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A comprehensive review on processing of Ni-Cr based superalloys through EDM and its variants

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Abstract

Electrical Discharge Machining (EDM) is acknowledged as one of the earliest non-conventional machining process employed successfully to process hard/difficult to machine materials. This process can produce components of complex geometries with precision. It works on the principle of thermo electric energy which removes material from non-contacted electrode and workpiece by the repeated sparks produced. The material from the workpiece and the tool is removed by melting and vaporization. The necessary condition for generating spark between the tool and the workpiece is that both the electrodes must be conductive in nature. This review article discusses the research studies conducted in EDM to enhance the process performance while machining Ni-Cr based Superalloys. These superalloys are extensively used in aerospace, automotive industry and gas turbines etc. Furthermore, this paper outlines the future research possibilities in the same field.

Keywords: Electrical Discharge Machining (EDM), Process parameters, Ni-Cr based superalloys

Nomenclature

EDM	Electrical Discharge Machining	*HAZ*	Heat Affected Zone
REDM	Rotary Electrical Discharge Machining	*MH*	Micro-Hardness
WEDM	Wire Electrical Discharge Machining	*SCD*	Surface Crack Density
µEDM	Micro Electrical Discharge Machining	*WLT*	White Layer Thickness
PMEDM	Powder-Mixed Electrical Discharge Machining	*OA*	Orthogonal Array
EDT	Electrical Discharge Turning	*RSM*	Response Surface Methodology
MRR	Material Removal Rate	*ANOVA*	Analysis of Variance
TWR	Tool Wear Rate	*GRA*	GreyRelational Analysis
EWR	Electrode Wear Rate	*PCA*	Principal Components Analysis
R_a	Surface Roughness	*OFAT*	One Factor at a Time
I_p	Peak Current	*OPAT*	One Parameter at a Time
V	Discharge Voltage	*CFD*	Computational Fluid Dynamics
P_{on}	Pulse-on Duration	*ANN*	Artificial Neural Networks
P_{off}	Pulse-off Duration	*CCD*	Central Composite Design
G	Inter-Electrode Gap	*WWR*	Wire Wear Rate
P	Electrode Polarity		

1. Introduction

EDM is a non-traditional machining process effectively employed to machine difficult-to-machine materials [1-4]. This process is utilized in modern industries to produce parts with higher precision, complex cavities with better surface quality [5-10]. The tool and the workpiece does come in direct contact which thereby helps in reducing residual stresses after machining [11-14]. Therefore, any conducive material can be processed on EDM irrespective of its hardness. The repeated discharge occurs between the tool and the work material in the presence of dielectric liquid. Than material from both the tool and the workpiece is removed by the erosive effect caused by these repeated small discharges. The basic working principle of EDM is applied in number of ways thereby resulting into number of variants like sinking EDM, WEDM, PMEDM, dry EDM and µEDM. Hence, this process is appropriate for both large and µ-scale machining.

1.1 EDM Working principle

In this process, the tool and the workpiece both must be electrically conductive. Both the tool and the specimen are dipped in the dielectric fluid. Commonly deionized water or kerosene is employed as a dielectric. A small gap generally known as 'spark gap' is to be maintained between the tool and

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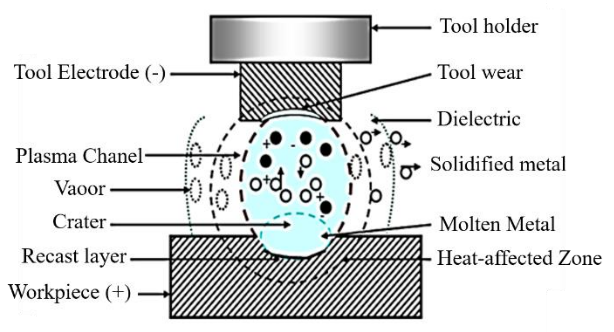

Figure 1 EDM Working principle [15]

the work material. First of all, a potential difference is applied between the two i.e. cathode and anode. An electric field is generated, depending upon the applied potential difference and the spark gap. Usually, workpiece is coupled to (+) ve terminal and electrode is coupled to (-) ve terminal. Since electric field generated, free electrons from the tool are released owing to the less bonding energy of electrons and this emission of electrons is termed as 'cold emission'. Then theses electrons are accelerated towards the work material passing through the dielectric. As these electrons attains velocity, they moves closer to the work surface, collision occurs between the electrons and molecules of the dielectric. Further, this collision results in ionization of the molecules of dielectric. More (+) ve ions and electrons produced owing to this collision. The repetition of this would help in increasing the ions and electrons between the gap. Very high concentration in the gap is described as 'plasma' as shown in Figure 1. Suddenly, a huge amount of (-) ve electrons will flow from electrode to the work material and (+) ve ions from work material to the tool. Movement of theses ions and electrons can be visualized as spark, which generates thermal energy. The electrons thus impact on the workpiece and ions on the electrode. Material removal from tool and the electrode would occur owing to the rise in temperature, which causes melting and vaporization of the material from both the electrodes.

The wide research has been done for machining of Ni-Cr based superalloys through EDM and its variants/hybrid processes. However, comprehensive literature is not available in the form of review. Thus, this paper discusses the said literature in the organized form. This paper starts with a brief introduction about EDM after that its working principle has been explained. The process parameters and performance measures are than discussed in detail. Further, EDM and its variants are discussed followed by researches conducted on theses superalloys. Conclusions and future scope of work are discussed further to enhance the competences of the process.

2. Process parameters

EDM process drives by various factors/parameters. These process parameters can be classified into two types, i.e. electrical parameters and non-electrical parameters. Various process parameters are shown in Figure 2 and the details of these parameters are discussed in the upcoming section

2.1 Electrical parameters

Most important electrical parameters are I_p, V, P, P_{on}/P_{off}, and G. These parameters are discussed below:

2.1.1 Pulse-on time (P_{on})

P_{on} is the time duration on which discharge takes place. It is expressed in terms of micro-seconds. Increase in P_{on} allows more amount of heat to pass and spread through the work material thereby deeper HAZ and larger WLT formed. Therefore, deeper and large size craters formed, which further increases R_a. Hence, P_{on} directly effects MRR [16-19] which increases with higher P_{on} [20]. MRR tends to decrease after attaining an optimum P_{on} value.

