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MACHINING OF STEEL ON WIRE ELECTRIC DISCHARGE MACHINE: A REVIEW

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Abstract: Wire electric discharge machining process (WEDM) is a technique of machining where machining take place without contact between the wire electrode and work piece. Over the past decade, the Wire EDM process has been a competitive and cost-effective option to meet the required equipment requirements from just a tool to a more complex process. Nowadays the WEDM process is often used for high-performance automotive, aerospace, railway, defence, small-scale industries, agricultural farming equipment etc. steel and different alloys of steel have gained popularity in all sectors simply because withstand high temperatures without failure, high strength and durability, high thermal conductivity and corrosion resistance. All of these properties of materials allow such elements to form part of all the above categories. Many of the metals and their alloys are very difficult to machining using conventional machinery due to their high hardness and the wearability of the tool. But over wire electric discharge machine, they are able to process things accurately without having to worry about hardness, toughness and complexity. This mechanical process is used to produce the most complex and complicated shape with a good surface finishing and a better degree of accuracy as compare over other machining processes. Here in our study the work carried out to describe the current research work in WEDM on steel and its alloys and the relation between the input parameters and their effects on the output responses. We will review the results of all these components in terms of removal rate, rate of wear resistance, deviation of size etc.

***Index Terms*–WEDM, P on, P off, Wire tension, MRR, R_a.**

1. INTRODUCTION

Wire electric discharge machining process (WEDM) has grown tremendously since it was applied before more than 30 years. In 1974, D.H. Dulebohn applied the optical line follower system to automatically control the shape and size of the components which have to be machine by the WEDM process. By 1975, its popularity increased rapidly, because the process and its capabilities were understood by the industries at the end of 1970, when computer numerical control (CNC) system was initiated into WEDM, which brought about a major evolution of the machining process [01]In recent years, the rapidly rising demand for materials with special characteristics in such advanced industrial applications as aerospace and surgical instruments, has led to the development of new materials. However, these materials are mostly difficult-to-cut using more conventional manufacturing processes. [02 - 06]WEDM has been widely used in many industries for high precision and quality. [07]

In wire edm process the wire is kept in tension using a mechanical tensioning device which tends to reduce the tendency of producing inaccurate parts. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire, eliminating the mechanical stresses during machining. The material removal mechanism in WEDM involves the complex erosion effect of electric sparks generated by a pulsating direct current power supply between two closely spaced electrodes in dielectric liquid. The electrode and work piece are separated by a small gap being immersed in dielectric fluid. An electric spark is produced in this small gap and the work piece material is eroded. The wire electrical discharge machining has been found to be the most potential electro thermal process among the other non-traditional machining processes.[08] This is due to its capability to meet the requirements of the present-day product manufacturing industries for machining of any kind of electrically conductive work, irrespective of its mechanical properties with the scope of achieving required shape and size with enhanced productivity, better surface finish characteristics and better dimensional accuracy features at comparatively reduced costs. [09]

The wire electric discharge machine that removes the material is a very useful method for making tools and jobs now a days. In wire electric discharge machining process direct contact between the work piece and the tool (Wire) is not available. During process the sparks occur when current flows are made between the tool and the working metal by keeping it at a small distance and being fed continuously by a dielectric medium between them. These sparks can produce extremely high temperatures that melt the work piece material and produce erosion.[10] The wire used in the WEDM machine has a very small diameter and the wire path is controlled by CNC, a computer-controlled machine that produces the desired shape and size. in the process, the wire moves upside down and the table movement is straight. Movement of both wire and table is controlled by a CNC controller. [11]

WEDM is a specialized machining technology. It is able to accurately machine the element of complex shape and design. Wire Electric discharge machining (EDM) is one of the most advanced and successful manufacturing methods used to machine materials that are difficult-to-cut. [12-16] Many high-quality materials and their alloys having very high brittleness hardness and toughness are very difficult to machine through traditional mechanical processes such as turning, grinding, molding etc. The solution to this problem is to make unusual machines. Wire Electrical Discharging Machining (WEDM) is used to make components of such types of materials.[17] WEDM is being used in modern industries to facilitate complex machining processes and achieve highly accurate machining [18-25].

The current era of large alloys is popular in all fields simply because of their high thermal conductivity without deformities and other factors. Such types of alloys are used to make aircraft parts, automotive parts, nuclear plant etc. These materials have good mechanical strength, corrosion resistance, heat resistance and good environmental stability. These things are difficult to do with the normal clicking process which is why an electric cutting machine is used to make such type of alloys. [26]

The different types of alloys are: Nickel based, Cobalt based, Iron based and many more. Duplex stainless steel (DSS) a two-phase alloy based on the iron-chromium-nickel (Fe-Cr-Ni) is preferred instead of austenitic stainless steel because of its high strength leading to economic benefits. Among stainless steels, DSS stays in between ferrite and austenite stainless steels which combine the inherited benefits of both phases. [27] Duplex stainless steel (DSS) is becoming more impressive than austenitic stainless steel (ASS) due to its high strength leading to economic benefits and weight loss. Duplex stainless steels are named as "Duplex" because, it is of two-phase microstructure consisting of grains of austenitic and ferritic stainless steel, possessing high corrosion resistance and excellent mechanical properties. [28] The low coefficient of temperature increase and the thermal conductivity of duplex stainless steel make it an excellent material for the construction of heat exchangers and pressure vessels. In addition, DSS is widely used in seawater, chemical and storage tanks for plants for desalination, gin and paper industry. [29]

In recent years, WEDM has been the most versatile method used in the turbo machinery industry for the production of Turbine engine parts. When comparing conventional machining process. WEDM may be shown to be very economical and efficient in the direct use of a variety of materials from Die steel to super-alloys. [26]

1.1 MAJOR WEDM PARAMETERS

The selection of machining parameters plays a significant role to obtain better response parameters. There are many machining parameters like pulse-on time, pulse off time, servo voltage, peak current, dielectric flow rate, wire feed nozzle height, wire tension etc., which affect the response parameters like MRR, SR, recast layer, Over cut Corner error etc. Many researchers have tried to achieve the selection of best optimum machining parameters, but it is very difficult to obtain these completely due to the complexity of the process. Wire electric discharge machining (WEDM) is a very effective process used for that type of materials which are difficult to machine using conventional machining processes. The different process parameters in wire EDM are used to control the performance of undergoing machining process. During machining process Input parameters like pulse on time, pulse off time wire tension, wire feed rate etc. plays a major role in the quality of machining. Therefore, proper selection of input parameters is very essential for machining in WEDM in order to get the desired shape of work piece. All the process parameters are generally controllable machining input factors which determine the conditions in which machining will carried out. These machining parameters affects the performance and output of machine, and these performances are checked using various performance measures.[31] some of the Machining parameters, such as the servo reference voltage, wire feed, pulse on time, pulse off time and wire tension, have a significant impact on the quality of the product generated by the WEDM process. The right parameters help to produce a faster material removal rate and a smoother surface finish. [32] Some of the parameters are discussed here.

1.1.1 Pulse on Time: Pulse on time can be defined as the time when machining operation is performed mechanically. Pulse on time is a time during which voltage is to be applied between electrode and work piece. It is representing as P on and it's generally expressed as microsecond (μs). Pulse on time parameter mostly affects the response variable like material removal rate and surface roughness. If higher is the pulse on time, then higher sparking energy because of that material removal rate is more, but at same time not get good surface finish. Because of that it is necessary to set proper value of pulse on time. [30] It is the period at which a spark produces between piece of work and wire electrode. it is defined as the time during which the machining is performed if we increase the time of the Pulse on at the same time the rate of the material removal, the cutting rate, wire wear and surface roughness increases. This happens just because with increase in value of pulse on time, Energy supply increases with pulse on time, therefore a greater number of particles will strike to the work piece. This energy supplied is directly proportional to the cutting rate during this time. As particles penetrate more deeply due to increase in energy, the recast layer will also be thick. This results in increasing the value of surface roughness with increase in pulse on time. [33]. With increase of pulse on time, energy per pulse increases and as a result, more material is removed per pulse. This discharge energy directly decided by pulse parameter settings (i.e., pulse on time). These results in increased machining speed and also increase the gap force (force induced due to spark). At higher pulse on time, sparking occurred frequently and due to this frequent sparking, rate of melting material increases. This molten metal partially flushed out due to the high-pressure dielectric flushing and remaining materials stacked on the work surface. As a result, lumping of molten metal takes place which forms different types of globules and making bigger crater in the machining zone. For that reason, the surface roughness (Ra) increases with the increase of pulse on time.[34]

1.1.2 Pulse off Time: The time period when there is no spark between the wire and the work piece during the mechanical process is called pulse off time or P off time. During this time dielectric ionization occurs. Pulse-off time or pulse interval is also defined as the time duration between consecutive sparks during which there is no current supply to the electrodes and deionization of dielectric takes place. During Pulse off Time the voltage is absent across this part of cycle the time off during which the pulse rests and the reionization of the die-electric takes place, can affect the speed of the operation in a large way. This time allows the molten material to solidify and to be washed out of the spark gap. If the pulse off-time is too short, it will cause sparks to be unstable, and then more short-circuiting will occur. On the other hand, a higher pulse off-time results in higher machining time, When the pulse off-time is insufficient as compared to on-time, it will cause erratic cycling and retraction of the advancing servo motor, slowing down the operation. Pulse interval will affect the speed and stability of the cut. In theory, the shorter the interval, the faster the machining operation will be. However, pulse interval must be greater than the deionization time to prevent continued sparking at one point More is the off time greater will be the machining time. But this is an integral part of the WEDM process and must exist. The time off also governs the stability of the process. An insufficient off time can lead to erratic cycling

