt to combine the beneficial features of two or more algorithms, and can be powerful methods for solving challenging non convex optimization problems. Some of the optimizations done using hybrid methods are ANN-Genetic algorithm, ANFIS-ABC algorithm, Taguchi-grey relation method, ANN-Non dominated sorting algorithm and ANN-Particle swarm optimization.

The above approaches are further classified based on their objectives; single objective and multi-objective optimization.

4.4 **Single Objective**

In an optimization problem of modelling a physical system that involves only one objective, then the task of finding the optimal solution is called single optimization. In single-objective optimization, it is possible to determine between any given pair of solutions if one is better than the other. As a result, usually obtain a single optimal solution.

4.5 Multiple Objectives

In many cases, the objectives are different in nature, and they are conflict among them. These problems are called Multi-objective Optimization Problems.

Multi-objective optimization does not exist in a straight forward method to determine if a solution is better than other. The method most commonly adopted in multi objective optimization to compare solutions is the one called Pareto dominance relation which, leads to a set of alternatives with different trade-offs among the objectives. These set of solutions are termed as Pareto optimal solutions or non-dominated solutions.

Therefore, in the multi-objective optimization process there are two distinguish tasks, namely: i) find a set of Pareto optimal solutions, and ii) choose the preferred solution out of this set. To do this, researchers have used two main approaches. The first is called the Multi-Criteria Decision Making (MCDM) approach which can be characterized by the use of mathematical programming techniques and a decision making method in an intertwined manner and the second one is Evolutionary Multi-objective Optimization (EMO). This approach is useful to solve multi objective optimization problems. Since evolutionary algorithms use a population based approach, they usually find an approximation of the whole Pareto front in one run.

5. Literature Review

Over the years, the WEDM has remained as a competitive and economical machining process. A significant amount of research has been done using the different methodologies for achieving the ultimate WEDM goals of optimizing the process parameters analytically with the complete elimination of the wire breakages. For better understanding, a detailed literature survey has been carried out by considering the effects of process parameters on the performance measures such as surface roughness, MRR, Kerf width, cutting speed, Wire wear ratio and Dimensional deviation, in various classes of work material.

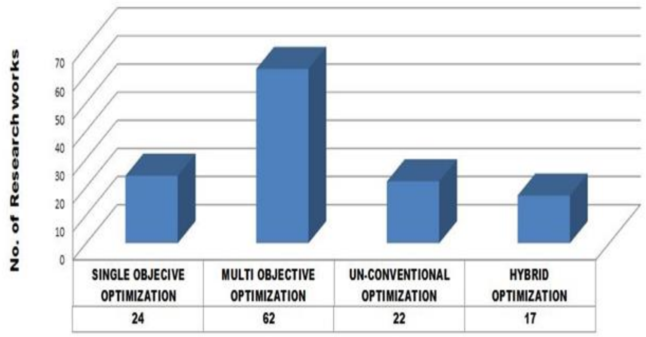

Figure3. Various optimization researches carried out in WEDM.

Figure 3 shows the various types of optimization techniques to optimize the process parameters and their numbers. The literature review is classified into four sections. First and the second sections deal with work related to single and multi-objective using WEDM. Third section highlights WEDM carried out using unconventional optimization techniques. Finally, fourth section deals with hybrid optimization.

Summary

This paper reveals that a substantial amount of work on different aspects of machining with WEDM has been reported. On the basis of literature review, following inference have been identified:

Optimization of process parameters such as pulse on time, servo voltage, peak current, wire feed, wire tension, pulse off time, dielectric fluid, flushing pressure and table feed plays a vital role in obtaining different desired performance measures such as surface roughness, material removal rate, kerf width, spark gap, wire wear ratio and dimensional deviation. The technology charts or operator reference manuals are not providing optimal process parameters which are to be set in the machine. The values of optimal process parameter varies material to material that makes the system more complex in nature. Hence, there is a need to generate optimal sets of process parameters satisfying the number of performance measures. In recent days very few researchers have made an attempt on single objective optimization because the need becomes multi-objective such as maximum material removal rate and minimum surface roughness. Most of the researchers have carried out multi objective optimization using traditional optimization techniques such as Taguchi method, min-max method, response surface methodology (RSM), weighted method. Multi objective optimization of process parameters is needed to be done using some evolutionary optimization techniques such as Artificial bee optimization, Ant colony optimization, Genetic algorithm, Sheep flock algorithm, Bio-geography based algorithm, Artificial neural network, Particle swarm optimization and Non-dominated sorting algorithm for better results. The above said algorithms were hybridized with Traditional or unconventional optimization techniques in order to increase the accuracy of the prediction of optimal process parameters. The hybridized algorithms utilized by different researchers are Taguchi-grey relation method, ANN-Genetic algorithm, ANFIS-ABC algorithm, ANN-Non dominated sorting algorithm and ANN-Particle swarm optimization.

Traditional approach

Single-Objective traditional approach

S.No	Author & Year	Machine	Materials	Process Parameters	Performance Measures	Methodology	Findings	Reference No.
1	Dain Thomas et al. (2015)	Sprintcut WEDM machine	Wire: Zinc coated brass wire Work piece: EN31 steel	*Pulse-on time *Pulse-off time *Wire tension *Peak current	*Material removal rate	Response surface methodology (RSM)	* From this work it is clear that major influence on MRR have been found to be pulse-on time and pulse-off time.	[22]
2	Giovanna Gautier (2015)	Not Mentioned	Wire: Brass wire Work piece: γ- titanium alloy	*Pulse-on time *Wire tension *Servo voltage	*Surface roughness	ANOVA and regression models	*It was found that lower values of T_{ON}, T_{OFF} and WT gives the highest Surface roughness.	[34]
3	Mohd Shahir Kasim et al. (2015)	Mitsubishi RA90 series CNC WEDM	Wire: Brass wire Work piece: Inconel 718	*Servo voltage *Wire feed rate *Current	*Surface roughness	Response surface methodology (RSM)	* Best Ra of 2.797μm (horizontal) and 2.806μm (vertical) by the combination of SV=42 v, WF=1.44mm/min and I=6A.	[53]
4	Baljit Singh et al. (2014)	Eco-cut CNC WEDM	Wire: Molybdenum wire Work piece: Titanium alloy	*Peak current *Pulse-off time *Servo voltage *Wire feed rate *Wire tension *Pulse-on time	*Material removal Rate	Taguchi approach	*Best MRR obtained when T_{ON}=120μs, T_{OFF}=55μs, WT=1300g, SV=80 v, WF=15mm/min and I=6A.	[15]
5	Brajesh Kumar Lodhi et al. (2014)	Electronica supercut 734 WEDM	Wire: Brass wire Work piece: AISI D3 steel	*Peak current *Pulse-off time *Wire tension *Pulse-on time	*Surface roughness	Taguchi approach	*Error associated with Surface roughness is 3.042% obtained when T_{ON}=18μs, T_{OFF}=51μs and IP=180A.	[19]
6	Kashid DV et al. (2014)	Sprintcut Elpuls 40 A Dlx	Wire: Brass wire Work piece: EN9 steel	*Pulse-on time *Pulse-off time *Wire feed rate	*Material removal rate	Taguchi method	*It is found that the pulse-on time (T_{ON}) and pulse-off time (T_{OFF}) are the most influencing parameters for material removal rate.	[43]