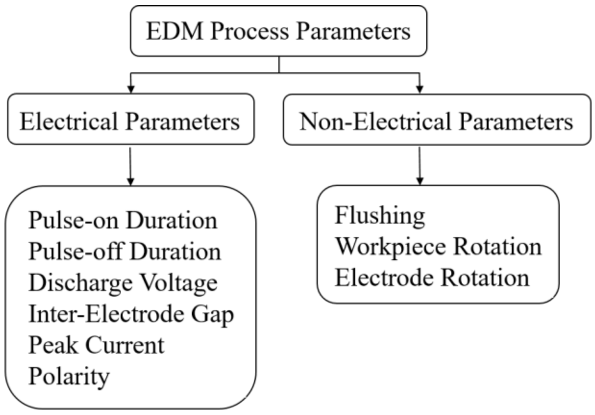

Figure 2 Process parameters

2.1.2 Pulse-off time (P_{off})

P_{off} is the time duration in which no discharge occurs. It is expressed in terms of micro-seconds. P_{off} after each P_{on} allows the flushing of debris from the machining gap. It also enhances cooling time. If P_{off} is too short, the flushing action not takes place properly thereby dielectric deionization will not occur in the next spark. As reported, the appropriate selection of the P_{off} confirms the stable machining [21-23].

2.1.3 Discharge voltage (V)

V is the average voltage in the small gap between the electrode and the workpiece while machining. It is connected with the spark gap and dielectric breakdown strength. V value increases till dielectric ionization occurs between the electrodes. After the current starts flowing, V minimizes and then become stable at the gap level. Hence, increase in V permits increase in the gap which further helps in proper flushing of debris particles and also supports to stabilize the machining cut. So, V regulates the spark gap size and overcut [24-27]. Lower value of V is suggested for most electrical conductive material and vice versa.

2.1.4 Peak current (I_p)

I_p is the amount of power utilized in this process and is considered as a most influential parameter while machining. The value of I_p increases till it reaches the programmed level during each I_p. As the value of I_p increases, the energy input increases thereby enhances MRR. The I_p has directly influences MRR, EWR and the accuracy [28-32]. Now a days, new better quality tools e.g. graphite can work on higher I_p deprived of much loss [33].

2.1.5 Electrode polarity (P)

P may be positive or negative. Normally polarity is determined by trials and is dependent on workpiece and tool material, pulse interval arrangements and density of current. Tool and workpiece both will have opposite charge polarity. Commonly, positive polarity is used for machining [34, 35].

2.1.6 Inter-electrode gap (G)

G is the distance between the workpiece and the tool electrode while machining. This distance is controlled by servo mechanism. This mechanism is planned in such a way that it respond well to average gap voltage [36]. The value of G generally lies in the range of 0.01-0.1 mm and few microns in μEDM [37, 38].

2.2 Non-electrical parameters

The non-electrical parameters are mainly flushing, electrode and workpiece rotation. These factors plays a critical role while optimizing the responses. The details of these factors are discussed below:

2.2.1 Flushing

Flushing refers to the dielectric flow speed towering the machining zone. Flushing aids in removing debris and also acts as a coolant. The type of dielectric employed also helps in enhancing the quality of the machined surface. Many researchers explored the oil-based synthetics to avoid harmful effects to the operator and the environment [39-41]. The method of flushing and type of dielectric affects the MRR, TWR and R_a [42-45].

2.2.2 Workpiece rotation

The process is basically termed as EDT, in which a precise spindle is attached to rotate the work material with the Sinking EDM. Workpiece rotary motion helps in distribution of the temperature of the workpiece as well as the dielectric circulation in the machining gap thereby providing better results for MRR and R_a [46]. Influence of machining parameters on process performance while machining titanium Ti-6Al-4V alloy was investigated utilizing EDT process at reverse polarity. Further, Taguchi-grey relational analysis has been employed to optimize responses like MRR and R_a simultaneously [47]. The MRR enhances as the increase in rotational speed and discharge energy, but also increases R_a [48]. The quality of the work surface was enhanced by introducing vibrations to the rotating SKD11 thereby minimizes white layer and micro-cracks [49]. In EDT process, authors observed that spindle speed and powder are the major factors contributing to MRR by utilizing Taguchi technique [50].

2.2.3 Electrode rotation

The rotary motion of the electrode provides improved flushing action and sparking efficiency [51]. Further, electrode rotation enhances the MRR and improves R_a owing to proper flushing [52-54]. In another investigation reported that MRR is majorly influenced by I_p, electrode rotation and duty factor while machining Inconel 718 using tubular electrode [55]. In a similar work, authors explored the influence of machining factors on composites utilizing rotary tubular electrode [56]. REDM was utilized with varying flushing methods and electrodes to examine the effect on MRR, TWR and R_a while machining composite [57]. Magnetic field was introduced to enhance the machining responses in REDM while machining EN-8 [58]. Servo-speed affects significantly the TWR and MRR utilizing μEDM with rotary electrode during machining of composites [59].

2.3 Performance measures

The performance of EDM are measured by number of factors, mainly MRR, TWR and R_a.

2.3.1 Material removal rate (MRR)

MRR is calculated by the volume of material removed per unit time. As compared to other non-traditional machining processes, lower MRR is one of the drawback of EDM process. Hence, it is important to enhance MRR of the process. Therefore, mechanism and methods of material removal were studied by various researchers with an aim is to enhance the MRR [60-66].

2.3.2 Tool wear rate (TWR)

TWR is calculated by the volume of electrode material removal per unit time. The researchers emphasized on reducing the TWR as it affects the tool shape and further decreases the accuracy level [67-69].