1.1.3 Wire Tension: The amount by which a wire is stretched between upper and lower wire guide in wire electric discharge machine during machining is known as wire tension. It is a very important parameter; it affects the wire breakage during working or machining. Among all important process parameters of the WEDM the wire tension is an important parameter which affects the wire breakage during machining and the also affects the accuracy due to change in frequency of oscillation during sparking and pause. It is observed that the value of the Surface roughness is higher for the lower values of wire tension and the roughness is low (surface finish is better) at higher value of wire tension. [35] This is because the wire moves with uniform velocity during sparking. The spark crates an impact force on the moving wire, the wire under impact is expected to vibrate. When the tension on wire is varied, it is expected to increase the frequency of wire vibrations on every impact. The impact force on wire is minute, frequency of the impact affected by spark is very high as the sparking frequency is very high. Under these circumstances the high frequency minute vibrations may result in the average variations in the spark gap minimum and the consequently the Surface roughness may decrease with the increase in the wire tension and vice-versa. However, no such significant effect has been observed on machining speed. It is required to give a limiting value of wire tension to avoid the wire breakage phenomenon under stable machining condition.[32]To keep wire straight the tension in wire must be high otherwise it will pull back in roller. Between desirable ranges, if the wire tension increases then there is also increase of cutting speed with accurate result. High value of tension decreases the vibration amplitude of wire and therefore lowers the value of width of the cut such that for same discharge energy the speed is high. Whenever the value of tension which is applied goes higher than the tensile strength then the wire will break down.[36]

If we talk about effect of wire tension on kerf width and material removal rate so Wire tension doesn't influence much to MRR Material removal rate is almost same by increasing wire tension. There is slight improvement in MRR after increasing wire tension because of tightness and straightness of wire only. Kerf width also remains almost same as the wire tension increases. It means wire tension doesn't have significant influence on it [35]

1.1.4 Wire Feed Rate: The rate by which the wire moves along the path for generating spark between wire and work piece is known as wire feed rate. There is a limit on machining accuracy due to dimensional consistency and positional accuracy of the wire. Uncertainties exist in working region due to unsupported section of wire remote from guides. Unsupported length changes with the thickness of job.[31] Wire repeats complex oscillations due electrical discharges. Although servo system tries to maintain gap between workpiece and wire, external and internal sources generate vibrations in the wire which ultimately influence the repetitive sparking process. Deviation of electrode from mean position affects the occurrence of the next discharge, breakdown voltage, and discharge energy as the gap is continuously changing due to vibrations.[24]. Amplitude of vibration equivalent to the spark gap might cause short-circuit. So, commercial machines are designed for rigidity to minimize the tool deflection. But still, it is not possible to completely eliminate these influences.

1.1.5 Peak current: The maximum amount of current that passes through the electrodes at a given pulse is known as the peak current. It is observed that the nature of the machined surface is highly influenced by the nature of sparking, which is dictated by levels of peak current and peak voltage used during machining[37]. The effect of peak current on surface roughness is observed that as we increase the peak current it increases the magnitude of surface roughness. [38] This is due to the fact that with increase in the peak current’s value leads towards increase in the energy and due to this fact, the number of discharges gets increases and hence more material gets eroded from the surface of material.[38] The average current is the average of the amperage in the spark gap measured over a complete cycle. This is read on the ammeter during the process. The theoretical average current can be measured by multiplying the duty cycle and the peak current (max. current available for each pulse from the power supply /generator). Avg. current is an indication of the machining operation efficiency with respect to MRR. The concept of maximum peak amperage that can be applied to the electrode is an important factor before determining the max. Peak amperage the frontal[07]

1.1.6 Spark gap voltage: The value of specific voltage for actual gap between work piece and electrode is known as spark gap voltage, it is also termed as open circuit voltage. Spark gap voltage regulates the sparking gap during wire electro discharge machining process hence the intensity of spark discharge that impacts on workpiece surface tends to vary with varying spark gap voltage. This change in spark impact conditions therefore influences the melting process which in turn contributes in variation of machined surface morphology [39]

1.1.7 Spark Gap: The minimum distance maintained between an electrode and a piece of process or machining operation is known as a spark gap. It is evident that the spark gap increases with increase in pulse on time, whereas spark gap decreases with increase in pulse off time corresponding to minimum value of pulse off time the spark gap decreases with increase in dielectric pressure, whereas the spark gap increases with increase in dielectric pressure corresponding to maximum value of pulse off time [40]

1.1.8 Influence of Dielectric and Flushing Pressure: The dielectric fluid insulates the electrodes before a large amount of energy is accumulated and concentrates the discharge energy to a small area, recover a desired gap condition after the discharge by cooling the gap and deionizing and flush away the debris of the work piece removed by spark. If flushing pressure is less than certain pressure value, then no machining. Machining speed increases with increased flushing pressure. [24] While the surface roughness decreases gradually with increased flushing pressure due to effective removal of debris. High temperature is registered along electric discharge area. In WEDM, the performance is subjected to varied parameters which include machine setting parameters, wire tool-work material pair and also allied like thickness, dielectric, dielectric flushing, etc. In this way the WEDM process invite thorough parametric optimization studies. Process responses with response to suitability of parameters have been a common research interest.[04]

1.2 Major response parameters

WEDM machining is generally used to machine complex intricate shapes which are hard-to-machine with required finish and accuracy in order to meet industrial requirements. It is found that Material removal rate, surface roughness, kerf width and topological parameters are governed by energy content of the pulse and the rate at which they are supplied. In addition to these, other controlling parameters like servo sensitivity, gap width and dielectric parameters etc. also contribute to the output performance [41]. The different output parameters taken by different researchers during WEDM machining is shown here.

1.2.1Material Removal rate (MRR): It is amount of material which to be removed per unit time. Material removal rate can be expressed in different units like mm3/min, gm/min etc. In the WEDM process, the conductive materials are machined with a series of electrical discharges (sparks) that are produced by an accurately positioned moving tool electrode and the work piece material. High- frequency pulses of alternating or direct current are discharged from the wire to the work piece material with a very small spark gap through an insulating dielectric fluid. At a particular time, many sparks are produced. During pulse on time (Ton) sparks are produced between work piece material and tool electrode and melting and vaporization takes place in material. Dielectric fluid act as a resistor until enough voltage is applied. Then the fluid ionizes and sparks occurs between the wire and work piece. Sparks precisely melt and vaporize the material. A filtration system is used to filter the eroded particles from the dielectric fluid and the filleted dielectric fluid is reused. The melted work piece material forms into WEDM chips. A filter then removes the chips and the dielectric fluid is reused.[08]

Material Removal Rate = (Weight of workpiece before machining - Weight of Workpiece after machining) / Time (gm/min)

Material Removal Rate = (weight of work piece before machining - weight of work piece after machining) / Density of material * time (mm3/min)

1.2.2 Surface Roughness: Surface roughness is the measure of the finely spaced micro-irregularities on the surface texture. Surface roughness is defined as the irregularities which are inherent in the production process. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. Surface roughness of any solid material will have a significant influence on the macroscopic contact angle measurement on its flat surface Surface roughness is measured with the help of surface roughness tester. Probe of surface roughness tester is moved perpendicular to lay the direction. There are three methods for surface roughness measurement first is average peak to valley height, second is root mean square method and third is the center line, Surface roughness is generally expressed in the micron (μm).[08]

1.2.3 Wire wear ratio: weighing the wire before and after machining. The difference in weight divided by the original weight is defined as WWR and is used to quantify wire wear. Wire wear is observed only partially at the circumference [42]In wire electric discharge machining wire wear ratio is also one of the response variables. Wire wear ratio can be calculated as follow. Wire wear ratio increases with the increase in pulse duration and open circuit voltage. It decreases with increase in wire speed increasing the pulse duration increases the WWR, whereas increasing the wire speed decreases the WWR [43].

Wire wear ratio = (Initial weight of wire **-** Final weight of wire)/ Initial weight of wire

1.2.4 Tool wear rate: It is difference between initial weight of electrode and final weight of electrode divided by time required for machining the workpiece. It is expressed in Gm/min. [08]

2. Literature Review

Metal can be machined by many common mechanical processes such as turning, grinding, drilling, tapping, grinding, sharpening, cutting, etc. The required strength hinders normal production processes and therefore, most authors recommend non-standard steel clicking processes. Here is a list of book reviews from 2010 to the latest. The table shows the work done by the authors in the various levels of instruments, parameters, their responses and major findings, leading to prospects for future research.