7	Kumar K et al. (2014)	Sprintcut 734 CNC WEDM	Wire: Molybdenum wire Work piece: Al-Sic	*Pulse-on time *Pulse-off time *Wire speed *Wire feed	*Surface roughness	Taguchi method	*Minimum surface roughness 1.257μm is achieved when T_{ON}=104 μs, T_{OFF}=42 and WF=0.5m/min.	[45]
8	Nandakumar C et al. (2014)	Electronica CNC WEDM	Wire: Zinc coated brass wire Work piece: Titanium Alloy grade 5	*Pulse-on time *Pulse-off time *Wire feed *wire feed rate	*Surface roughness	Taguchi method L18 orthogonal array	*From this work the minimum surface roughness of 1.8825 μm is achieved when T_{ON}=5 μs, T_{OFF}=8μs, WT=1000g and WF=3mm/min.	[60]
9	Parveen Kr Saini and Mukesh Verma (2014)	Elektra sprintcut734	Wire: Brass wire Work piece: Titanium alloy	*Gap voltage *Wire feed rate *Pulse time *Wire tension *Pulse width	*Material removal rate	Taguchi approach	* It is found that best MRR observed when V_G=20v, WF=4m/min, T=5μs, WT=0.5daN and PW=1.2μs.	[65]
10	Pratik A Patil et al. (2014)	Fine Sodick Mark Exedw	Wire: Brass wire Work piece: AISI D2 steel	*Pulse-on time *Wire tension *Peak current	*Material removal rate	Response Surface Methodology	*MRR increases as the peak current increases and MRR is influenced by the wire tension and pulse-on time.	[70]
11	Shinde VD et al. (2014)	Electronic Elcut CNC WEDM	Wire: Molybdenum wire Work piece: AISI D3 Tool steel	*Pulse-on time *Pulse-off time *Peak current *Wire speed	*Surface roughness	Taguchi approach	*The wire speed and pulse-on time shows strongest correlation to surface roughness as compared to current and pulse-off time	[100]
12	Singh H and Garg R (2009)	Electronica sprintcut CNC WEDM	Wire: Brass wire Work piece: H-11 die steel	*Pulse-on time *Pulse-off time *Gap voltage *Wire feed rate *Wire tension *Peak current	* Material removal rate	Taguchi approach	*It is found that MRR increases with increase in IP and T_{ON} while decreases with increase in T_{OFF} and SV	[101]
13	Rajesh Kumar et al. (2013)	omnicut CNC WEDM	Wire: Brass wire Work piece: EN24 steel	*Pulse-on time *Pulse-off time *Park gap voltage *Gap current	*Material removal rate	Taguchi method	*Best MRR of 28.25mm^3/min observed when SV=30v, T_{ON}=125μs and T_{OFF}=40μs.	[74]
14	Shah CD et al. (2013)	DK-7720 CNC WEDM	Wire: Molybdenum wire Work piece: Inconel-600	*Wire speed *Peak current *Pulse-on time *Pulse-off time	*Material removal rate	Taguchi L18 orthogonal array	*Pulse-on time, Pulse-off time and peak current are the influencing parameter on material removal rate	[97]

15	Subrahmanyam SV and Sarcar MMM (2013)	ELPULS 40A CNC WEDM	Wire: Brass wire Workpiece: EN-31	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Wire feed *Servo feed *Fluid pressure	*Surface roughness	Taguchi L36 orthogonal array	* It is found that Ra is 2.48μm obtained when T_{ON}=128μs, T_{OFF}=53μs, WF=4 m/min, SV=20 v, WT=2 Kilograms and IP=230A.	[105]
16	Abinash Kumar Swain et al. (2012)	Electra wirecut EDM	Wire: Brass wire Workpiece: Tungsten carbide	*Servo voltage *Spark on time *Spark off time *Capacitance	*Kerf width	Taguchi method	*Machining voltage is the most significant parameter for controlling the kerf width.	[2]
17	Basil Kuriachen et al. (2012)	Electronica ultracut	Wire: Brass wire Work piece: Titanium(grade 5)	*Pulse-on time *Pulse-off time *Voltage *Dielectric pressure	*Surface roughness	Mathematical model	*It is found that minimum surface roughness is obtained when T_{on}=20μs and dielectric pressure=15 kgf/cm^3.Prediction error obtained using this model is 7%.	[16]
18	Anish Kumar, Vinod Kumar and Jatinder Kumar (2012)	Electronica supercut 734 WEDM	Wire: Brass wire Work piece: Titanium	*Pulse-off time *Peak current *Pulse-on time *Wire feed *Wire tension	*Surface roughness	Response surface methodology	*It is found that Ra is 2.48μm obtained when T_{ON}=112μs, T_{OFF}=56μs, WF=7 m/min, SV=60 v, WT=980 grams and IP=120A.	[11]
19	Rajendran S and Marimuthu K (2012)	Electra Sprintcut 734	Wire: Brass wire Work piece: T90Mn2W50Cr45 Tool steel	*Pulse-on time *Pulse-off time *Peak current *Wire tension	*Material Removal Rate	Response surface methodology	*Pulse-on time is directly proportional to the material removal rate whereas wire tension is inversely proportional to the material removal rate.Material removal rate was optimized at 0.5 for the optimum value of peak current (200A) and wire tension of (7.5g).	[73]
20	Sivakiran S et al. (2012)	Omnicut CNC WEDM	Wire: Molybdenum wire Work piece: EN31 steel	*Pulse-on time *Pulse-off time *Bed speed *Current	* Material removal rate	Taguchi's $_{L16}$ approach	* It is found that best MRR observed when T_{ON}=24μs, T_{OFF}=6μs, BS=35 and I=5A.	[102]
21	Abdulkareem S et al. (2011)	Mitsubishi WEDM	Wire: Brass wire Work piece: SUS 304 steel	*Pulse-on time *Pulse current *Gap voltage	*Surface roughness	Full factorial design	*Wet wire EDM gives better surface integrity compared to dry wire-EDM. *Increase of pulse current and gap voltage also contributes poor surface integrity	[1]
22	Islam M N et al. (2010)	Fanuc robocut machine	Wire: Brass wire Workpiece:	*Pulse duration *Wire speed *Wire tension * flow rate	*Dimensional accuracy	Taguchi L27 orthogonal array	*Wire tension is the greatest affecting parameter on dimensional accuracy characteristics like linear error, flatness error and perpendicularity error.	[39]

			Mild steel 1040	*Discharge current				
23	Vishal Parashar et al. (2010)	Ezeecut plus WEDM	Wire: Brass wire Work piece: Stainless steel 304L	*Gap voltage *Pulse-on time *Pulse-off time *Wire feed *Flushing pressure	*Material removal rate	Regression analysis method	*From this results, material removal rate depends on gap voltage, pulse-on time and pulse-off time.	[122]
24	Kanlayasiri K and Boonmung S (2007)	Sodick model A280	Wire: Brass wire Workpiece: DC53 cold die steel	*Pulse-peak current *Pulse-on time *Pulse-off time *Wire tension	*Surface roughness	Regression analysis	*It is found that maximum prediction error of the model is less than 7% and the average percentage error of prediction is less than 3%.	[41]