2.3.3 Surface roughness (R_a)

R_a is expressed by the quality of surface, which belongs to the flatness or smoothness of the machined surface. Even though this process is fundamentally a material removal process, efforts have been done to utilize this process as an additive and/or surface treatment technique [70].

3. Types of EDM processes

3.1 Sinking EDM

In sinking EDM process, the number of sparks occurs repeatedly to erode the material from the workpiece. Figure 3 shows the schematic of sinking EDM. Generally, Copper is utilized as a tool material to machine the work material. The main function of the flushing nozzle is to flush the machining debris from the machining gap. The main function of the vertical tool feed system is to provide constant feed to the tool. Filter was attached to remove the impurities/debris from the dielectric fluid. The pump was attached for sending the dielectric to the filter. In this process, workpiece can be machined, either by replicating the tool shape or by 3D (three dimensional) tool movement or by the combination of both. Temperature in the machining zone lies in the range of 8000°C - 12,000 °C during machining. Generally, copper and graphite are utilized as an electrode material. Fresh electrode was employed for final finishing owing to variation in electrode geometries while rough machining. Sinking EDM uses hydrocarbon dielectric owing to its positive influence on the R_a and TWR [71, 72]. The same dielectric filtrated to take out debris particles.

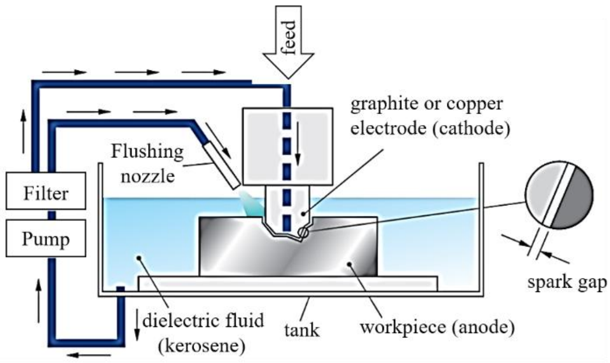

Figure 3 Schematic diagram of sinking EDM [73]

3.2 Wire EDM

In wire EDM process, the material is machined by a metallic wire which moves through a defined path. The material is eroded by number of sparks produced between the non-contacted wire and the work material. Figure 4 shows the schematic of the WEDM. Deionized water is generally used a dielectric in this process. Filter was attached to clean the impurities/debris from the dielectric fluid. The pump was attached for sending the dielectric to the filter. Wire pulley arrangement was attached to continuously travel the wire from the spool which helps to provide fresh wire continuously while machining.

Table 1 Comparison between different variants of EDM

S. No.	Type of EDM	Working	Application	Schematic
1	Sinking EDM	In this process, work material and tool are completely submerged in the dielectric liquid. Generally, kerosene or commercial EDM oil is used as a dielectric fluid. As potential difference is applied between these two, the dielectric breaks down to form a spark, it further strikes the workpiece and increases the localized temperature. This helps in melting and vaporization of both the electrodes, henceforth material is eroded from both the electrodes.	Manufacturing of mold and die, aerospace and automotive industries. It can produce blind features.	Refer to Figure 3
2	WEDM	In this process, conductive wire (0.2mm - 0.3mm) is utilized as a tool. Generally, kerosene or commercial EDM oil is used as a dielectric fluid. The tool i.e. wire moves continuously between the two fixed pulleys and either the work material or the tool is moved towards the tool. Thus, the spark is initiated between the two electrodes. This process is appropriate for through profile cutting. This process cannot process blind features. The most significant feature is that a complex shaped can be cut easily without employing a forming tool.	Manufacturing of dies, punches, and tools.	Refer to Figure 4
3	Dry EDM	A thin walled electrode is utilized through which this gas/air is supplied. In this process, high pressurized gas such as helium, argon is used as dielectric fluid. The purpose of this high pressurized gas is to cool the machining gap and to remove the debris particles from the gap. This variant was developed to decrease the pollution caused by the vapors produced from dielectric while machining.	This process is used especially where an environmentally-friendly environment is required as it tends to eliminate environmental problem.	Refer to Figure 5
4	μEDM	The working principle of μEDM is similar to WEDM and sinking EDM with the only difference that machining is done at micro-scale level to conquer the today's need of miniaturization.	Manufacturing of micro-shafts, micro-holes, micro molds and dies, tool inserts, micro filters, housings for micro-engines, surgical equipment.	-------
5	PMEDM	In this process, the powder is mixed with dielectric media. The presence of these particles modifies the mechanism completely from traditional process. As the voltage is applied, the spark gap increases by the presence of particles between the tool and workpiece. Early explosion and faster sparking takes place owing to the chain formation which further helps in bridging the spark gap between the electrodes, causes faster erosion from the work surface, hence enhancing MRR.	Manufacturing of engine blocks, cylinder liners, piston heads and carburetors.	Refer to Figure 6

Wire diameter lies in the range of 0.1 to 0.3 mm. Generally, it is made up of copper, brass and steel coated materials. The workpiece is to be fixed on the CNC worktable. This process has wide range of applications in the field of die making, electronics, medicine and automotive industries [74, 75]. The zinc-coated brass wire improves the performance process [76-78].

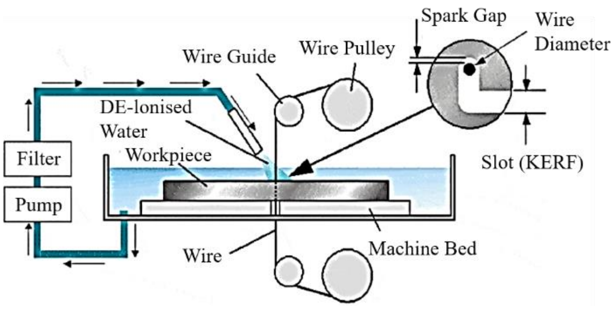

Figure 4 Schematic diagram of WEDM [79]

3.3 Micro EDM (μEDM)

The working principle of μEDM is similar to WEDM and sinking EDM with the only difference that machining is done at μ-scale level. Capabilities of this process includes machining of micro-shafts, micro-holes up to the diameter of 5 μm [80] and 3D complex micro-cavities. On this process, various researchers proposed numerical simulation model with validation of experimental data [81]. The values for power dissipation, crater area, current density are predicted reasonably by this model. Plasma temperature, crater radius, single discharge MRR were predicted by utilizing the models which were comparable to the experimental data [82].