S. No	Author/Year of Publication	Material/ Grade	Parameters	Optimum Values	Results	Remarks
1	Prasath.K, R.Prasanna (2018)	MS (AISI 1015)	P on - 4 TO 6 WFR - 2 to 6 V - 50 to 70	MRR Ra P on 5 4 WFR 2 2 V 50 60	MRR 9.3314 TO 12.8532 RA -7.53154 TO -3.69383	MRR increases with P on Ra minimized by increasing WFR and V
2	M. Durairaj, D. Sudharsun (2013)	SS (S 304)	V - 40 to 55 WFR - 2 to 8 P on - 4 to 10 P off - 4 to 10	Ra KW P on 6 4 P off 10 6 WFR 2 2 GV 40 50	Ra 2.02 to 2.85 KW 0.294 to 0.311	Ra Min. at V = 40V WFR = 2mm/min P on 6 µs P off 10 µs
3	Ahmed A. A. Alduroobi, Alaa M. Ubaid (2020)	S (AISI 1045)	P on - 10 to 25 P off - 20 to 40 Sf - 500 to 700	P on 25 P off 20 Sf 700	MRR 2.362 to 16.236 Ra 1.25 to 2.47	Increased value of P on increases value of MRR and at the same time decreases R_a with increased P off.
4	Swarup S. Deshmukh a, Shaikh Zubair (2019)	S (AISI 4140)	V - 10 to 30 WFR - 4 to 10 P on -110 to 125 P off - 45 to 55	Ra KW P on 110 125 P off 45 45 WFR 6 4 V 30 20	Ra 1.4903 to 3.7336 KW 0.275 to 0.323	Surface roughness and kerf width both decreases from 1.725 to 1.455 micro meter and 0.341 to 0.275 mm respectively.
5	M. A. Hassan, N. S. Mehat (2019)	S (AISI 4140)	P on - 3.2 to 12 Ip - 1.5 to 12.5	P on - 3.2 Ip - 1.5	Ra 118.14 to 1454.38 nm	Higher value of current and pulse on timing results in poor surface finish.
6	Kultar Singh Saini, Sandeep Singh (2017)	SS (S 304)	P off - 1 to 4 WFR - 6 to 12 WT - 6 to 9 V - 40 to 55	P off - 2.84 WFR - 12 WT - 6.3 V - 54.91	Ra - 11.7317 to - 6.2351 KW 0.192 to 0.293	For getting better surface finishing there should be high wire speed, high wire tension, and high voltage gap.
7	Pankaj R. Patil, P.M. Solanki (2017)	D2 Tool Steel	P on - 16 to 48 P off - 6 to 10 Ip - 5 to 9	P on - 48 P off - 10 Ip - 9	Ra - 16.6502 to - 10.3703	Most effective parameter is current on surface roughness but pulse off time has very less effect on roughness.
8	S. Banerjee, B. Panja (2017)	SPS (EN 47)	V 50 to 60 WFR - 6 to 10 P on -4 to 8 P off - 8 to 12	V - 50 WFR - 8 P on 8 P off 8	MRR 2.5792 to 18.0422	Maximum material removal rate can be achieved at higher value of P on time along with lower value of pulse off time and voltage gap.

9	Kashif Ashfaq& Nadeem Ahmad Mufti (2018)	SCS SS (SS 316) + MS (SA 516)	WD 0.20 to 0.30 SV 30 to 50 P on 3 to 5 WFR 60 to 220 mm/sec	WD 0.3 SV 40 P on 3 WFR 220mm/sec	Ra (ss) - 0.11 to 1.00 Ra (ms) - 0.03 to 1.00	Wire Diameter has significant effects on surface roughness.
10	Sujeet Kumar Choubey, Shankar Singh (2017)	AISI D2 Tool Steel	Ip 60 to 240 P on 0.5 to 2.6 WFR 5 to 9 WT 90 to 138	MRR Ra Ip 240 60 P on 2.6 0.6 WFR 5 9 WT 90 138	MRR 5.1 to 38.1 Ra 3.64 to 1.47	Ip, P on and WFR have more influence on MRR and P on has more influence on Ra
11	Partha Protim Das, Sunny Diyaley (2018)	S (EN 31)	P on 110 to 120 P off 30 to 40 SV 20 to 40 WT 5 to 7	P on 115 P off 35 SV 40 WT 5	MRR 0.05141 to0.10407 g/min Ra 3.6 to 2.2	Servo voltage is found the most affecting parameter which affects material removal rate and surface roughness.
12	Rusdi Nur1, Muas M. (2019)	S (EMS 45)	WFR 8 to 12 Ip 3 to 7	WFR 10 mm/min Ip 7 Amp	Ra 2.855 to 2.401 um	Higher the value of current the finishing of straight gear is poorer.
13	Tina Chaudhary, Arshad Noor Siddique (2018)	SS (AISI 304)	WT 5 to 22		MRR 3.22 to 3.80 Ra 7.02 to 3.03 KW 0.244 to 0.254	Wire tension has significant effect on Ra and MRR
14	Neeraj Sharma, Rajesh Khanna (2014)	S (HSLA)	P on 111 to 117 P off 36 to 50 SV 30 to 50 Ip 120 to 180 WT 6 to 10 gm	P on 117 P off 50 SV 49 Ip 180 WT 6 gm	OC 11 to 49.5	minimum overcut (i.e., 9.9922 micro m)
15	M. Manjaiah, Rudolph F. Laubscher (2016)	S (AISI D2)	P on 110 to 130 P off 30 to 42 SV 20 to 60 WFR 2 to 6	MRR Ra P on 130 110 P off 36 36 SV 20 60 WFR 2 2	MRR 0.6075 to 9.396 mm3/min Ra 3.05 to 1.28 um	Pulse on time and servo voltage has maximum effects on material removal and surface roughness.
16	Abhishek Singh, Dipankar Bose (2010)	MS	P on 10 to 70 P off 3 to 15 SV 02 to 10 WFR 35 to 75		MRR 13.008 to 114.647mm3/min CS 0.513 to 5.243 mm	By using proposed statistical techniques, it is possible to increase CS and material removal rate.
17	A Pramanik, A. K. Basak (2018)	DSS (2205)	P on 4 to 8 P off 22 to 66 WT 1000 to 1800 KN		MRR Ra KW	Low value of wire tension and short pulse on time provides better MRR as compare to long pulse off time and high value of wire tension.
18	G ugrasen, Bhagwan M R Ravindra v (2018)	SS (304)	P on 20 to 28 P off 5 to 7 Ip 4 to 6		MRR 15.85 to 17.15 Ra 1.85 to 1.76	P on has more effect on Ra of the materials
19	Krishna eswara, choo chee hua, kameswari prasad rao (2018)	Die steel	SF 4 TO 15 WFR 90 TO 130			The result shows that increased value of SF and Wire speed increases thickness of recast layer.
20	Anand S Shivade (2014)	AISI D3 STEEL	P on P off Ip WFR	MRR	MRR DD	Dimensional deviation is affected by $I_{p.}$ and material removal rate is affected by pulse on time and current.
21	2018/S. Banerjee	EN47 spring steel	P on P off SV WFR	MRR	MRR	P on time is the most affecting variable for MRR as compare to the other parameters like servo voltage, pulse off time etc.

Numerous research reports have been found to emphasize the effectiveness of WEDM boundaries.

Dongre et al. [44] had investigated the effect of WEDM parameters on cutting silicon ingots and found that voltage and puls on-time had a significant impact on kerf width. Singh et al. [45] applied hot die steel (H-11) to WEDM and validated the results of the process parameters in the MRR using a single time-change method. MRR increases due to increased pulse rate

Time (Ton). Bhaskar et al. [46] designed the experiments using the Taguchi and L16 OA process with four input parameters, i.e., pulse-on, pulse-off, bed speed and still in response parameters such as removal rate (MRR) and local pressure (Ra). The Wire EDM test that analyses two different parameters of the same parametric values and compared the performance characteristics in terms of MRR and local complexity was a new attempt. Tests were performed on two different components namely EN 19 and AISI 420 (SS 420) and the results obtained showed that EN 19 was better suited for MRR and AISI 420 for better terrestrial completion. Shivkant Tilekar, Sankha Shuvra Das and PK Patowari [47] investigated the effect of the parameters process on the local sharpness and width of the aluminium and soft steel kerf using a single feedback process. Test, spark time, start time, current input and cable supply level were used as input parameters while many other parameters were considered as fixed parameters. With the ANOVA method, the spark of time and the current installation time have been shown to have a significant effect on the colour surface of the aluminium and thin metal respectively. In the case of kerf width, the ratio of cable supply and spark at the time had a significant impact on aluminium and small steel respectively. Chin-Chang Yeh & Kun-Ling Wu et al [48] used wireless emission devices (WEDM) to process polycrystalline silicon ingot, and to influence the effects of facial features. Initially, two different dielectric, pure water and sodium pyrophosphate powder, were attempted to compare their effects on speed and size. In experiments, pure water containing sodium pyrophosphate powder has been shown to improve the efficiency of the process and improve local smoothness. From the first experimental results, it can be found that the dielectric cutting velocity of phosphorus is 1.48 times higher than in pure water. Taha A. El-Taweel et al [49] investigated the effect of the parameter on the use of the CK45 metal by EDM wire. The investigative parameters investigated were supply speed, activity factor, water pressure, telephone incompatibility and telephone speed observed and process procedures such as removal rate (MRR), tool wear rate (TWR), and condition size (SR) were assessed. By using the response method to find out that the rate of iron removal is usually increased by increasing the speed of the feed, the activity factor and the water pressure.