Multi-Objective Traditional Approach

S.NO	AUTHOR & YEAR	MACHINE	MATERIALS	PROCESS PARAMETER	PERFORMANCE MEASURES	METHODOLOGY	FINDINGS	Reference No.
1	Alpesh M Patel and Vishal Achwal (2015)	Electronica 5535-R50 ZNC series CNC WEDM	Wire: Brass wire Work piece: Aluminum A1050A	*Discharge voltage *Wire feed *Wire tension *Discharge current	*Electrode wear rate *Material removal rate	Taguchi's L_9 orthogonal approach	*It is found that maximum MRR of 0.041 gm/min and minimum EWR obtained when (V=35volt, WF=6m/min, WT=6N and IP=4A).	[7]
2	Amitava Mandal et al. (2015)	Elektra maxicut 734 CNC WEDM	Wire: Zinc coated Brass wire Work piece: Nimonic C-263 super alloy	*Pulse-on time *Pulse-off time *Servo voltage *Dielectric flow rate	*Cutting rate *Spark gap *wire wear ratio *surface roughness	Response surface methodology (RSM)	*It is found that maximum CR of 2.224 mm/min and minimum spark gap of 40µm obtained when (T_{ON}=1.35 µs, T_{OFF}= 120 µs, SV=35 volts and FR=4 liters/min), minimum Ra of 1.38 µm obtained when (T_{ON}=0.95 µs, T_{OFF}= 200 µs, SV=75 volts and FR=8 liters/min) and the maximum WWR of 0.765 obtained when (T_{ON}=1.35 µs, T_{OFF}= 120 µs, SV=75 volts and FR=8 liters/min).	[9]
3	Bijender Singh et al. (2015)	Electronica sprintcut CNC WEDM	Wire: Brass wire Work piece: Stainless steel 410	*Pulse-on time *Pulse-off time *Wire tension *Wire feed	*Material removal rate *Surface roughness	Taguchi & regression analysis	*Maximum MRR of 4.2 mm^3/sec obtained when (T_{ON}=131µs, T_{OFF}=50µs, WF=4m/min and WT=11g) *Minimum Ra of 3.74µm obtained when (T_{ON}=121µs, T_{OFF}=55µs, WF=5m/min and WT=9g).	[17]
4	Chengal Reddy V, Deepthi N and Jayakrishna N (2015)	Not Mentioned	Wire: Brass wire Work piece: Aluminium HE30	*Wire tension *Peak current *Pulse-off time *Pulse-on time	*Material removal rate *Surface roughness	Taguchi & regression analysis	*From the results it shows that GRA method is effective tool for optimization and optimal machining conditions obtained are T_{ON}=112µs, T_{OFF}=61µs, IP=11A and WT=780gm.	[20]
5	Dhruvh H Gajjar et al. (2015)	Electronica sprintcut CNC WEDM	Wire: Molybdenum Work piece:	*Pulse-on time *Pulse-off time *Servo voltage	*Material removal rate *Surface roughness	Response surface methodology (RSM)	*Best MRR, KW and Ra are obtained when T_{ON}=130µs, T_{OFF}=60µs and SV=30 volts.	[25]

			EN-31 tool steel		*Kerf width			
6	Dodun Oano et al. (2015)	Japax L250A CNC WEDM	Wire: Not Mentioned Work piece: Alloyed steel205Cr115	*Wire speed *Pulse-off time *Pulse-on time *Wire tension.	*Cutting speed *Surface roughness *Wire wear ratio	Grey relation analysis (GRA) and Taguchi approach	* Best CS, WWR and Ra are obtained when T_{ON}=0.5µs, T_{OFF}=0.066µs and I=0.5A.	[27]
7	Ganesh Dongre et al. (2015)	Not Mentioned	Wire: Molybdenum Work piece: Silicon wafer	*Peak current *Duty cycle *Work piece height *Wire diameter	*Kerf loss *Slicing speed *Surface roughness	Response surface methodology (RSM) approach	*Optimization of kerf loss (50µm), slicing speed (2.5mm/min) is obtained when peak current=1A, Wire diameter=40µm and duty cycle=50%.	[31]
8	Milton Peter J et al. (2015)	Ezeecut Plus EZ-01 WEDM	Wire: Brass wire Work piece: Inconel 718	*Pulse-on time *Pulse-off time *Wire feed *Gap voltage	*Material removal rate *Surface roughness	Taguchi method	*Pulse-on time is the most significant parameter for material removal rate, while the gap voltage has the most influences on surface roughness.	[52]
9	Nagaraja R et al. (2015)	Not Mentioned	Wire: Not Mentioned Work piece: Bronze alumina alloy	*Pulse-on time *Pulse-off time *Wire feed	*Material removal rate *Surface roughness	Taguchi method	*To achieve the Ra and MRR are T_{ON}=10µs, T_{OFF}=5µs and WF=2m/min.	[57]
10	Naga Raju B et al. (2015)	Ultracut CNC WEDM ,	Wire: Not Mentioned Work piece: Aluminium MMC	*Pulse-on time *Pulse-off time *Peak current	*Material removal rate *Surface roughness	Response surface methodology (RSM)	* It is found that maximum MRR is 0.8790 mm^3/min and the minimum Ra is 0.9640µm obtained when T_{ON}=100µs, T_{OFF}=55µs and IP=11.86A.	[58]
11	Nandakumar C et al. (2015)	Electronica CNC WEDM	Wire: Zinc coated brass Work piece: Titanium	*Pulse-on time *Pulse-off time *Wire feed	*Material removal rate *Surface roughness	Response surface methodology	*Maximum MRR of 0.6623g/min and the minimum Ra of 0.3734µm obtained when T_{ON}=3.4545µs, T_{OFF}=4.1761µs and WF=1m/min.	[59]
12	PrashantSinha et al. (2015)	Sprintcut WEDM machine	Wire: Zinc coated Brass wire Work piece: AISI D3 steel	*Servo voltage *Pulse-on time *Pulse-off time *Peak current	*Material removal rate *Surface roughness	Taguchi method	*It is found that servo voltage, pulse on time and peak current are significant factor for Material removal rate, while peak current and servo voltage for surface roughness.	[69]
13	Ramamurthy A et al. (2015)	Electrika CNC WEDM'	Wire: Not Mentioned Work piece: Titanium alloy	*Pulse-on time *Pulse-off time *Servo voltage *Wire material *Peak current	*Material removal rate *Surface roughness	Taguchi and grey relation analysis	*It is found that maximum MRR is 0.0025 mm^3/min and the minimum Ra is 2.095µm obtained when T_{ON}=30µs, T_{OFF}=90µs, SV=80V and IP=4A.	[77]
14	Ramamurthy A et al. (2015)	Electrika CNC WEDM'	Wire: Not Mentioned	*Pulse-on time *Pulse-off time *Wire tension	*Material removal rate *Surface	Grey relation analysis and Taguchi	*Maximum MRR is 159.1574 mm^3/min and the minimum Ra is 2.567µm obtained when T_{ON}=110µs, T_{OFF}=30µs and WT=7kg.	[78]

			Work piece: Titanium alloy		roughness			
15	Sachin Dev Barman et al. (2015)	Electronica elpuls 40A sprintcut WEDM	Wire: Brass wire Work piece: Tungsten carbide	*Pulse-on time *Pulse-off time *Peak current *Wire feed rate	*Cutting rate *Surface roughness	Grey Relation Analysis (GRA) and Taguchi approach	*GRA method is effective tool for optimization and optimal machining conditions obtained are T_{ON}=18µs, T_{OFF}=40µs, IP=200A and WF=7m/min.	[86]
16	Sivaraman B et al. (2015)	Maxicut WEDM	Wire: Brass wire Work piece: Titanium	*Pulse-on time *Pulse-off time *Gap voltage *Wire tension *Wire feed rate *Table feed	*Surface roughness *Material removal rate	Taguchi approach	*From the optimization, it is found that maximum MRR of 0.823 g/min and minimum Ra of 1.687 µm obtained when (T_{ON}=5 µs, T_{OFF}= 7 µs, GV=5 volts, WT= 900g, WF=7m/min and TF=6 mm/min	[104]
17	Suresh Babu S et al. (2015)	Ezeecut plus WEDM	Wire: Not Mentioned Work piece: Not Mentioned	*Pulse-on time *Pulse-off time *Peak current	*Surface roughness *Material removal rate	Taguchi's L_{18} orthogonal array	*Maximum MRR is obtained when T_{ON}=36µs, T_{OFF}=6µs and IP=3A, and the minimum Ra is obtained when T_{ON}=34µs, T_{OFF}=7µs and IP=1A.	[107]
18	Takalae AM et al. (2015)	Electronica Sprintcut 734 CNC WEDM	Wire: Not Mentioned Work piece: AISI 304 steel	*Pulse-on time *Peak current .	*Surface roughness *Material removal rate	Taguchi method	*It is found that the pulse-on time and peak current increases with increase in MRR and surface roughness increases, as pulse-off time (T_{ON}) increases.	[110]
19	Vinod Kumar et al. (2015)	sprintcut WEDM	Wire: Zinc coated brass wire Work piece: Monel-400	*Discharge current *Pulse-on time *Pulse-off time *Servo voltage	*Material removal rate *Surface roughness	Response Surface Methodology	*From the work it is clear that highest desirability of MRR and Ra is achieved by setting parameters like IP=103 A, T_{ON}=113 µs, T_{OFF}=37 µs and SV=50 V.	[121]
20	Vivek Aggarwal et al. (2015)	Elektra sprintcut 734'	Wire: Zinc coated brass wire Work piece: Inconel 718	*Wire tension *Pulse-on time *Pulse-off time *Wire feed *Servo voltage	*Cutting rate *Surface roughness	Response Surface Methodology	*From the work it is clear that highest CR 2.55 mm/min and lower surface roughness 2.54µm is obtained when T_{OFF}=14µs, WF=5.97g, SV=16v, WT=691.78g, T_{ON}=0.62µs and IP=210 A.	[123]
21	Amitesh Goswami and Jatinder Kumar (2014)	Electra- Elpuls 40A DLX CNC	Wire: Brass wire Work piece: Nimonic-80A	*Pulse-off time *Peak current *Pulse-on time *Wire feed *Wire tension	*Metal removal rate *Surface roughness	Taguchi L27orthogonal array.	*It is found that MRR and Ra increases with increase in pulse-on time and decreases with increase in pulse-off time.	[10]
22	Arjun Biloria and Rupinder Singh (2014)	Not Mentioned	Wire: Brass wire Work piece: EN31 steel	*Servo voltage *Discharge current *Wire tension	*Cutting width *Metal removal rate *Surface roughness	Taguchi L9 orthogonal array.	*It is found that IP has a greater influence on the MRR followed by voltage. *Wire tension had influence on MRR.	[13]
23	Dipti Ghanashyam Gonjari (2014)	Ezeecut plus CNC WEDM	Wire: Brass wire	*Pulse-on time *Pulse-off time	*Material removal rate	Taguchi's L_9 orthogonal array	*It is found that MRR and Ra are mainly affected by Pulse-off time (T_{OFF}) and Sensitivity (S).	[26]