3.4 Dry EDM

In dry EDM, instead of dielectric a high pressure gas or air is used as an alternative of dielectric fluid [83-87]. A thin walled electrode is utilized through which this gas/air is supplied. The purpose of this high pressurized gas is to cool the machining gap and to remove the debris particles from the gap as shown in Figure 5. This variant was developed to decrease the pollution caused by the vapors produced from dielectric while machining as well as the cost associated to manage the waste. This process helps in enhancing MRR and reducing EWR [88-90].

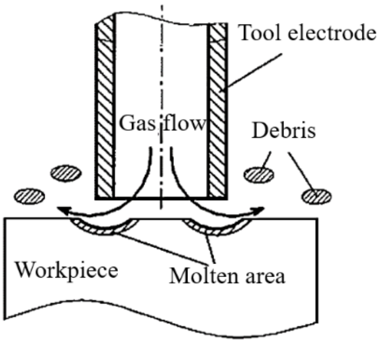

Figure 5 The principle of dry EDM [91]

3.5 Powder mixed EDM (PMEDM)

A powder of suitable material is mixed in the dielectric medium. Presence of these powder particles modifies the mechanism completely from conventional EDM process [92]. The machining gap which is filled up with these powder particles increases from 25-50 to 50-150 µm while applying suitable voltage [93]. Further, these particles place themselves and gathers in the machining area. Early explosion and faster sparking takes place owing to the chain formation which further helps in bridging the spark gap between the electrodes, causes faster erosion from the work surface, hence enhancing MRR. A typical PMEDM setup is shown in Figure 6. This arrangement is to be held on the machine table. A stirring arrangement was attached to avoid settling down of the abrasives at the bottom of the PMEDM tank. Pump is attached to circulate the dielectric and also helps in flushing of the debris. The magnets are provided to disperse the machining debris from the abrasives. This method is helpful only when work material is magnetic in nature whereas powder is not.

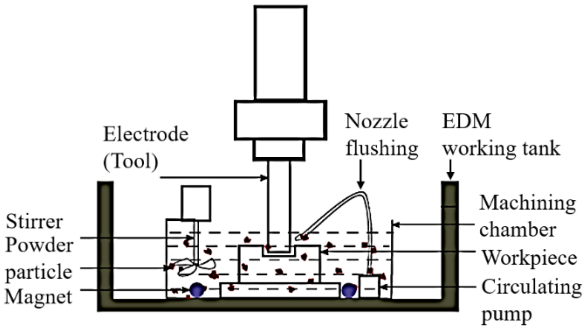

Figure 6 Typical PMEDM setup [94]

Also refer to Table 1, which discusses the comparisons between different variants of EDM.

4. Recent studies of Ni-Cr based superalloys through EDM process

Ni-Cr based superalloys are employed successfully in modern industries owing to its light weight and resistance to oxidation at higher temperature i.e. up to 1250°C. These superalloys displays outstanding properties like good surface stability, higher toughness and ductility, corrosion and oxidation resistance, creep resistance at high temperature [95-97]. Generally, Ni-Cr based superalloys (especially Inconel) are extra-alloyed with Al, Ti, Nb, Co, Cu and W to enhance mechanical and corrosion resistance. Inconel materials are most extensively used in aircraft turbines, rocket engines, power generation turbines, nuclear plants, chemical treatment plants [98]. Figure 7 illustrates the material distribution in GF CF6 aircraft engine, it displays that almost 50% contribution is of the Ni-based alloys and Inconel [99]. Therefore, machining of Inconel has become a dynamic research area. Several researchers have reported major issues while machining these superalloys. These are as follows [100-104]:

- During machining, it retains higher strength.
- Increase of tool wear because of the existence of carbides and hard abrasive elements in microstructure and tendency of work hardening during machining.
- Rising temperature at the tip of tool, thermal effects seem unfavorably predominant during machining (i.e. poor thermal conductivity).
- It maximizes diffusion wear for various tool materials because of higher chemical affinity.
- More tendency to join and to form built-up edge.
- Because low specific heat and higher cutting temperature.

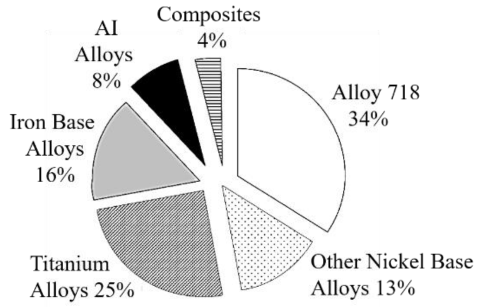

Figure 7 Materials distribution for GE CF6 engine [99]

Therefore, to resolve these problems, the non-traditional machining processes such as abrasive water jet machining (AWJM), electrochemical machining (ECM), wire electrical discharge machining (WEDM), laser beam machining (LBM) are successfully employed for machining of these superalloys [105-108]. Out of several non-conventional methods, EDM is popular, specifically for die and mould making industries [109]. EDM is a commonly utilized non-traditional machining method of processing any electrically conductive workpiece into complicated and intrinsic shapes [110]. The tool and the workpiece does not form direct contact thereby reducing residual stresses after machining [111-114]. However, there are some challenges related to the EDM concerning lesser MRR and poor machined surface quality of the parts produced [115]. For surmounting these drawbacks, certain modifications have been made in the process thereby resulting into number of process variants i.e. sinking EDM, WEDM, PMEDM, Dry EDM and µEDM. Therefore, these variants enables to attain higher MRR and low R_a. The relevant literature (research conducted) for Inconel grades by EDM and its variant are discussed in Table 2. Furthermore, different grades of Inconel processed with corresponding EDM process are summarized in Table 3.