Sharma P. et Al. (2017) used Taguchi design approach with Grey relational analysis (GRA) for robust design while machining Inconel 706.The design was used for optimization of input parameters (pulse on time (TON), pulse off time (TOFF), servo voltage (V) and wire feed (WF) on output parameters (material removal rate (MRR) and surface roughness (SR)). For experimentation, they used a 0.25 mm diametric zinc coated brass wire as tool electrode. For investigation they used Electronic Eco cut CNC wire cut electronic discharge machine (WEDM). Analysis of variance (ANOVA) and Principal Component Analysis (PCA) were used for the analysis of experiment results. After analysis of experimental results, they found that Ton and Toff are significant process parameters on MRR and SR. They calculated the optimized values (Ton105µs, V- 32v, WF- 4m/min and Toff - 27µs) of process parameters on WEDM for better and efficient machining [50].Moura ova KA. et Al. (2016) experimented on MAKINO EU 61 WEDM CNC Machine to study the comparison between four types of workpieces as titanium alloy (Ti-6Al4V) with two types of heat-treated processes and a thermally untreated workpiece of titanium alloy and iron rhodium alloy on output parameter of surface roughness whereas input parameters were Ton, Toff, WF, IP (Peak current) and V (Spark gap set voltage). They used penta cut E brass wire with diameter 0.25mm as tool electrode. Analysis on surface roughness of the work pieces was done by FIB (focused ion beam fabrication) and surface morphology approach. After analysing the results, they found that only untreated Titanium alloy among the four workpiece materials had no sign of Globules [51].Sharma H. et Al. (2016) provided an examination on outcome and optimization of input parameters for output parameters Cutting speed, Kerf width and SR in WEDM using H21 die tool steel as work piece material. Tungsten wire was used as tool electrode for this work. Taguchi’s L18 orthogonal array was used for design of experiments. Discharge current, TON, TOFF, WF and WT (Wire tension) was used as input process parameters. After analysis and optimization of experiments results, it was found that the average cutting speed was mostly affected by TON, TOFF and WF during the rough cut and SR was not affected by any selected factor. Kerf width was mostly affected by discharge current, TON, TOFF and WF during ruff cut [52]

Choudhuri B. et Al. (2016) reported the influence of process parameters (TON, TOFF, IP, V and WT) on performance parameters (cutting speed and kerf width) for optimization. H21 tool steel was used as workpiece and soft brass wire (0.25 mm diameter) as tool electrode on Elektra Sprint cut CNC WEDM. For this investigation, Experiments were designed by central composite design technique (CCD) and total number of experiments that were performed is 47. For optimization and analysis of experimental results two methodologies viz. RSM and ANN (artificial neural network modeling), particle swarm optimization (PSO) was used throughout. After optimization and analysis of experimental results, they concluded that ANN-particle swarm optimization (PSO) hybrid methodology is ideal technique than RSM and better alternative of RSM because of its optimal level of optimization of WEDM process parameters [53]

Goswami A. et Al. (2016) had performed experiment on Electronica Sprintcut (Electra El plus 40A DLX) CNC to examine the influence of input parameters like TON, TOFF, IP and wire off-set (WO) on performance parameters i.e., MRR, SR and WWR. For the experiment they used Nimonic 80A alloy as Cutting material and Brass wire (diameter 0.25 mm) as a tool electrode. L27 orthogonal array of Taguchi methodology was applied for design of experiments. For analysis and optimization ANOVA and GRA techniques were used. After optimization and analysis of experimental results, they found that TON is the most significant parameter for MRR and SR. During trim cut machining it is also revealed that trim cut machining is compatible with high value of surface finish [54].

Rajmohan K. et Al. (2016) used Taguchi technique of L27 orthogonal array to examine the major influencing factors that affect the performance parameters MRR, SR and kerf width whereas the process parameters were TON, bed travel speed. For experimentation they used molybdenum wire with diameter of 0.18 mm and 2205 DSS alloy as workpiece material on EDM DK 7744 WEDM machine. ANOVA was used for analysis of experimental result. After analysis of experimental results, they found that TON is influential process parameter on SR and Kerf. They also concluded that value of SR and kerf width decreased with the increases in the level of TON [55].

Bobbili R. et Al. (2015) explored the effect of WEDM operation parameters (Ton, Toff, IP and V) on performance parameters (MRR, SR and Gap current). They used L18 Orthogonal array of Taguchi design approach for design of experiments. ANOVA and GRA techniques were used for analysis of results. For the experiments, they used Al-MgSi based alloy grade 6063 as a cutting material on WEDM. After analysis of experimental results, they found that Ton, IP, V are the most significant variable on performance parameters of WEDM and they also concluded that performance parameters were improved by employing GRA technique [56].

Chinnadurai T. et Al. (2015) studied on CNC WEDM for high MRR by using two tool electrode wires one is uncoated brass wire and another is zinc coated brass wire, both of the wires having same diameter (0.25mm). TON, TOFF, IP, V, WF, WT and SF were selected as Process parameters. For this study, they used AISI 4140 as a work piece material on WEDM. Taguchi L18 full factorial orthogonal array had been selected for design of experiments, and analysis of experimental results was done by using ANOVA. After optimization and analysis of experiments results, they found that Ton is most significant parameter on MRR for uncoated brass wire and for coated brass wire Ton, Toff and V was the significant parameters on MRR. They also concluded that the zinc coated brass tool electrode had given superior results, as comparable to the uncoated brass electrode wire [57].

Nour bakhsh F. et Al. (2013) described the effect of WEDM process parameters like as pulse width, time between two pulses, servo reference mean voltage, strike pulse current, injection pressure, wire tension and peak voltage on cutting speed, surface integrity and wire rupture by comparing the two wires. The influence of zinc coated brass wire was compared with high-speed brass wire. Experiment was performed on Charmilles model 2020 WEDM, they used titanium alloy (TI6AL4v) as a workpiece material and two type of wire electrode (high speed brass and zinc coated brass wire) each of 0.25 mm diameter. The experiments were designed based on Taguchi L18 orthogonal array and ANOVA was used for analysis. After optimization and analysis of experiments results, they found that the zinc coated brass wire resulted higher cutting speed and smother surface finishing as compared to the high-speed brass wire [58].

Sachdeva G. et Al. (2013) performed experimental investigation on Electronica Sprintcut CNC WEDM. H21 die tool steel was used as workpiece for the experiment. The tool electrode used for the experiment was zinc coated brass wire (0.25mm diameter). The input parameters were taken as Ton, Toff, WF, WT, IP on output parameters cutting speed, die width and SR. L18 mixed level orthogonal array of Taguchi's design methodology used for the design of the experiments. For the analysis and optimization of experimental results ANOVA technique was used. After optimization and analysis of experimental results it was found that IP &Ton are the most significant parameters on die width., TOFF & IP are the most significant parameters on SR and, TOFF & TON are the most significant parameters on cutting speed [59].

Bobbili R. et Al. (2013) conducted the experiments on ULTRA CUT WEDM to study the effect of process parameters such as TON, TOFF, WT, WF, V and WP on performance parameters such as MRR and SR. For experimentation, they used zinc coated brass wire (.25mm diameter) as tool electrode and high strength armour steel block as workpiece. By using Taguchi design approach, L27 orthogonal array had been selected for design of experiments. For the analysis of experimental results ANOVA technique was used. After optimization and analysis of experiments results, they found that TON, TOFF, V are the most significant parameters on both performance parameters and also concluded that optimum setup of process parameters for better performance of CNC WEDM are achieved by applying ANOVA [60].

Shandilya P. et Al. (2013) experimented on Electronica Ecocut CNC WEDM on process parameters TON, TOFF, V, on output parameter average cutting speed of WEDM and also present a comparison of optimization and analysis techniques. For experimentation diffused brass wire (0.25 mm diameter) was used as tool electrode and SiCp/6061 Al alloy as a workpiece material. RSM and ANN techniques were used for optimization and analysis of experimental results. After optimization and analysis, it was found that V is highly significant process parameter on cutting speed. On the other hand, after comparing optimization and analysis techniques they concluded that ANN analytical results were three times better than RSM analytical results [61]

Goswami A. et Al. (2014) explored the effect of process parameters on performance parameters. For this investigation, the selected process parameters were TON, TOFF, V, IP, WF and WT. Performance parameters were MRR and SR. He had selected Nimonic 80A as a workpiece material and soft brass wire (0.25mm) as a tool electrode. Electronica Sprint cut Electra El plus 40A DLX CNC WEDM was used for experimentation. L27 orthogonal array was used for design of experiments. Utility concept, Single & Multi response techniques are used for optimization and ANOVA was used as analysis Techniques. After optimization and analysis of experimental results, he found that the TON and TOFF are highly significant process parameters on MRR. Ton and V are highly significant process parameter on SR but other process parameters were less significant on both performance parameters. He also concluded that for considering optimal level of process parameters for both performance parameters of WEDM, single response optimization method provide better results as compared to multi response optimization method [62].