			Work piece: AISI D7 material	*Wire Feed *Sensitivity	*Surface roughness			
24	Garg M P et al.(2014)	Electronica sprintcut 734 CNC WEDM	Wire: Diffused brass wire Work piece: Titanium alloy	*Pulse on time *Pulse off time *Peak current *Servo voltage *Wire feed *Wire tension	*Cutting speed *Surface roughness	Response surface methodology	*Cutting speed is found to increase with increase in T_{ON} and decrease in T_{OFF} and SV.	[32]
25	Selvakumar G et al. (2014)	Electra supercut 734 series 2000 CNC WEDM	Wire: Brass wire Work piece: 5083 aluminum alloy	*Wire tension *Pulse-on time *Pulse-off time *Peak current	*Cutting speed *Surface roughness	Taguchi approach	*CS was independent on wire tension and Ra was independent on pulse-off time and wire tension.	[95]
26	Sivanaga Malleswara Raouthor S and Parameswara Rao Ch VS (2014)	Elcut 334	Wire: Brass wire Work piece: 18-4-1 grade HSS	*Power input *Job thickness	*Surface roughness *Material removal rate	Mathematical model	*From the work it is clear that the maximum error obtained in the calculated values and experimental values are less than 2%.	[103]
27	Vedansh Chaturvedi and Anil Kumar Sharma (2014)	Ultracut-2F	Wire: Brass wire Work piece: OHNS steel	*Servo feed rate *Wire tension *Flushing pressure *Wire feed	*Material removal rate *Surface roughness	Taguchi method	*It is found that the optimum machining setting to achieve the Ra and MRR are WT= 1900grams, FP= 1.5 kg/cm^2, SF= 0.5mm/min and WF=8.5 m/min.	[118]
28	Vijaybabu T et al. (2014)	Electronica undercut CNC WEDM	Wire: Brass wire Work piece: Titanium	*Pulse-on time *Pulse-on time *Peak current *Pire tension *Servo voltage *Servo feed	*Material removal rate *Surface roughness	Taguchi approach	*It is found that best Ra observed when (T_{ON}=128µs, T_{OFF}=48µs, SV=30v, WT=6m/min and IP=220A) and best MRR observed when (T_{ON}=112µs, T_{OFF}=60µs, SV=70v, WT=6m/min and IP=150A).	[119]
29	Adeel ikram et al. (2013)	Not Mentioned	Wire: Brass wire Workpiece: Tool steel D2	*Wire feed *Pulse-on time *Pulse-off time *Open voltage *Wire tension *Servo voltage *Pressure	*Surface roughness *Kerf width *Material removal rate	Taguchi L18 orthogonal array	*It has been found that pulse-on time is the most significant factor affecting the surface roughness, kerf and material removal rate.	[4]
30	Danial Ghodsiyeh et al. (2013)	Sodick series AQ537L WEDM	Wire: Zinc-coated brass wire Work piece: Titanium alloy	*Pulse-on time *Pulse-off time *Peak current *Servo voltage	*Surface roughness *Sparking gap *Wire lag *Wire wear rate	Response surface methodology	*It is found that the optimum response is obtained when T_{ON}=6µs, T_{OFF}=8µs, SV=50V and IP=16 A.	[23]
31	Durairaj M et al. (2013)	Not Mentioned	Wire: Brass wire Work piece:	*Pulse-on time *Pulse-off time *Wire Feed *Servo voltage	*Surface roughness *Kerf width	Taguchi approach and Grey relation analysis (GRA)	*From the optimization, it is found that maximum MRR and min kerf width can be achieved when T_{ON}=4µs, T_{OFF}=4µs, V=50V and WF=2mm/min	[28]

			Stainless steel 304					
32	Farnaz Nourbakhsh et al.(2013)	Charmilles WEDM	Wire: Brass wire Work piece: Titanium alloy	*Pulse width *Servo voltage *Wire speed *Peak current *Wire tension	*Cutting speed *wire rupture *Surface integrity	Taguchi L18 orthogonal array	* From the work it is clear that MRR increases with increase of peak current and pulse width. *Surface roughness was found increase with pulse width and decrease with pulse interval.	[30]
33	Geetha M et al. (2013)	5 axis-CNC WEDM	Wire: Brass wire Work piece: Stainless steel 304	*Pulse-off time *Pulse-on time *Wire tension *Water pressure	*Material removal rate *Surface roughness	Response surface methodology	*It is found that the multiple regression coefficients (R^2) for Ra and MRR were found to be 0.888 and 0.966.	[33]
34	Lokeshwara Rao T et al. (2013)	Elektra Sprintcut 734	Wire: Brass wire Work piece: Titanium Grade 5	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Servo voltage	*Material removal rate *Surface roughness	Taguchi method	*The pulse time and peak current are the most influencing factor for performance Measures.	[47]
35	Meena KL et al. (2013)	Elektra opticut-434 CNC WEDM	Wire: Brass wire Work piece: (A1-6063)/silicon carbide (SiC)	*Pulse-on time *Pulse-off time *Servo voltage *Wire feed *Wire tension *Peak current	*Width of cut *Surface roughness *Material removal rate	Taguchi's L_9 orthogonal approach	*From the optimization, it is found that maximum MRR can be achieved at high value of mesh size.	[51]
36	Neeraj Sharma et al. (2013)	Electronica sprintcut 734 CNC WEDM'	Wire: Brass wire Work piece: HSLA	*Pulse-on time *Pulse-off time *Peak current *Wire tension	*Cutting speed *Dimensional deviation	Response surface methodology	*From the work it is clear that for both CS and DD, T_{ON} is the most significant process parameter.	[62]
37	Rajyalakshmi G and Venkata Ramaiah P (2013)	ultracut-2F CNC WEDM	Wire: Brass wire Work piece: Inconel 825	* Pulse on time *Pulse off time *servo voltage *wire tension *flushing pressure *servo feed rate *wire feed	*Material removal rate *Surface roughness *Spark gap	Taguchi L36 orthogonal array	*It is found that the optimum machining setting to achieve the Ra and MRR are T_{ON}=105µs, T_{OFF}=50µs, WT= 9kg-f, FP= 15 kg/cm^2, SF= 1100 mm/min and WF=2 m/min.	[75]
38	Ravindranadh Bobbili et al. (2013)	Ultracut WEDM	Wire: Zinc coated brass wire Work piece: High armor steel.	*Pulse-on time *Pulse-off time *Peak current *Wire tension	*Material removal rate *Surface roughness	Taguchi method	* From the results it is observed that, the pulse time and servo voltage is the most influencing factor for performance measures.	[81]
39	Sanjeev KR Garg et al. (2013)	Robofil-290 CNC wire EDM	Wire: Diffused wire Work piece: Al/Zro_2	*Pulse width * pulse time *Servo voltage *Wire feed rate, *Wire tension	*Cutting velocity *Surface roughness	Response surface methodology and grey relation techniques	*Grey relation analysis produce optimum percentage change in CV (5.85%) and Ra (13.37%). *Diffused wire electrode provides better results compared to brass wire electrode.	[88]