5. Conclusions

Based on the intensive scrutiny of literature on the EDM processes of Ni-Cr based superalloys, the following observation can be drawn:

- It is evident from the Table 3 that most of the published research work is on Inconel 718 as compared to other Inconel grades.
- I_p and P_{on} considerably affected the process performance while machining Ni-Cr based superalloys.
- Machining with Cu electrode leads to lower EWR and higher MRR as compared to tungsten and graphite electrodes.
- Most of the research work is conducted on sinking EDM and WEDM. Comparatively less research work is done by other EDM process variants.
- In WEDM, smaller wire diameter is preferred over the wire of larger diameter as it improves productivity as well as quality of work surface.
- Many researchers have contributed on optimization of the process parameters (i.e. mainly electrical parameters along with flushing pressure) to improve the responses. But, very less work has been reported on optimization of non-electrical parameters.
- Zinc coated wire is preferred where higher productivity is required as compared to hard brass and diffused wire whereas diffused wire has moderate effect on both quality of surface produced and productivity as compared to hard brass and zinc coated wire.

Table 2 Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process parameters	Response parameters	Techniques used	Findings and inferences
Torres et al. (2017) [116]	Sinking EDM	600	Copper infiltrated graphite (C-Cu).	I_p (2,4,6,8 A), P_{on} (25,50,75,100 µs), Duty cycle (0.3,0.4,0.5,0.6), P (+, -)	Mean spacing of profile irregularities (60.60 µm), Peak count (164.80 cm^{-1})	ANOVA	To attain the lowermost R_a the optimized settings are I_p (2 A), P_{on} (25 µs) and duty cycle (0.5) along with positive polarity.
Rahul et al. (2016) [117]	Sinking EDM	601	Graphite electrode	V (60,70,80,90V), I_p (5,7,9,11A), P_{on} (200,300,400,500µs), Duty Factor (70,75,80,85%), Flushing pressure (0.3,0.4,0.5,0.6 bar)	MRR, EWR, R_a, SCD	L16 OA	The optimized parameters for satisfying response parameters are attained are V (80V), I_p (7A), P_{on} (500µs), duty factor (80%), flushing pressure (0.3bar) and found that optimal parameters vary by varying different grades of Inconel.
Singh et al. (2018) [118]	Sinking EDM	601	Electrolytic copper	V (50,65,80V), I_p (6,9,12A), P_{on} (50,10,150 µs)	MRR, R_a	ANOVA and RSM	It is clear from the results that as currents increases MRR and R_a increases.
Kuppan et al. (2008) [119]	EDM (Drilling)	718	Electrolytic copper tube	I_p (2,4,6,8,10A), P_{on} (20,40,60,80,100 µs), Duty factor (45,50,55,60,65%), Electrode speed (0,100,200,300,400 rpm)	MRR, Depth averaged R_a	RSM (CCD)	P_{on} is not significant on MRR but influences the depth average R_a and speed of electrode leads to increase in MRR.
Xavior et al. (2018) [120]	Sinking EDM	718	Copper	I_p (8,14,20 A), P_{on} (200,400,810 µs), V (4,6,8 V), P_{off} (100,150,200 µs)	R_a, Tensile strength, Hardness, WLT	L9 OA	Increase in current, current pulse duration enhances material removal and tensile strength and hardness decreases.
Li. et al. (2014) [121]	Sinking EDM	718	Cu and Cu-SiC electrode	P_{on} (2.4,4.2,7.5,13,24.5 µs), I_p (3.2,5.6,14.2,18.4, 25.6A), pulse-interval (18µs)	MRR, R_a, EWR	---	As compared to the Cu electrode, the fabricated Cu-SiC electrode increases material removal efficiency and improves R_a. The electrode wear rate of newer electrode was lesser as compared to Cu electrode.
Ahmad et al. (2015) [122]	Sinking EDM	718	Copper electrode	I_p (20,30,40 A) P_{on} (200,300,400 µs), Depth of Cut (3mm), V (120V)	MRR (34.94 mm^3/min), EWR (-0.0101 mm^3/min), R_a (8.53µm)	---	The process parameters explored for maximum MRR are I_p (40A) and P_{on} (400µs). Lesser value of I_p and P_{on} must be selected for attaining good surface finish and for reducing EWR author recommended longer P_{on} but it unfavorably affects I_p
Rahul et al. (2017) [123]	Sinking EDM	718	Copper	V (50,60,70,80,90 V), I_p (3,5,7,9,11A), P_{on} (100,200,300,400,500 µs), Duty factor (65,70,75,80,85%), Flushing Pressure (0.2,0.3,0.4,0.5,0.6 bar)	MRR, EWR, R_a, SCD, WLT, MH	L25 OA	Owing to the Taguchi's optimization theory, in this article, the concept of satisfaction function had been introduced in this research. The optimized process parameters to satisfy the response parameters are V (80V), I_p (11) A, P_{on} (100µs), duty factor (85%) and flushing pressure (0.4bar).
Sahu et al. (2018) [124]	Sinking EDM	718	Copper	I_p (10,15,20 A), P_{on} (100,200,300 µs), V (20,24,28 V)	MRR, SCD, WLT, MH	---	Development of Nickel-Niobium was found out on the machined work surface. MH increases as compared to parent material due to the carbon enrichment on machined surface. P_{on} significantly affects the WLT, MRR and SCD.