Ergun et al. (2015) performed an experiment to study the effects of the machining parameters on SR and MRR using WEDM process during cutting of Al/B4C composite by hot pressing. Using ANOVA technique, the obtained, Ton value indicated more effect on SR whereas wire tension revealed significant effect on MRR. The conclusion being, SR increases with increase in B4C particles in the composite. [63]

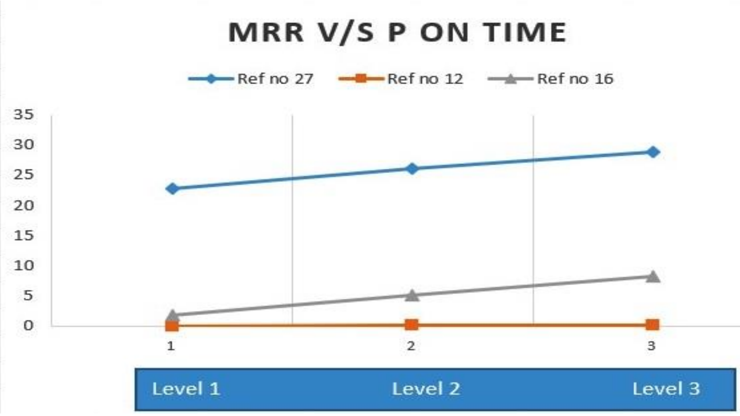
Manjaiah et al. (2016) conducted an experimental work on D2-Steel material by WEDM process by using machining parameters (Pulse-on time, Pulse-off time, Servo voltage, and Wire feed) on the response parameters i.e., Material Removal rate (MRR) and Surface Roughness (SR). The results depict that MRR increases with increase in pulse on time (Ton) and Ra decrease with increases in Servo Voltage (SV). It was concluded that the recast layer thickness increases with the increase in Ton, oxides are formed on the machined surface and the hardness was increased. [64]

2.1 Summary of Literature Review

Many researchers have worked hard to work with different process parameters, electrode / wire materials, work materials, dielectric equipment, etc. The effect of the process parameters on the responses is considered to be the main objective.

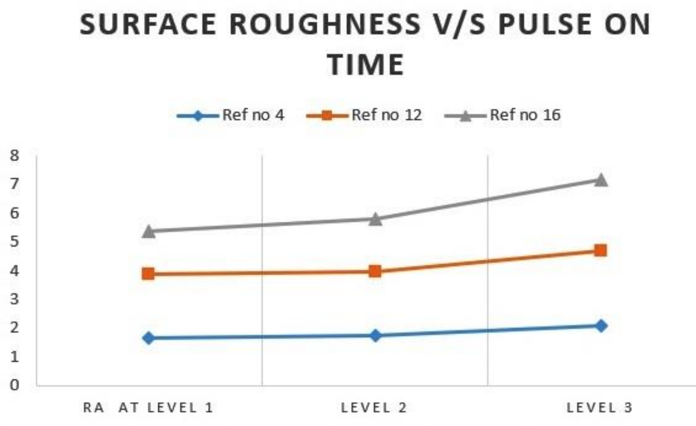
2.1.1 Effect of Pulse on Time: The rate of removal of an object is directly proportional to the amount of energy used during a time strike. The higher the pulse value over time, the more energy generated will also increase and will lead to more heat energy generation.if we increase the time of the Pulse on at the same time the rate of the material removal, the cutting rate, wire wear and surface roughness increases. This happens just because with increase in value of pulse on time, Energy supply increases with pulse on time, therefore a greater number of particles will strike to the work piece. This energy supplied is directly proportional to the cutting rate during this time. As particles penetrate more deeply due to increase in energy, the recast layer will also be thick. This results in increasing the value of surface roughness with increase in pulse on time. [33]. as we expand the Pulse while the power supply of the spark increases, which often develops a greater impact on the surface of the equipment and results in higher deviation [65, 72].high MRR can be achieved using high pulse-on-time [73,11,30,70,65] It can be seen that an increase in Pulse time leads to an increase in MRR. This is because high pulse-on-time values produce longer sparks and therefore release more spark energy transferred to the wire and This results in the production of violent sparks and forces (gas bubbles) leading to the formation of abnormal holes deep in WEDM areas, cable deviation, melting and placement of wire particles in high performance areas increase MRR.[74]

comparative graph for MRR vs P on (µs)			
MRR at Level 1	**Level 2**	**Level 3**	**Reference**
22.83	26.12	28.83	**27**
0.04705	0.0825	0.0971	**12**
1.863	5.2245	8.343	**16**



Here from the graph, we see that as hitting time increases the rate of removal of material also increases. This is because high pulse-on-time values produce longer spans and therefore more spark energy is transferred to the wire andtherefore a greater number of particles will strike to the work piece. This energy supplied is directly proportional to the cutting rate during this time. As particles penetrate more deeply due to increase in energy, the recast layer will also be thick. This results in increasing the value of surface roughness with increase in pulse on time [75] The lowest possible size is found when running at its lowest range. It was found that the characteristics of each parameter affect the variability of response at a different rate. Equipment, local hardness as a response variable, concludes, hitting the control element at a time has a greater impact on the sharpness of the surface.[76]

comparative graph for Ra vs P on (µs)			
Ra at Level 1	**Level 2**	**Level 3**	**Reference**
1.6763	1.7453	2.085	**4**
2.2	2.2	2.6	**12**
1.5	1.85	2.46	**16**

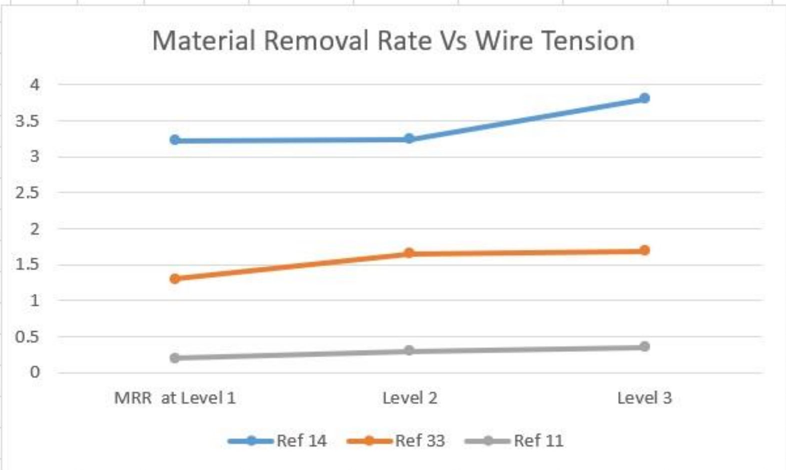


2.1.2 Effect of Pulse off time: With a lower value of Pulse off time, there is a greater amount of discharge in a given time, resulting in an increase in the rate of removal of material. The low pulse OFF time results in a higher deviation and the faster pulse OFF leads to a lower deviation in size [66] the increase in the time of the Pulse off leads to a decrease in MRR without certain readings from the expected location due to certain reasons such as power outages and wire breakage. it can be seen that a high MRR rate can be achieved at low P off levels. [11,30]As the time goes up the MRR decreases with a small amplitude of variance. [65,69] This is because the amount of output within the desired time becomes smaller due to the time between the two increasing pulses (hitting time) leading to lower cutting speeds. Also, it may be due to a decrease in the melting point and the amount of spark ignition in the plasma channel causing low MRR.

Closing time has important effects in addition to the intensity of the space. Surface roughness (Ra) is reduced by increasing pulse off time. It can be seen that Ra's lower grades can be reached at lower pulse off levels. [11] This is mainly due to a decrease in spark emissions and an increase in the time interval between the emission particles. Analysis of the effect of kerf width variation shows that the heart rate is the largest influential parameter compared to other parameters. The ANOVA effect of the kerf width shows that timing has a greater impact on parameters than pulse on time and wire feed. the results show that with increasing pulse off time the width of the kerf decreases [77, 78]. This is because with the reduction of the discharge time, the discharge during the discharge also increases as the discharge force strikes harder.

2.1.3 Effect of Wire Tension: The amount by which a wire is stretched between upper and lower wire guide in wire electric discharge machine during machining is known as wire tension. It is a very important parameter; it affects the wire breakage during working or machining. among all important process parameters of the WEDM the wire tension is an important parameter which affects the wire breakage during machining and the also affects the accuracy due to change in frequency of oscillation during sparking and pause. it is observed that the value of the Surface roughness is higher for the lower values of wire tension and the roughness is low (surface finish is better) at higher value of wire tension. [35] This is because the wire moves with uniform velocity during sparking. The spark crates an impact force on the moving wire, the wire under impact is expected to vibrate. When the tension on wire is varied, it is expected to increase the frequency of wire vibrations on every impact. The impact force on wire is minute, frequency of the impact affected by spark is very high as the sparking frequency is very high. Under these circumstances the high frequency minute vibrations may result in the average variations in the spark gap minimum and the consequently the Surface roughness may decrease with the increase in the wire tension and vice-versaIn WEDM cord tension is the most important parameter that affects the termination of wires during mechanical breakdown. [81,78,79,69] High tension reduces the magnitude of the vibration of the cable which is why it reduces the cut width so that the speed is higher with the same output power. [67]The effect of the local sharp wire friction indicates that Ra increases the inconsistency of a certain value and then begins to decrease with inconsistency with the increase of the wire inconsistency. Surface Roughness is high in low tension values and roughness is low in high tension values [81,80,79,69]. Very long vibrations can lead to moderate and small spark gap fragments and as a result the Surface Roughness may decrease with increasing wire friction and vice versa. This is because a low wire rack will cause a vibration of the fence which increases the stiffness of the face