40	Taha A El-Taweel and Ahmed M Hewidy (2013)	CK-45 steel W-B30J.S CNC WEDM	Wire: Brass wire Work piece: AISI 304 steel	*Water pressure *Wire speed *Wire tension *Duty factor *Feeding speed	*Material removal rate *Tool wear rate *Surface roughness	Mathematical model	*From the work it is clear that MRR increases with increase of feeding speed, duty factor and water pressure. The effect of wire tension and wire speed on MRR is limited.	[109]
41	Yu Huang et al. (2013)	W-A530 WEDM	Wire: Brass wire Workpiece: Tool steel YG15	*Pulse-on time *Pulse-off time *Wire tension *Wire speed *Water pressure *Feed rate	*Surface roughness *Material removal rate	Taguchi L18 orthogonal array	*In this work comparison of rough and finish cutting is done based on the influencing parameters on surface roughness and material removal rate.	[124]
42	Aniza Alias et al. (2012)	Mitsubishi FX Series	Wire: Brass wire Work piece: Titanium	*Feed rate *Current *Wire speed *Wire tension *Voltage	*Surface roughness *Kerf width *Material removal rate	Not Mentioned	*Machine feed rate has proven to be the influencing parameter this work.	[12]
43	Boopathi S and Sivakumar K (2012)	CNC-E3-MCJ WEDM	Wire: Brass wire Work piece: M2 high speed steel	*Pulse-off time *Pulse-on time *Gap voltage *Air pressure *Discharge current	*Surface roughness *Material removal rate	Taguchi approach	*It is found that pulse-on time, discharge current and gap voltage are the parameters used to increase the material removal rate and to improve the surface finish.	[18]
44	Chockalingam K et al. (2012)	ROBOFIL 290P CNC WEDM	Wire: Brass wire Work piece: AISI T-15 HSS steel	*ap voltage *Pulse duration *Fluid pressure *Wire tension *Wire velocity	*Material removal rate *Surface roughness *Spark gap *Dimensional deviation	Taguchi design	*Pulse-off time (T_{off}) is more significant factor for multiple performance measures.	[21]
45	Goswami Amitesh et al. (2012)	Electronica Sprintcut CNC WEDM	Wire: Brass wire Work piece: Nimonic 80A	*Pulse-off time *Pulse-on time *Peak current *Spark gap set voltage	*Material removal rate *Cutting speed	Taguchi method	*Investigation indicates that the cutting speed and material removal rate, both increases with increase in pulse-on time and peak current, while decreases with increase in pulse-off time and spark gap set voltage.	[35]
46	Manoj Malik et al. (2012)	Not Mentioned	Wire: Zinc coated Brass wire Work piece: Tungsten carbide	*Pulse-on time *Duty factor *Pulse peak current	*Material removal rate *Electrode wear rate *Surface roughness	Grey-based Taguchi method	*From the optimization, it is found that pulse peak current is the most critical factor affecting EWR, MRR & Duty factor is the least significant parameter.	[50]
47	Rizauddin Ramli et al. (2012)	HQ-35F CNC WEDM	Wire: Brass wire Work piece: Tool steel grade D2	*Open circuit voltage *Pulse duration *Dielectric flushing pressure *Wire speed	*Material removal rate *Surface roughness	Taguchi method	*It is found that significant parameters contributed to the kerf width are OV (47%), T (20%) and WS (15%). *The average of kerf width from the three experiments was 0.255mm and from that, the error margin is only 1.53%, which satisfied our data.	[83]
48	Selvakumar G et al.	Electra supercut	Wire:	*Wire tension	*Material	Taguchi L18	*Surface roughness and Material removal rate are influenced by pulse-	[96]

	(2012)	734 series CNC WEDM	Brass wire Workpiece: Monel 400 alloy	*Flushing height *Job thickness *Corner angle *Pulse-on time *Pulse frequency *Peak current *Servo voltage	removal rate *Surface roughness *Corner error	orthogonal array	on time and peak current. *Corner accuracy is influenced by flushing nozzle height, job height and corner angles.	
49	Swati D Lahane et al. (2012)	Elektra CNC WEDM'	Wire: Copper wire Work piece: HSS steel	*Pulse-on time *Pulse-off time *Wire feed *Upper flush	*Material removal rate *Wire wear rate	Taguchi method weighted principle component method	*It is found that maximum MRR and the minimum WWR obtained when (T_{ON}=7µs, T_{OFF}=8µs, WF=7m/min and UF=8kg/cm^2).	[108]
50	Aqueel shah et al. (2011)	G43S CHMER EDM	Wire: Brass wire Workpiece: Tungsten carbide	*Open voltage *Pulse-on time *Pulse-off time *Servo voltage *Wire feed *Wire tension Dielectric pressure	*Material removal rate *Kerf width *Surface roughness	Taguchi orthogonal L27 design	*It is found that material thickness is the influencing parameter on material removal rate and kerf width. *To obtain a fine surface finish, the spark energy will have to be reduced	[14]
51	Sathishkumar D et al.(2011)	Electronica Ecocut 4-axis CNC WEDM	Wire: Brass wire Workpiece: Al6063/SiC_p	*Pulse-on time *Pulse-off time *Gap voltage *Wire feed	*Material removal rate *Surface roughness	Taguchi L9 orthogonal array	*It is inferred that the increase in volume percentage of SiC results in decrease of MRR and increase of Ra.	[93]
52	Kamal Jangra et al. (2010)	Sprintcut CNC WEDM	Wire: Zinc coated brass wire Work piece: D3 tool steel	*Pulse-on time *Pulse-off time *Wire feed rate *Wire tension *Peak current	*Cutting speed *Surface roughness *Dimensional lag	Taguchi method and Grey relation analysis (GRA)	*Using GRA, performance obtained are cutting speed (3.80 mm/min) and dimensional lag (0.008 mm). But surface roughness is poor and can be improved by increasing the weight in GRA.	[40]
53	Saurav Datta and Siba Sankar Mahapatra (2010)	Robofil 100 CNC WEDM	Wire: Zinc coated copper wire Workpiece: D2 tool steel	*Pulse duration *Discharge current *Pulse frequency *Wire speed *Wire tension *Flow rate	*Material removal rate *Surface roughness *Kerf width	Taguchi method and Grey relation analysis (GRA)	*It is found that discharge current, pulse duration and wire speed are the influencing parameters for material removal rate, surface roughness and Kerf width.	[94]
54	Routara BC et al. (2009)	Agiecut 220 WEDM	Wire: Brass wire Workpiece: AISI A7 die steel	*Gap current *Gap voltage *Wire feed rate *Duty factor	*Surface roughness *Material removal rate	Grey relation analysis	*In this paper it is observed that MRR and SR are improved together using the grey relation method.	[85]