Table 2 (continued) Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process Parameters	Response parameters	Techniques used	Findings and inferences
Vishnu et al. (2018) [125]	Sinking EDM	718	Electrolytic copper	P (+, -), P_{on} (50,100,150 µs), P_{off} (30,60,90 µs), I_p (5,10,15 A)	MRR, R_a, TWR	L18 OA + ANN	The accuracy of prediction model i.e. ANN for MRR (98.82%), TWR (88.02%) and R_a (93.97%). Therefore, ANN model is beneficial in optimizing the process parameters for attaining required MRR and R_a.
Sahu et. al. (2018) [126]	PMEDM	718	Copper	I_p (15,20,25,30 A), V (230 V), P_{on} (2000 µs), P_{off} (500 µs), Flushing pressure (0.5 kg/cm^2), P (+), G (50 microns), Depth of cut (0.75 mm), Powder concentration (6 g/l)	MRR, TWR, R_a, SCD, WLT	---	Addition of SiC powder to dielectric media during EDM improved MRR, TWR reduced, higher surface finish, and lesser SCD better surface morphology. During PMEDM process, thicker white layer (due to improper flushing and higher volume of material removal) was formed on machined surface.
Rahul et al. (2016) [127]	Sinking EDM	625	Graphite electrode	V (60,70,80,90V), I_p (5,7,9,11A), P_{on} (200,300,400,500µs), Duty Factor (70,75,80,85%), Flushing pressure (0.3,0.4,0.5,0.6 bar)	MRR, EWR, R_a, SCD	L16 OA	The optimized parameters for satisfying response parameters are attained are V (90V), I_p (5A), P_{on} (200 µs), duty factor (70%), flushing pressure (0.6 bar) and found that optimal parameters vary by varying different grades of Inconel.
Rahul et al. (2017) [128]	Sinking EDM	718	Brass, Graphite, Copper	V (65,75,85 V), I_p (4,6,8 A), P_{on} (200,300,400 µs), Duty factor (75,80,85 %), Flushing pressure (0.4, 0.5, 0.6 bar)	MRR, TWR, R_a, SCD	L27 OA	The optimized process parameters are V (65V), I_p (8A), P_{on} (200µs), duty factor (85%), flushing pressure (0.6bar) with Cu electrode to satisfy the response parameters. Therefore, Cu electrode is preferred over brass and graphite for machining Inconel 718 and out of all process parameters, I_p was found to be most significant on response parameters.
Li. et al. (2014) [129]	WEDM	718	Brass wire electrode	V (80,120,200 V), I_p (8,16 A), P_{on} (0.2,0.4,0.9 µs), P_{off} (1.5,3.0,3.8 µs), Wire Speed (8, 10 m/min.), Wire tension (1.0,1.4, 1.6daN), Flushing (80,550 MPa), P (+, -)	MRR, R_a	---	Higher material removal efficiency because of lower thermal conductivity of the workpiece material and micro cracks did not arise on work surface as Inconel 718 material have higher toughness.
Kumari et al. (2017) [130]	Sinking EDM	825	Graphite, Tungsten, Brass, Copper	I_p (6, 8,10A).	MRR, R_a, SCD, WLT, Micro-indentation hardness	---	MRR, R_a, WLT increases with the increase in peak current but SCD first decreases than starts increasing. Out of the four electrodes maximum volume the material removed by copper electrode.

Table 2 (continued) Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process parameters	Response parameters	Techniques used	Findings and inferences
Tanjilul et al. (2018) [131]	EDM (Drilling)	718	Brass	I_p (13.4, 26,38.4. 48.8 A), G (200 μm), P_{on} (20 μs), P_{off} (6 μs), Vacuum (with, without)	Machining time, Drilling depth, Average R_a, Particles size	CFD model	An innovative flushing system is proposed for vacating debris particles efficiently. Debris size increases with the increasing current. Depth of drilling, suction and flushing pressure can be calculated by putting already calculated debris particle size in CFD model.
Naik et al. (2017) [132]	W-EDT	718	Zinc coated brass wire electrode	Rotational speed (150,250 rpm), P_{on} (108,116,124 μs), P_{off} (24,32,40 μs), V (18,36,54 V), wire feed rate (2,4,6 m/min), flushing pressure (1.8,2,2.2 bar)	MRR (3.2968 mm^3/min)	L18 OA	The optimized parameters are rotational speed (250rpm), P_{on} (124μs), P_{off} (40μs), V (18V), wire feed rate (2m/min), and flushing pressure (1.8bar) for maximizing MRR and pulse on time has most significant effect on the same.
Holmberg et al. (2017) [133]	WEDM	718	CuZn36, γ-messing coating	Cutting speed (0.36 mm/min), Wire diameter (0.25 mm), Nozzle gap (0.1 mm), Nozzle diameter (6.5 mm), Wire feed (15-machine setting)	Residual stresses, R_a, Surface contamination	---	Here, two post processes in combination are required to recover the intermittent surface of recast layer produced after machining. Shot peening process produces smoother surface however high-pressure water jet and grit blasting produces rough surface of the workpiece.
Lipiec et al. (2018) [134]	EDM (Drilling)	718	Copper	P_{on} (100, 500, 1000 μs) I_p (3,3.5,4,4.5,5 A) V (80,100, 120 V), Electrode rotation speed (400 1/min), dielectric inlet Pressure (8 MPa)	Linear tool wear, Side gap, Taper angle, Drilling speed, L/D ratio (above 15)	---	Increasing P_{on} increases drilling efficiency whereas efficiency starts decreasing beyond 500 μs P_{on}. The best parameters for achieving greater depth and higher drilling speed are dielectric medium pressure (80 bar) and electrode rotation speed (400 1/min) allows for proper debris removal from the gap which also agrees to increase voltage and current.
Ay et al. (2012) [135]	μEDM	718	Copper–tungsten (Cu – 75 wt% W)	I_p (100,200,500,1000 mA), P_{on} (3, 12, 25, 50 μs)	The hole taper ratio, hole dilation	L16 OA	As energy density is higher, the hole taper ratio, EWR and hole dilation increase by increasing P_{on} and I_p both.
Singh et al. (2018) [136]	μEDM (Drilling)	718	Tungsten carbide (94% WC, 6% Co)	Ultrasonic power (0,40,80,120 W), I_p (1,2,3 A), P_{on} (6,12,18 μs), P_{off} (20,30,40 μs), Reverse Polarity, Frequency (25 kHz)	MRR, TWR, Hole taper	OPAT	It was investigated that use of ultrasonic vibrations leads to enhanced MRR, lesser TWR and hole taper and also explored reduction in debris re-solidification at the rim and periphery which improves quality and accuracy of holes manufactured. The optimum process parameters for improving MRR are I_p (3A) and P_{on} (6μs) whereas 12μs P_{on} for lower TWR and hole taper.