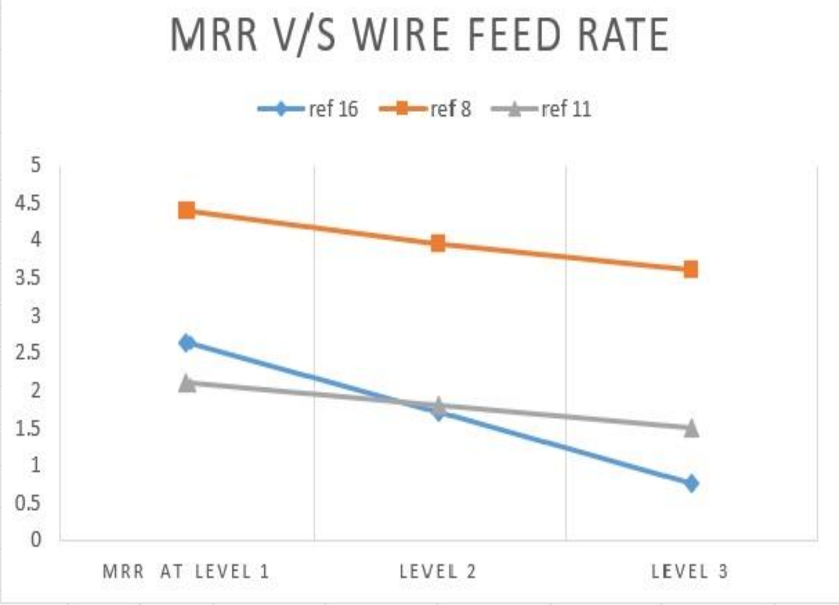
comparative graph for MRR vs WT			
MRR at Level 1	Level 2	Level 3	Reference
3.22	3.24	3.8	**14**
1.3	1.65	1.69	**33**
0.2	0.3	0.35	**11**



As we can see here from the graph that as we increase wire tension it slightly increases material removal rate because of tightness and straightness of wire.

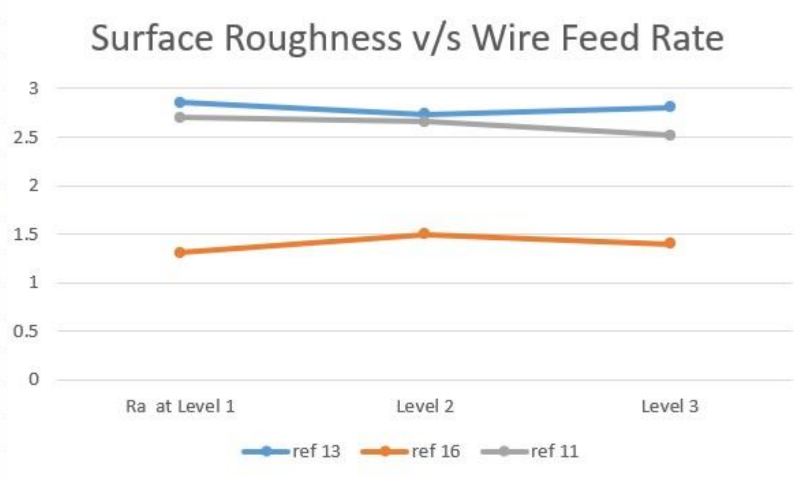
2.1.4 Consequence of Wire Feed Rate: The Surface Roughness decrease with increase in wire feed rate, but with the increase in wire feed, the consumption of the wire increases and the machining cost also increases [68]. Material removal rate decreases linearly whereas surface roughness decreases non-linearly with increase in wire feed rate. Firstly, surface roughness slightly decreases non-linearly to a certain value then start decreasing nearly linearly. At higher wire feed rate. [30,26,81,80,65] Minimum surface roughness can be achieved using higher wire feed but Higher MRR can be achieved using lower wire feed.

comparative graph for MRR vs WFR			
MRR at Level 1	Level 2	Level 3	Reference
2.6325	1.701	0.7695	**16**
4.397	3.95	3.61	**8**
2.1	1.8	1.5	**11**



As shown in above graph we can see that as value of wire feed rate increases the material removal rate slightly decreases. it is observed that the MRR is higher both at lower and higher levels of wire feed than the canter level of wire feed. This is because increase in wire feed increases the rate of cutting speed, which in turn increases the rate of spark discharge. More amounts of material melting and erosion takes place for higher spark discharge. Hence, MRR was more at higher wire feed

comparative graph for Ra vs WFR			
Ra at Level 1	Level 2	Level 3	Reference
2.855	2.736	2.809	**13**
1.31	1.5	1.4	**16**
2.7	2.66	2.52	**11**



2.1.5 Effect of peak Current: As we increase the value of peak current it increases Material Removal rate, Surface Roughness and Wire Wear Rate it is the biggest factor which affects the surface roughness.

3. Concluding Remarks

From literature review related to single and multi-objective optimization process parameters of Wire electric discharge machining from 2013 to 2020 following observations are made

In WEDM response variable such as material removal rate and surface roughness is mostly influenced by variation of pulse on time and current.

The increase in pulse ON time with minimum voltage and wire feed rate leads to increases in material removal rate

The Analysis resulted that the pulse on time has major influence on the surface roughness and kerf width

4. REFERENCES

[01] Garg, M. Pal jain, A. Bhushan, G. (2014) "An investigation of wire electric discharge machining of high temperature titanium Alloy Process of 5th & 26th all India Manufacturing Tech, Design and research Conf (AIMTDR 2014), IIT Guwahati, Assam, India.

[02] Pérez, J.; Llorente, J.; Sanchez, J. Advanced cutting conditions for the milling of aeronautical alloys. J. Mater.Process. Technol. **2000**, 100, 1–11.

[03] Komanduri, R.; Hou, Z.-B. On thermoplastic shear instability in the machining of a titanium alloy (Ti-6Al-4V).Metal. Mater. Trans. A **2002**, 33, 2995.

[04] Benes, J. Cutting Difficult Machine Materials. Available online: http://www.Americanmachinist.com/304/ Issue/Article (accessed on 24 January 2007).

[05] Ruszaj, A.; Skoczypiec, S.; Wyszy´ nski, D. Recent developments in abrasive hybrid manufacturing processes.Manag. Prod. Eng. Rev. **2017**, 8, 81–90.

[06] Patel, P.R.B.S.M. A Review of Parametric Optimization of Wire Electric Discharge Machining. Indian J.Appl. Res. **2015**, 5, 60–62.

[07] Y.F. Tzeng, F.C. Chen, Multi-objective optimization of high-speed electrical discharge machining process using a Taguchi fuzzy-based approach, Mater. Des., Vol. 28, pp. 1159–1168, 2007.

[08] Swarup S. Deshmukh, Vijay S. Jadhav, Ramakant Shrivastava. (2019), "Review on Single and Multi-objective Optimization Process Parameters of EDM Using Taguchi Method and Grey Relational Analysis", Materials Today: Proceedings

[09] Garg Rohit, 'Effect of process parameters on performance measures of wire electrical discharge machining', May 2010, NIT, Kurukshetra-136 119, Haryana, India

[10] Effect of spark gap voltage and wire electrode feed rate on machined surface morphology during Wire EDM process Abhinaba Roya *, Narendranath S.b Materials Today: Proceedings 5 (2018) 18104–18109

[11] Chaudhary, Tina and Siddiquee, Arshad Noor (2017) "Effect of wire tension on different output responses during wire electric discharge machining on AISI 304 stainless steel" Proceed Mater Sci, page 67 to 76.

[12] Chiang, K.-T.; Chang, F.-P. Optimization of the WEDM process of particle-reinforced material with multipleperformance characteristics using grey relational analysis. J. Mater. Process. Technol. 2006, 180, 96–101.

[13] Hewidy, M.; El-Taweel, T.; El-Safty, M. Modelling the machining parameters of wire electrical dischargemachining of Inconel 601 using RSM. J. Mater. Process. Technol. 2005, 169, 328–336.

[14] Kumar, A.; Maheshwari, S.; Sharma, C.; Beri, N. Research developments in additives mixed electrical discharge machining (AEDM): A state of art review. Mater. Manuf. Process. 2010, 25, 1166–1180.

[15] Lee, S.; Li, X. Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. J. Mater. Process. Technol. 2001, 115, 344–358.

[16] Yu, Z.; Jun, T.; Masanori, K. Dry electrical discharge machining of cemented carbide. J. Mater. Process. Technol.2004, 149, 353–357.

[17] Amrish, Raj D. and Senthilvelan, T. (2015) Mater Today: Process, 82 to 90. Banu, Asfana Mazilah, Abu Bakar (2017) “Experimental Analysis of WEDM Process Parameters on Surface Roughness and Kerf using Taguchi Method” International Journal of Engineering Materials and Manufacture, 2(4) 103-109.

[18] Beri, N.; Maheshwari, S.; Sharma, C.; Kumar, A. Technological advancement in electrical discharge machiningwith powder metallurgy processed electrodes: A review. Mater. Manuf. Process. 2010, 25, 1186–1197.