55	Mahapatra SS and Amar Patnik (2006)	Robofil100	Wire: Brass wire Work piece: D2 tool steel	*Pulse duration *Discharge current *Pulse frequency *Flow rate *Wire tension *Wire speed	*Material removal rate *Surface finish	Taguchi method	* It is found that the predicted error of MRR is 4.062% and RF is 1.53%.	[48]
56	Manna A and Bhattacharyya B (2006)	Electronica supercut-734 CNC WEDM	Wire: Brass wire Work piece: Aluminium reinforced silicon carbide metal matrix composite	*Pulse-on time *Pulse-off time *Peak current *Wire feed *Wire tension *Servo voltage *Gap voltage	*Material removal rate *Surface roughness *Gap current *Spark gap	Taguchi based L18 orthogonal array	*Wire tension and wire feed are the influencing parameter for surface roughness. *Open gap voltage and pulse-on time are the influencing parameter for Material removal rate.	[49]
57	Ramakrishnan R and Karunamoorthy L (2006)	Robofil 290 5-axis CNC WEDM	Wire: Zinc coated brass wire Work piece: Tool steel	*Pulse-on time *Wire tension *Delay time *Wire feed *Current density	*Material removal rate *Surface roughness *Wire wear ratio	Taguchi L16 orthogonal array	*It is found that pulse-on time and ignition current density are the influencing parameters for surface roughness.	[76]
58	Hewidy M S et al. (2005)	Elektra Maxicut 434 CNC WEDM	Wire: Brass wire Work piece: Inconel 601	*Peak current *Duty factor *Wire tension *Water pressure	*Surface roughness *Material removal rate *Wire wear rate	Response surface methodology	*Material removal rate generally increases with increase in peak current and water pressure.Wear ratio increases with increase of peak current.	[36]
59	Sarkar S et al. (2005)	Electra supercut 734 Series 2000 CNC WEDM	Wire: Brass wire Workpiece: γ-titanium aluminide	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Servo voltage *Flushing pressure	*Cutting speed *Surface finish *Dimensional deviation	Taguchi method	*Dimensional deviation and surface roughness are independent of pulse-on time	[91]
60	Ahmet Hascalyk and Ulas Caydas (2004)	Sodick A320D/EX21 WEDM	Wire: Brass wire Work piece: AISI D5 tool steel	*Pulse duration *Open voltage *Wire speed *Flushing pressure	*Surface roughness *Metallurgical structure	Not Mentioned	*Surface roughness increased when the pulse duration and open circuit voltage were increased	[5]
61	Liao Yu et al. (2004)	Not Mentioned	Wire: Not Mentioned Work piece: Inconel 718	*Pulse-on time *Pulse-off time *Arc on time *Arc off time *Servo voltage	*Machining speed *Surface roughness	Taguchi method	*It was observed that MRR increases with increase in discharge on time and servo voltage. *Surface roughness increased with rate of energy input.	[46]
62	Nihat Tosun et al. (2004)	Sodick A320D/EX21 WEDM	Wire: Brass wire Workpiece: AISI 4140 steel	*Open circuit voltage *Pulse duration *Wire speed *Flushing pressure	*Cutting Kerf *Material removal rate	Regression analysis method	*Mathematical model has been generated between machining parameters and performance measures. *Open circuit voltage is the influencing parameter than pulse-on time.	[63]

Unconventional approach
Single-objective unconventional approach

S.NO	AUTHOR & YEAR	MACHINE	MATERIALS	PROCESS PARAMETER	PERFORMANCE MEASURES	METHODOLOGY	FINDINGS	Reference No.
1	Piyush Pant et al. (2014)	Not Mentioned	Wire: Not Mentioned Work piece: D3 die steel	*Gap voltage *Wire feed rate *Pulse-on time	*Surface roughness	Artificial neural network (ANN) approach	*It is found that best Ra of 4.57μm observed when V_G=30v, WF=25m/min and T_{ON}=30μs.	[66]
2	Sankara Narayanan G et al. (2014)	Not Mentioned	Wire: Copper wire Work piece: Copper	*Spark-off time *Spark-on time *Current *Gap range *Feed rate *Spindle feed *Flushing pressure	*Material removal rate	Artificial neural network	* The optimal process parameters can be predicted out by using this model to increase the production rate	[89]
3	Krishna Prasad VS et al. (2013)	Ultracut CNC WEDM	Wire: Brass wire Work piece: Inconel 825	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Servo voltage	*Surface roughness	Artificial neural network and Regression analysis	* Predicted values of surface roughness by ANN and regression analysis when compared, NN yields better average error of 5.5% than regression analysis of 16.04%.	[44]
4	Pragya Shandilya et al. (2013)	Ecocut WEDM	Wire: Brass wire Work piece: SiC_P /6061Al metal	*Servo voltage *Pulse-on time *Pulse-off time *Wire feed rate	*Cutting speed	Response surface methodology (RSM) and Artificial neural network (ANN) approach	*Maximum absolute percentage error of average cutting speed in the ANN prediction is 5.25%, while in RSM it is around 15.07%. *It is observed that the ANN model is three times better than RSM.	[68]
5	Vijaya Bhaskara Reddy et al. (2013)	Agiecut 220 WEDM	Wire: Zinc coated brass wire Work piece: WP7V steel	*Pulse duration *Open voltage *Wire speed *Dielectric *Flushing pressure	*Surface roughness	Artificial neural network	*In the prediction of surface roughness value the average errors for regression and neural network are found to be 13.97% and 6.07% respectively. It is observed that, Predicted values in neural network with two hidden layers are very close to the experimental results than regression.	[120]
6	Vamsi Krishna Pasam et al. (2010)	Robofil 310 CNC WEDM	Wire: Zinc coated brass wire Work piece: Titanium alloy	*Pulse current *Pulse duration *Pulse time *Servo speed *Servo voltage *Injection pressure *Wire speed *Wire tension	*Surface finish	Taguchi method and Genetic algorithm	*Mathematical model is obtained using regression analysis. *The developed model is optimized by genetic algorithm and surface roughness of 1.85μm is obtained with selected optimum parameters.	[115]
7	Esme U et al. (2009)	Acutex WEDM	Wire: Brass wire	*Pulse duration *Open circuit	*Surface roughness	Neural Network (NN) And Regression Analysis Model	*Prediction error value is 4.78% for NN and 7.17% for regression model, thus NN yields better prediction	[29]