Table 2 (continued) Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process Parameters	Response parameters	Techniques used	Findings and inferences
Rahul et al. (2016) [137]	Sinking EDM	718	Graphite electrode	V (60,70,80,90V), I_p (5,7,9,11A), P_{on} (200,300,400,500µs), Duty factor (70,75,80,85%), Flushing pressure (0.3,0.4,0.5,0.6 bar)	MRR, EWR, R_a, SCD	L16 OA	The optimized parameters for satisfying response parameters are attained are V (90V), I_p (5A), P_{on} (200µs), duty factor (85%), flushing pressure (0.4bar) and found that optimal parameters vary by varying different grades of Inconel.
Naik et al. (2016) [138]	W-EDT	718	Copper	Rotational speed (150,250 rpm), P_{on} (108,116,124 µs), P_{off} (24,32,40 µs), V (18,36,54 V), wire feed rate (2,4,6 m/min), Flushing pressure (1.8,2.0,2.2 bar)	MRR, R_a	L18 OA	MRR and R_a are typically influenced. At lower V and P_{on}, micro voids and micro globules are reduced.
Haq et al. (2018) [139]	PMEDM	718	Electrolytic copper (99.9% pure)	P_{on} (40,80,120 µs), I_p (4,8,12 A), P_{off} (15,20,25µs), Powder concentration (0,3,6 g/l)	R_a (2.8 µm), MRR (99.5 g/min)	RSM (CCD) + ANOVA	The best response parameters values can be attained with the process parameter values I_p (7.1A), P_{on} (75.51 µs), P_{off} (25 µs) and powder concentration (6 g/l). R_a is directly affected by P_{on} and I_p and inversely affected by P_{off} and powder concentration.
Kumar et al. (2018) [140]	PMEDM	825	Copper	I_p (2,5,8 A), P_{on} (8,14,20 µs), V (10,30,50 V), Powder concentration (0.6 g/litre)	MRR, R_a, TWR	RSM (Box–Behnken)	Response parameters are influenced by all three process parameters i.e. I_p, V and P_{on} and also concluded that optimum powder concentration is 0.6g/l.
Kumar et al. (2017) [141]	PMEDM	825	Copper	I_p (2,5,8 A), P_{on} (4,7,10 µs), V (10,30,50 V),	MRR (47 mg/min), R_a (1.487 µm),	RSM (Box–Behnken)	The nano powder (Al_2O_3) was used for machining with deionized water as dielectric. The results confirmed that all three process parameters were significant. Nano powder EDM machining results attained improvement in surface topography and vast reduction in microcracks in comparison to conventional sinking EDM.
Hewidy et al. (2005) [142]	WEDM	601	Brass wire (CuZn377)	I_p (3,4,5,6,7 A), Duty factor (0.375,0.43,0.50,0.60,0.75) Wire tension (7,7.5,8,8.5,9 N), Dielectric fluid pressure (0.3,0.4,0.5,0.6,0.7 MPa)	MRR, (8mm^3/min), Wear ratio, R_a (less 0.8 µm)	RSM (central composite-second order ratable design)	MRR also increases with increase in fluid pressure. MRR, R_a, wear ratio enhanced with the increase of the I_p. With the increase of wire tension and duty factor the value of R_a decreases.
Sharma et al. (2016) [143]	WEDM	706	Hard brass wire, Diffused wire, Zinc-coated wire (Cu-63% + Zn-37%)	Wire Feed (3,6,9 m/min.), V (60,40,20 V), P_{off} (52,39,26 µs), P_{on} (105,110,115 µs), Discharge energy (0.0353,0.0369,0.0386 J)	Cutting speed, R_a, WLT, Residual stresses, MH	---	As compared to hard brass and zinc coated wire, diffused wire has moderate effect on both quality of surface produced and productivity. It was explored that hard-brass wire machined surface offers minimum residual stresses, thinner recast layer, lower R_a and minimum variation in hardness. Zinc coated wire is applicable where higher productivity is required and produces rougher surface.