[19] Ho, K.; Newman, S.; Rahimifard, S.; Allen, R. State of the art in wire electrical discharge machining (WEDM).Int. J. Mach. Tools Manuf. 2004, 44, 1247–1259.

[20] Hsieh, M.-F.; Tung, C.-J.; Yao,W.-S.;Wu, M.-C.; Liao, Y.-S. Servo design of a vertical axis drive using duallinear motors for high-speed electric discharge machining. Int. J. Mach. Tools Manuf. 2007, 47, 546–554.

[21] Lim, H.;Wong, Y.; Rahman, M.; Lee, M.E. A study on the machining of high-aspect ratio micro-structuresusing micro-EDM. J. Mater. Process. Technol. 2003, 140, 318–325.

[22] Singh, S.; Maheshwari, S.; Pandey, P. Some investigations into the electric discharge machining of hardenedtool steel using different electrode materials. J. Mater. Process. Technol. 2004, 149, 272–277.

[23] Tzeng, Y.-F.; Chen, F.-C. A simple approach for robust design of high-speed electrical-discharge machiningtechnology. Int. J. Mach. Tools Manuf. 2003, 43, 217–227.

[24] Tzeng, Y.-F.; Chen, F.-C. Multi-objective optimisation of high-speed electrical discharge machining processusing a Taguchi fuzzy-based approach. Mater. Des. 2007, 28, 1159–1168.

[25] Surleraux, A.; Pernot, JP.; Elkaseer, A.; Bigot, S. Iterative surface warping to shape craters in micro-EDMsimulation. Eng. Comput. 2016, 32, 517–531.

[26] Khan, Z. A. Siddiqui, A. N. and Khan, N. Z. (2014) “Multi response optimization of wire electrical discharge machining process parameters using Taguchi based grey relational analysis” Procedia materials science, 6, 1683-1695.

[27] Nomani J, Pramanik A, Hilditch T, Littlefair G. Chip formation mechanism and machinability of wrought duplex stainless steel alloys. The International Journal of Advanced Manufacturing Technology 2015, 80(5-8), 1127-35.

[28] R.D. Koyee, R. Eisseler, S. Schmauder, “Application of Taguchi coupled Fuzzy Multi Attribute Decision Making (FMADM) for optimizing surface quality in turning austenitic and duplex stainless steels, Measurement”, Vol. 58, pp.375–386, 2014.

[29] Gaurav D. Sonawane, Vikash G. Sargade, (2020), “Machinability Study of Duplex Stainless Steel 2205 During Dry Turning”, International Journal of Precision Engineering and Manufacturing volume 21, pages969–981

[30] Jaber E. Abu Qudeiri, Ahmad Saleh, Aiman Ziout, (2019) “Advanced Electric Discharge Machining of Stainless Steels: Assessment of the State of the Art, Gaps and Future Prospect” MDPI journal 907,3390.

[31] Kapoor J, Singh S and Khamba J, 2010, Recent developments in wire electrodes for high performance WEDM, Proceedings of the world congress on engineering, 2, pp. 1-4.

[32] Chen, X.; Wang, Z.; Wang, Y.; Chi, G. Investigation on MRR and machining gap of micro reciprocated Wire-EDM for SKD11. Int. J. Precis. Eng. Manuf. 2020, 21, 11–22.

[33] DAV National Congress on Science, Technology & Management, November 7-8, 2014 Effect of Pulse on Time on Performance Parameters of WEDM Rajeev Kumar1 and Amit Kohli2

[34] K. Mandal et al., Published by EDP Sciences 2020 Experimental investigation of process parameters in WEDM of Al 7075 alloy *Kingshuk Mandal*1*, *Dipankar Bose*2, *Souren Mitra*1 and *Soumya Sarkar*1

[35] Effect of wire tension on different output responses during wire electric discharge machining on AISI 304 stainless steel Tina Chaudhary Arshad Noor Siddiquee Arindam KumarChanda defence technology volume 15 issue 4 august 2019 541-544

[36] Review on process parameters of WEDM Shubham Sharma A JOURNAL OF COMPOSITION THEORY Volume XII Issue VII JULY 2019 ISSN: 0731-6755

[37] Effect of peak current and peak voltage on machined surface morphology during WEDM of TiNiCu shape memory alloys Abhinaba Roy, S. Narendranath & Alokesh Pramanik Journal of Mechanical Science and Technology volume 34, pages3957–3961 (2020)

[38] IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320–334X Effect of Peak Current on the Performance of WEDM Rajeev Kumar March 2016

[39] Effect of spark gap voltage and wire electrode feed rate on machined surface morphology during Wire EDM process Abhinaba Roya *, Narendranath S.b Materials Today: Proceedings 5 (2018) 18104–18109

[40] International Journal of Engineering Science and Innovative Technology (IJESIT) Volume 2, Issue 1, January 2013 Spark Gap Optimization of WEDM Process on Ti6Al4V Kuriachen Basil, Dr. Josephkunju Paul, Dr. Jeoju M.Issac

[41] Mishra, P. K. (2007): Non-Conventional Machining, Narosa Publishing House, New Delhi.

[42] Analysis of WEDM Process with Respect to Wire Wear and Wire Consumption, CIRP 95 (2020) 313–318, Conference on Electro Physical and Chemical Machining (ISEM 2020), Fabian Kneubühler et al

[43] N. Tosun, C. Cogun An investigation on wire wear in WEDM J. Mater. Process technol., 134 (2003), pp. 273-278

[44] Dongre, G. G.; Vesivkar, C.; Singh, R.; Joshi, S. S. "Modeling of Silicon Ingot Slicing Process by Wire-electrical Discharge Machining" Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2013, 227, 1664–1678

[45] H.Singh, Effects of process parameters on material removal rate in WEDM, Achievement in materials and manufacturing engineering, Vol 32 2009.

[46] Bhaskar Reddy, D. Reddy, and E. Reddy, "Experimental Investigations on Mrr and Surface Roughness of EN 19 & SS 420 Steels In Wire- Edm Using Taguchi Method," Int. J. Eng. Sci. Technol., vol. 4, no. 11, pp. 4603–4614, 2012.

[47] Shivkant Tilekar, Sankha Shuvra Das, P.K Patowari, "Process Parameter Optimization of Wire EDM on Aluminum and Mild Steel using Taguchi Method‖", Procedia Materials Science 5(2014) 2577-2584.

[48] Chin-Chang Yeh, Kun-Ling Wu, Jyh-Wei Lee, Biing-Hwa Yan, ―Study on surface characteristics using phosphorous dielectric on wire electrical discharge machining of polycrystalline silicon‖, International Journal of Advance Manufacturing Technology (2013) 69:71–80

[49] Taha A. El-Taweel, Ahmed M. Hewidy, "Parametric Study and Optimization of WEDM Parameters for CK45 Steel." International Journal of Engineering Practical Research (IJEPR) Volume 2 Issue 4, November 2013, pp. 156- 169.

[50] Sharma P, Chakradhar D, Narendranath S. „Analysis and Optimization of WEDM Performance Characteristics of Inconel 706 for Aerospace Application. Silicon. 20171;10(3):921-930.

[51] Mouralova KA, Zahradnicek RA, Hrdy RA. Occurrence of globule of debris on surfaces machined by WEDM. MM Sci. J. 2016:1630-1633.

[52] Sharma H, Gupta D. "Optimization of Process Parameters of Wire Cut Electronic Discharge Machining", Global journals blog, http://blog.gjre.org/2016/02/optimization-of-processparameters-of.html

[53] Choudhuri B, Sen R, Ghosh S, Saha S. “A Comparative Modeling and Multi- Objective Optimization in Wire EDM Process on H21 Tool Steel Using Intelligent Hybrid Approach”. International Journal of Engineering and Technology (IJET), Vol 8, Issue No. 6, 2016-17, 3102-3111.

[54] Goswami A, Kumar J. Trim cut machining and surface integrity analysis of Nimonic 80A 44alloy using wire cut EDM. Engineering Science and Technology, an International Journal, 2016, 20(1), 175-186.

[55] Rajmohan K, Kumar AS. Experimental investigation and prediction of optimum process parameters of micro-wire-cut EDM of 2205 DSS. The International Journal of Advanced Manufacturing Technology. 2017 Oct 1;93(1-4):187-201.

[56] Bobbili R, Madhu V, Gogia AK. Multi response optimization of wire-EDM process parameters of ballistic grade aluminium alloy. Engineering Science and Technology, an International Journal. 2015 Dec 1;18(4):720-726.

[57] Chinnadurai T, Vendan SA. Contemplating the performance measures of wire cut EDM based on process parameters for AISI 4140. Materials Today: Proceedings. 2015 Jan 1;2(4- 5):1067-1073.

[58] Nourbakhsh F, Rajurkar KP, Malshe AP, Cao J. Wire electrodischarge machining of titanium alloy. Procedia CIRP. 2013 Jan 1; 5:13-18.

[59] Sachdeva G, Khanna R, Yadav P, Nara A, Singh N. Experimental study of H-21 punching dies on wire-cut electric discharge machine using Taguchi"s method. International Journal of Scientific & Engineering Research. 2013;4(5):569-577.