		machine tool	Work piece: AISI 4340 steel	voltage *Wire speed *Flushing pressure				

Multi-Objective Unconventional Approach

S.NO	AUTHOR & YEAR	MACHINE	MATERIALS	PROCESS PARAMETER	PERFORMANCE MEASURES	METHODOLOGY	FINDINGS	Reference No.
1	Ravindranadh Bobbili et al. (2015)	Electronica machine tools	Wire: Brass wire Work piece: Aluminum alloy 7017	*Pulse-on time *Pulse-off time *Peak current *Spark gap set voltage	*Material removal rate *Surface roughness	Buckingham pi theorem	*Rise in pulse-on time from 0.85µs to 1.25µs causes improvement in MRR and minimize of surface finish.	[80]
2	Saeid Shakeri et al. (2015)	Robofil 200 WEDM	Wire: Zinc coated brass Wire Work piece: Cementation alloy steel	*Pulse current *Pulse frequency *Wire speed *Servo speed	*Material removal rate *Surface roughness	Linear regression model and feed forward backpropagation neural network	*Mean prediction error is 0773% for artificial neural network and 2.547% for regression model	[87]
3	Muthukumar V et al. (2014)	Electronica ecocut CNC WEDM	Wire: Not Mentioned Work piece: AISI D3 steel	*Pulse-on time *Pulse-off time *Wire feed *Gap voltage	*Material removal rate *Surface roughness *Kerf width	particle swarm optimization algorithm	*Best predicted MRR=0.03276g/min, KW=0.2842mm and Ra=2.7694µm are obtained when T_{ON}=6µs, T_{OFF}=8µs, GV=50v and WF=10mm/min.	[56]
4	Nixon Kuruvila and Ravindra HV(2014)	CONCORD DK7720C WEDM machine	Wire: Molybdenum wire Work piece: Hot die steel	*pulse-on time *pulse-off time *peak current * *bed-speed **flushing pressure	*Material removal rate *Dimensional error *Surface roughness	Taguchi method an L16 orthogonal array with genetic algorithm	*It is found that the pulse-on time increases with increase in MRR and when T_{ON} decreases good surface roughness is attained. *Similarly smaller current is suggested for better surface finish.	[64]
5	Thella Babu Rao and Gopala Krishna A (2014)	CT 520A CNC WEDM	Wire: Not Mentioned Workpiece: Al7075/SiC_p metal matrix composites	*Particulate Size *Volume of SiC_p *Pulse-on time *Pulse-off time Wire tension	*Wire wear ratio *Surface roughness *Material removal rate	Non-dominated sorting genetic algorithm-II	*In the proposed work, evolutionary algorithm NSGA-II was used to find the optimal solutions. *The optimal solution were confirmed by taking SEM examinations.	[111]
6	Ugrasen G et al. (2014)	Concord DK7720C four axes CNC WEDM	Wire: Molybdenum Work piece: EN31	*Pulse-on time *Pulse-off time *Peak current *Bed speed	*Accuracy *Surface roughness *Volumetric material removal rate	Multiple regression analysis (MRA), Group method data handling technique (GMDH), Artificial neural network	*By comparing the three theoretical methods for estimation of machining performances, it was found that artificial neural network fitting function has an edge over MRA and GMDH method. *It is observed that neural network trained with 70% of the data, gives good prediction results.	[113]

7	Ugrasen G et al. (2014)	Concord DK7720C four axes CNC WEDM	Wire: Molybdenum Wire Work piece: Tungsten Carbide cobalt	*Pulse-on time *Pulse-off time *Peak current *Bed speed	*Accuracy *Surface roughness *Volumetric material removal rate	Back propagation feed forward neural network (BPNN) and Levenberg-Marquardt algorithm (LMA)	*It is observed that neural network trained with 70% of the data in training set gives good prediction results.	[114]
8	Vates UK et al. (2014)	Electronica-Maxicut	Wire: Chromium coated Copper alloy wire Work piece: D2 die steel	*Gap voltage *Flush rate *Pulse-on time *Pulse-off time *Wire feed *Wire tension	*Material removal rate *Surface roughness	Response surface methodology (RSM) and Artificial neural network	*It is found that predicted root mean square of surface roughness using ANN is 1.90%, while in RSM is 9.322%. Thus it is concluded that ANN is best modelling tool for surface roughness than RSM	[117]
9	Mohinder P Garg et al. (2012)	Electronica 4 axis sprintcut CNC WEDM	Wire: Brass wire Workpiece: Titanium alloy	*Pulse on time *Pulse off time *Peak current *Servo voltage *Wire feed *Wire tension	*Cutting speed *Surface roughness	Non-dominated sorting genetic algorithm-II	*From the validation it shows that the prediction results are very close to the experimental results..	[54]
10	Rajarshi Mukherjee et al. (2012)	Elekita Maxi-cut 434 CNC WEDM	Wire: Brass wire Work piece: Inconel 601	*Pulse duration current *Pulse frequency *Wire speed *Wire tension *Dielectric flow rate	*Material removal rate *Surface roughness *Kerf width	Ant colony optimization Genetic algorithm Particle swarm optimization Sheep flock algorithm Artificial bee colony Biogeography- based optimization	*MRR of 0.173 g/min, KW of 0.208mm and Ra of 6.630mm obtained when pulse duration= 10.95ms, frequency=42.92KHz, wire speed=7.62m/min, wire tension=1161.72g and dielectric flow rate=1.32bars.	[72]
11	Abolfazl Golshan et al. (2011)	ONA R250 series 5-axis WEDM	Wire: Brass wire Work piece: Cold-work steel 2601	*Electrical current *Pulse-0ff time *Gap voltage	*Surface roughness *Material removal rate	Non-Dominated Sorting Genetic Algorithm (NSGA-II)	*Surface roughness of 2.754(µm) and MRR of 6.698(mm^3/min) and after optimization using genetic algorithm, it is noticed that Ra reduced to value of 2.716(µm) while MRR increased to 11.0936 (mm^3/min).	[3]
12	Kapil kumar and Sanjay Agarwal (2011)	Sprint-cut CNC Wire EDM	Wire: Zinc coated copper wire Work piece: M2 high speed steel	*Pulse-on time *Pulse-off time *Wire feed *Wire tension **Flushing pressure *Pulse peak current	*Surface roughness *Material removal rate	Taguchi method and non-dominated sorting genetic algorithm-II	*It is found that the material removal rate and surface finish is influenced by pulse peak current, pulse-on time, pulse-off time and wire feed. *The results also indicate that the material removal rate and surface roughness vary linearly.	[42]
13	Sarkar S et al. (2008)	Supercut 734 WEDM	Wire: Not Mentioned Work piece: Not Mentioned	*Pulse-on time *Peak current *Flow rate *Wire offset	*Surface roughness *Dimensional accuracy *Cutting speed	Response surface methodology (RSM) and it is optimized by desirability function approach and Pareto algorithm	*The developed Pareto optimization algorithm is superior compared to desirability function approach.	[92]

14	Dan Scott et al. (2007)	ROBOFIL 100 CNC WEDM	Wire: Not Mentioned Work piece: D2 tool steel	*Pulse duration *Discharge current *Pulse frequency *Wire tension *Wire speed	*Surface roughness *Wire wear ratio *Spark gap *Cutting rate	Explicit Enumeration And Dynamic Programming	* Maximum MRR obtained when (T=1.35 μs, I=1.405 A, PF=0.725 kHz, WT=1.159 kg, FR=0.315 liters/min and WS=0.338 m/min). *Minimum Ra obtained when (T=0.36 μs, I=0.118 A,PF=0.119 kHz, WT=0.098 kg, FR=0.096 liters/min and WS=0.047 m/min).	[24]
15	Sarkar S et al. (2005)	Electra Supercut 734 Series 2000 CNC WEDM	Wire: Brass wire Work piece: γ-titanium aluminide	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Flow rate *Servo voltage	*Cutting speed *Wire offset	Feed-forward back-propagation neural network	*Surface quality decreases as the cutting speed increases and the value of surface roughness is 2.44μm and a cutting speed is 2.65mm/min.	[90]

Hybrid approach

single-objective hybrid approach

S.NO	AUTHOR & YEAR	MACHINE	MATERIALS	PROCESS PARAMETER	PERFORMANCE MEASURES	METHODOLOGY	FINDINGS	Reference No.
1	Neeraj Sharma et al. (2014)	Electronica sprintcut 734 CNC WEDM'	Wire: Brass wire Work piece: HSLA	*Pulse-on time *Pulse-off time *Peak current *Wire tension *Gap voltage	*Overcut	Response surface methodology coupled with Genetic algorithm (GA)	*The optimum response characteristics overcut is 9.9922μm obtained when T_{ON}=117 μs, T_{OFF}=50 μs, IP=180 A, SV=49 V and WT=6 g.	[61]
2	Pragya Shandilya et al. (2014)	Ecocut WEDM	Wire: Diffused brass wire Work piece: Aluminium 6061	*Servo voltage *Pulse-on time *Pulse-off time *Wire feed	*Kerf width	ANN integrated with genetic algorithm	*Maximum percentage absolute error between the experimental value and ANN predicted value is 5.34%, while 2.39% with genetic algorithm.	[67]
3	Shandilya A et al. (2012)	Ecocut WEDM	Wire: Diffused brass wire Work piece: SiC_p/ 6061 Al MMC	*Servo voltage *Pulse-on time *Pulse-off time *Wire feed rate	*Surface roughness	Response surface methodology with genetic algorithm	*The maximum percentage absolute error between the experimental value and GA predicted value is 3.5%.	[99]