[60] Bobbili R, Madhu V, Gogia Ak. Effect of Wire-EDM Machining Parameters on Surface Roughness and Material Removal Rate of High Strength Armor Steel, Materials and Manufacturing Processes, 2013, 28:4, 364-368

[61] Shandilya P, Jain PK, Jain NK. RSM and ANN modeling approaches for predicting average cutting speed during WEDM of SiCp/6061 Al MMC. Procedia Engineering. 2013 Jan 1; 64:767-774.

[62] Goswami A, Kumar J. Optimization in wire-cut EDM of Nimonic-80A using Taguchi's approach and utility concept. Engineering Science and Technology, an International Journal. 2014 Dec 1;17(4):236-246.

[63] Ekici, E., Motorcu, A. R., & Kus, A. (2015). Evaluation of surface roughness and material removal rate in the wire electrical discharge machining of Al/B4C composites via the Taguchi method. Journal of Composite Materials. 0(0) 1– 12.

[64] Manjaiah, M., Laubscher, R.F., Kumar, A., & Basavarajappa, S. (2016). Parametric optimization of MRR and surface roughness in wire electro discharge machining (WEDM) of D2 steel using Taguchi-based utility approach. International Journal of Mechanical and Materials Engineering, 11(1).

[65] Nandakumar, C Mohan, B and Srisathirapathy, S. (2014) “Optimization of process parameters of titanium alloy grade 5 using cnc wire-cut EDM”Advance Material Research, 984 pages 56-61.

[66] Naresh Kumar, Naveen Krishna, (2018) “Optimization of WEDM Process Parameters on Duplex 2205 steel using Grey Relational Analysis” International journal Of Modern Engineering Research (IJMER).

[67] Pandey, P.C. and Shan, H.S. (2015) “Modern Machining Processes", Tata McGraw-Hill Publishing Company, page 79-80.

[68] Rao, Pujari Srinivasa Koona, ramji and Satyanarayana, Beela (2014) “Experimental Investigation and Optimization of Wire EDM parameters for Surface Roughness, MRR and White layer in machining of aluminum alloy” International conference on Advances in Manufacturing and Materials Engineering, AMME vol. 5, page. 2197-2206.

[69] Rao, Sreenivasa and Venkaiah (2013) “Review on wire cut edm process” International journal of advanced trends in computer science and engineering vol. 2, page 12-17.

[70] Kumar, K.R Sreebalaj, V.S and Ganesan, V. (2015) “Analysis of kerf width and cutting speed characteristics of aluminum/tungsten carbide composites’ Miner Met Mater Engg, page.47-56.

[71] Umare, Ankit and Parchand, Shubham (2017) “WIRE CUT EDM PROCESS - A REVIEW” IJARIIE – ISSN (o), Vol-3 Issue-6 page.2395-4396.

[72] Anand S.Shivade and Vasudev D. Shinde (2014) “ Multi-objective optimization in WEDM of D3 tool steel using integrated approach Taguchi method and Grey relational analysis”, J Ind Eng. Int 10:149-162.

[73] A. Pramanik, A.K. Basak, A.R. Dixit, S. Chattopadhyay (2018) “Processing of duplex stainless steel by WEDM” ELSEVIER, volume -130, page 137-144.

[74] Sujeet Kumar Chaubey, Shankar Singh, Abhishek Singh. (2018), "Some investigations into machining of AISI D2 tool steel using wire electro discharge machining (WEDM) process", Materials Today: Proceedings.

[75] Durairaj, M. Sudha sun, D. and Swamy Nathan, N. (2013) “Analysis of Process Parameters in Wire EDM with Stainless Steel using Single Objective Taguchi Method and Multi Objective Grey Relational Grade” International Conference On design and manufacturing, Icon, Procedia Engineering 64, page 868 – 877.

[76] www.iaeng.org, internet source

[77] Danial, G Golshan, A and Izman, S. (2014) “Optimizing material removal rate (MRR) in WEDM machining titanium alloy (Ti6Al4V) using the Taguchi Method”, JBrazSocie Mech Sci Engg, 36page301 to 310.

[78] Kumar, Rajeev and Singh, Shankar (2015) “Current Research Trends in Wire Electrical Discharge Machining: An Overview” International Journal on Emerging Technologies 3, page 33-40.

[79] Kumar, Sandeep (2013) Current Research Trends in Electrical Discharge Machining: A Review” Research Journal of Engineering Sciences, Vol. 2(2), page 56-60.

[80] K. Rajmohan, A Senthil kumar, (2018) “Experimental investigation and prediction of optimum process parameters of micro-wire-cut EDM of 2205 DSS” The international journal of advanced manufacturing technology,93, 187-201.

[81]Singh, Navjot Kumar, Parlad and Goyal, Kushal deep (2013) “Effect of Two Different Cryogenic Treated Wires in Wire Electrical Discharge Machining of AISI D3 Die Steel”, Journal of Mechanical Engineering, Vol. ME 43 No. 2, page 54-60.

[82] Hassan, Abdel Gawad EI Hofy, (2015) “Advanced Machining Processes”, Tata McGraw-Hill Publishing Company, page 115-139.

[83] Kumar, A. (2013) Modelling of Micro Wire Electro Discharge Machining (WEDM) In Aerospace Material, NIT Rourkela.

[84] Muniappan, A. and Thiagarajan, C. (2017) “EFFECT OF WIREEDM PROCESS PARAMETERS ON CUTTING SPEED OF AL6061 HYBRID COMPOSITE” International Journal of Mechanical Engineering and Technology (IJMET), Volume 8, Issue 10, pp. 185–189.

[85] Ho K. H., Newman S. T., Rahimifard S. and Allen R. D., ‘State of the art in wire electrical discharge machining (WEDM)’, International Journal of Machine Tools & Manufacture 44 (2004) 1247-1259

[86] Harsh Saini, Irfan Khan, Sushil Kumar (2017) “Optimization of Material Removal Rate of WEDM Process on Mild Steel Using Molybdenum Wire”, International Journal of Advanced Engineering, Management and Science (IJAEMS), Vol-3, Issue-10, ISSN: 2454-1311.

[87] Sanjib Kr Rajbongshi, Meinam Annebushan Singh, (2018) “A comparative study in machining of AISI D2 steel using textured and nontextured coated carbide tool at the flank face”, Journal of Manufacturing Processes 36 (2018) 360–372

[88] Surinder Kumar, Parveen Kumar (2016) “Investigation of Material Removal Rate for wire-cut EDM of EN-31 Alloy Steel using Taguchi Technique”, International Journal of Scientific & Engineering Research, Volume 7, Issue 12, ISSN 2229-5518

[89] Vikram Singh, S.K. Pradhan (2014) “Optimization of WEDM parameters using Taguchi technique and Response Surface Methodology in machining of AISI D2 Steel”, Procedia Engineering 97 (2014) 1597 – 1608

[90] K.D. Mohapatra, S.K. Sahoo (2018), “A multi objective optimization of gear cutting in WEDM of Inconel 718 using TOPSIS method”, Growing science ltd. Materials Today: Proceedings 5 (2018) 4793–4802.

[91] M. Manjaiah, Rudolph F. Laubscher1, Anil Kumar (2016) “Parametric optimization of MRR and surface roughness in wire electro discharge machining (WEDM) of D2 steel using Taguchi-based utility approach”, International Journal of Mechanical and Materials Engineering, 10.1186/s40712-016-0060-4

[92] Suvranshu Pattanayak, Debanshu shekhar Khamari, Rajnikant ranbida (2016) “optimization of process parameters of machining h-11 die steel in wire edm”, International Journal of Mechanical and Production Engineering, Volume- 4, Issue-12, ISSN: 2320-2092

[93] Ugrasen G, M R Bhagawan Singh, H V Ravindra. (2018) “Optimization of Process Parameters for SS304 in Wire Electrical Discharge Machining using Taguchi Technique”, Materials Today Proceedings 2877-2883.

[94] S. Banerjee, B. Panja and S. Mitra. (2018) “Study of MRR for EN47 Spring Steel in WEDM” Materials Today: Proceedings 5, 4283–4289.

[95] P. Saha, D. Tarafdar, S. K. Pal, P. Saha, A. K. Srivastava, and K. Das, "Modeling of wire electro-discharge machining of TiC/Fe in situ metal matrix composite using normalized RBFN with enhanced k-means clustering technique", Int J Adv Manuf Technol, Vol. 43. pp. 107-116, 20099

[96] Effect of wire tension on different output responses during wire electric discharge machining on AISI 304 stainless steel Tina Chaudhary Arshad Noor Siddiquee Arindam KumarChanda defence technology volume 15 issue 4 august 2019 541-544

[97] Review on process parameters of WEDM Shubham Sharma A JOURNAL OF COMPOSITION THEORY Volume XII Issue VII JULY 2019 ISSN: 0731-6755

[98] Effect of peak current and peak voltage on machined surface morphology during WEDM of TiNiCu shape memory alloys Abhinaba Roy, S. Narendranath & Alokesh Pramanik Journal of Mechanical Science and Technology volume 34, pages3957–3961 (2020)

[99] IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320–334X Effect of Peak Current on the Performance of WEDM Rajeev Kumar March 2016

[100] International Journal of Engineering Science and Innovative Technology (IJESIT) Volume 2, Issue 1, January 2013 Spark Gap Optimization of WEDM Process on Ti6Al4V Kuriachen Basil, Dr. Josephkunju Paul, Dr. Jeoju M.Issac