Multi-Objective Hybrid Approach

S.NO	AUTHOR & YEAR	MACHINE	MATERIALS	PROCESS PARAMETER	PERFORMANCE MEASURES	METHODOLOGY	FINDINGS	Reference No.
1	Ravindranadh Bobbili et al. (2015)	Electronica CNC WEDM'	Wire: Not Mentioned Work piece: Ballistic grade aluminum alloy	*Pulse-on time *Pulse-off time *Peak current *Spark gap set voltage	*Material removal rate *Surface roughness *Gap current	Taguchi method coupled with grey relation analysis	*Optimum response characteristics such as GC, Ra and MRR are improved with 6% error by employing GRA.	[79]

2	Zhen Zhang et al. (2015)	5-axis CNC WEDM' .	Wire: Not Mentioned Work piece: Not Mentioned	*Pulse-on time *Pulse current *Water pressure *Wire feed rate	*White layer thickness *Surface crack density *Surface roughness	Back propagation neural network (BPNN) integrated with genetic algorithm	*From the optimization, it is found that minimum Ra obtained when (T_{ON}=8.09µs, I=2.05A, WP=2.42kg/cm^2 and WF=0.55mm/min), minimum WLT obtained when (T_{ON}=9.08µs, I=3.29 A, WP=6.79kg/cm^2 and WF=0.78mm/min) and the minimum SCD of obtained when (T_{ON}=8.76µs, I=2.24 A, WP=4.36kg/cm^2 and WF=0. 39mm/min).	[125]
3	Varun A et al. (2014)	Ultracut WEDM	Wire: Not Mentioned Work piece: EN353 steel	*Pulse-on time *Pulse-off time *Servo voltage *Peak current	*Material removal rate *Surface roughness *Kerf widh	Grey relational analysis (GRA) coupled with Genetic algorithm (GA)	*From the optimization, it is found that maximum MRR=8.522 mm^3/min, minimum Ra=1.19µm and KW=0.33mm obtained when T_{ON}=109µs, T_{OFF}=52µs, SV=13v and IP=12A.	[116]
4	Ali Vazini Shayan et al. (2013)	Tehran ekram CNC AW-500	Wire: Not Mentioned Work piece: tungsten carbide	*Pulse-on time *Pulse-off time *Gap set voltage *Discharge current *Wire tension	*Current velocity *Surface roughness *oversize	Back propagation neural network with Particle swarm optimization	*Results indicated that BPNN-PSO has superiority in finding optimal solutions rather than mathematical model.	[6]
5	Probir Saha et al. (2013)	Electra Maxicut-523 CNC WEDM	Wire: Brass wire Work piece: Titanium Carbide reinforced manganese steel	*Pulse-on time *Pulse-off time *Gap voltage *Wire feed rate	*Cutting speed *Kerf width	Hybridization of a radial basis function network (RBFN) and non-dominated sorting genetic algorithm (NSGA-II)	*Increase in the average gap voltage lead to the decrease of cutting speed but increase of kerf width * It was found that the proposed technique is superior to the weighted sum method.	[71]
6	Resa Kashiry Fard et al. (2013)	Tehran ekram CNC AW-500 WEDM	Wire: Brass wire Workpiece: Al-SiC metal matrix composite	*Pulse-on time *Pulse-off time *Gap voltage *Discharge current *Wire feed *Wire tension	*Cutting velocity *Surface roughness	ANFIS-ABC technique	*It is found that pulse-on time and discharge current were found to be the significant parameters. *Optimal results were obtained through ANFIS-ABC technique.	[82]
7	Subramanyam SV et al. (2013)	Sprintcut ELPULS 40A DLX CNC WEDM	Wire: Zinc coated copper wire Work piece: H13 die steel	**Spark gap voltage *Pulse-on time *Pulse-off time *Peak current *Wire tension *Wire feed rate *Flushing pressure	*Material removal rate *Surface roughness	Grey-Taguchi method	*Study is made to establish mathematical models to find the optimal values for SR and MRR.	[105]
8	Amini H et al. (2011)	R250 High-precision 5-axis CNC WEDM	Wire: Not Mentioned Work piece: Titanium diboride	*Wire feed *Power *Voltage *Servo *Time off	*Surface roughness *Material removal rate	Artificial neural network and Genetic algorithm	*MaterialRemoval rate increases and surface roughness increases with increase in the power and voltage. *GA helps to predict the optimal parametric setting for WEDM, which is 94% accurate.	[8]

9	Rong Tai Yang et al. (2011)	CW-430F CNC WEDM'	Wire: Brass wire Work piece: Pure tungsten	*Pulse-on time *Pulse-off time *Servo voltage *Wire feed rate *Wire tension *Flushing pressure	*Material removal rate *Surface roughness *Corner deviation	Response surface methodology (RSM) and back-propagation neural network (BPNN) integrated simulated annealing algorithm	*BPNN/SAA approach produced better quality than the RSM method.	[84]
10	Hsien-Ching Chen et al. (2010)	CW-430F WEDM	Wire: Brass wire Work piece: Pure tungsten	*Pulse time *Servo voltage *Wire feed rate *Wire tension *Water pressure	*Cutting velocity *Surface roughness	Integration of back- propagation neural network (BPNN) and simulated annealing algorithm (SAA)	*From the results it shows that BPNN/SAA method is effective tool for optimization of WEDM Process parameters.	[38]
11	Muthu Kumar V et al.(2010)	Electronica Ecocut CNC Wedm	Wire: Brass Workpiece: Incoloy 800	*Gap voltage *Pulse-on time *Pulse-off time *Wire feed	*Material removal rate *Surface roughness *Kerf width	Grey-Taguchi method	*It is found that material removal rate shows an increased from 0.05351 g/min to 0.05765 g/min, the surface roughness shows a reduced value of 3.31 µm to 3.10µm and kerf width reduces from 0.324 to 0.296mm	[55]
12	Tzeng C-J et al. (2010)	CW-430F WEDM	Wire: Brass wire Work piece: Pure tungsten	*Pulse-on time *Pulse-off time *Servo voltage *Wire feed rate *Wire tension *Water pressure	*Surface roughness *Material removal rate	Back propagation neural network integrated with genetic algorithm and Response surface methodology	*The predicted value from RSM model for MRR is 0.2532 g/min and Ra is 1.3625 µm, while in BPNN/GA for MRR is 0.2731 g/min and Ra is 1.3197 µm. Thus the proposed BPNN/GA approach gives better prediction than RSM method.	[112]
13	Shajan kuriakose and Shunmugam M S (2005)	Robofil 310 WEDM	Wire: Zinc coated brass wire Workpiece: Titanium alloy	*Pulse-on time *Pulse-off time *Wire speed *Wire tension *Servo voltage *Injection pressure	*Cutting velocity *Surface finish	Non-dominated sorting genetic algorithm	*In this paper it is found that hybridization will increase production rate considerably by reducing the machining time.	[98]
14	Huang J.T & Liao Y.S (2003)	Not Mentioned	Wire: Brass wire Work piece: SKD11 alloy	*Pulse-on time *Pulse-off time *Wire velocity *Table feed rate *Wire tension	*Material removal rate *Gap width *Surface roughness	Taguchi coupled with grey relational analysis	*Table feed rate and Ton have the main influence in MRR. *Ton has a significant influence on G and Ra.	[37]

Conclusion

From the literature review it is found that material removal rate is mostly influenced by pulse on time and pulse off time. The surface roughness is predominantly depends on pulse on time and servo voltage. Machining voltage and pulse duration determines the Kerf width, and dimensional deviation is influenced by pulse duration and wire tension.

Future Work

From this paper it is understood that there is a need for increasing the accuracy of the prediction of optimal process parameter, which may be solved by hybridization for developing an expert system to provide optimal process parameters to achieve desired performance measures for different materials in CNC wire cut EDM.

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