Table 2 (continued) Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process parameters	Response parameters	Techniques used	Findings and inferences
Welling (2014) [144]	WEDM	718	Brass wire	V (80,200 V), P_{on} (0.5,0.4,0.6µs), P_{off} (0.6,5.0,5.4 µs), I_p (4,10 A), Offset (0.138,0.143,0.217 mm)	Surface integrity, Fatigue strength, R_a (0.8 µm)	---	Thin white (recast) layer is visible on the machined surface with a 2 µm average thickness. Furthermore, during investigation no surface defects and micro cracks were found. Bending moment of the same magnitude found for both broached and wire machined specimen and also concluded that WEDM is a substitute to broaching process for constructing fir tree slots.
Sharma et al. (2015) [145]	WEDM	706	Standard brass	P_{on} (105,110,115,120,125 µs), P_{off} (18,27,36,45,54 µs) V (20,35,50,65,80 V) Wire feed (2,4,6,8,10 m/min) Servo feed (5,10,15,20,25 mm/min), Flushing pressure (1.37,1.67,1.96,2.25,2.55 bar)	MRR, R_a, Recast surface, MH	OFAT	The average recast layer reported that lies in the range of 10 to 50 µm. Quenching phenomenon due to dielectric fluid while machining shows that decrease in subsurface MH. V, P_{off} and P_{on} strongly influences MRR as well as R_a but servo feed appears ineffective.
Klocke et al. (2014) [146]	WEDM	718	Standard brass wire, Ni-coated wire, high-speed-cutting wire,	P_{on}, P_{off}, V, Offset	R_a, Production time (one slot), WLT, Surface integrity	---	When compared to standard brass wire, 33% reduction in manufacturing time (single slot) by the use of coated high-speed cutting wire electrodes. By the use of standard brass wire electrode, the finest surface integrities and accuracies were achieved. The unwanted contamination of Cu and Zn can be reduced by Ni coated wires.
Hewidy et al. (2005) [147]	WEDM	601	Brass wire (CuZn377)	I_p (3,4,5,6,7 A), Duty factor (0.375,0.43,0.50,0.60,0.75) Wire tension (7,7.5,8,8.5,9 N), Dielectric fluid pressure (0.3,0.4,0.5,0.6,0.7 MPa)	MRR (8mm^3/min), Wear ratio, R_a (0.8 µm)	RSM (central composite-second order ratable design)	MRR, R_a, wear ratio enhanced with the increase of the I_p. With the increase of wire tension and duty factor the value of R_a decreases. MRR also increases with increase in fluid pressure.
Rahul et al. (2016) [148]	Sinking EDM	825	Graphite electrode	V (60,70,80,90V), I_p (5,7,9,11A), P_{on} (200,300,400,500µs), Duty factor (70,75,80,85%), Flushing pressure (0.3,0.4,0.5,0.6 bar)	MRR, EWR, R_a, SCD	L16 OA	The optimized parameters for satisfying response parameters are attained are V (80V), I_p (5A), P_{on} (300µs), duty factor (85%), flushing pressure (0.4bar) and found that Optimal parameters vary by varying different grades of Inconel.

Table 2 (continued) Relevant literature for Inconel grades by EDM and its variant

Authors (Year) [Reference No.]	Process	Inconel grade	Tool	Process parameters	Response parameters	Techniques used	Findings and inferences
Sharma et al. (2018) [149]	WEDM	718	Zinc coated wire	I_p (2,12 A), P_{on} (105,112 µs), P_{off} (20,36 µs), V (10,20 V), Servo Feed (200,2150 mu), Wire offset (0,50 µm)	WLT, MH, Residual stresses	---	Negligible WLT and very low tensile residual stresses reported by trim offset technology. Under the same technology, subsurface MH was spotted unaltered.
Klocke et al. (2014) [150]	WEDM	718	Brass wire	P_{on}, P_{off}, V, Offset	R_a, Surface integrity, WLT	---	Researcher reported that best surface integrities are attainable at critical process areas and parts which are more critical. Fir tree slots are produced by WEDM with negligible WLT.
Atzeni et al. (2015) [151]	WEDM	718	Zinc coated brass wire (CuZn37)	I_p (8,16,24,32,48 A), P_{on} (0.03,0.16,0.20,0.25 µs), Wire feed rate (1.2,1.3,1.4,8.1,8.3 mm/min)	R_a, MH	---	Author concluded that as the value of nominal energy per length increases then the R_a also increases.
Sharma et al. (2017) [152]	WEDM	706	Zinc-coated brass wire	P_{on} (105,115,125 µs) P_{off} (27,45,63 µs) Wire Feed (2,4,6m/min) V (24,32,40 V)	MRR, R_a, MH	L9 OA (GRA and PCA)	Taguchi-GRA-PCA hybrid method is used and optimum controlled parameters are wire feed (4 m/min), P_{off} (27 µs), P_{on} (105 µs) and V (32 V).
Kumar et al. (2018) [153]	WEDM	825	Plain brass wire	P_{on} (107,109,111,113,115 µs), P_{off} (32,35,38, 41,44 µs), V (42,46,50,54,58 V), I_p (110,120,130,140,150 A), Wire Tension (8,9,10,11,12 kg-f), Wire feed rate (4,5,6, 7,8 m/min)	MRR (41.822 mm^2/min), R_a (2.445µm), WWR (0.01758)	RSM (CCD) + GRA	Authors reported improvement in MRR by 13.62% and reduction in R_a and WWR by 13.97% and 4.03% respectively by using multi-response optimization technique. Investigational outcomes presented that P_{off}, P_{on}, I_p and wire feed significantly affected the MRR and surface integrity both.
Ramakrishnan et al. (2008) [154]	WEDM	718	Brass wire	P_{on} (0.6,0.8,1.2 µs), Delay time (4,6,8 µs), Wire feed speed (8,12,15 m/min), I_p (8,12,16 A)	MRR, R_a	L9 OA	Increasing I_p and P_{on} helps in enhancing MRR but also degrades the quality of machined surface. For both the response parameters, wire feed speed also plays an important role.
Sharma et al. (2016) [155]	WEDM	706	Standard brass (150,200,250 µm)	Discharge energy (0.353, 0.0369, 0.0386 J) P_{on} (105,110,115 µs) P_{off} (52,39,26 µs) V (60,40,20 V) Wire feed (3,6,9 m/min)	Cutting speed, R_a, Recast layer formation, MH	---	It was explored that wire of smaller diameter is beneficial over the wire of larger diameter as it improves productivity as well as quality of work surface. But, with a problem of wire breakage as it has minimum tensile strength as compared to larger diameter. The main factors which contributes to wire rupture are V and P_{on}.

Table 3 Different grades of Inconel processed with corresponding EDM process

Inconel grades	EDM Process [Reference number]
Inconel 600	Sinking EDM [116]
Inconel 601	Sinking EDM [117] [118] WEDM [142] [147]
Inconel 625	Sinking EDM [127]
Inconel 706	WEDM [143] [145] [152] [155]
Inconel 718	Sinking EDM [120-125] [128] [137] EDM (Drilling) [119] [131] [134] W-EDT [132] [138] WEDM [129] [133] [144] [146] [149] [150] [151] [154] µEDM [135] [136] PMEDM [126] [139]
Inconel 825	Sinking EDM [130] [148] WEDM [153] PMEDM [140] [141]

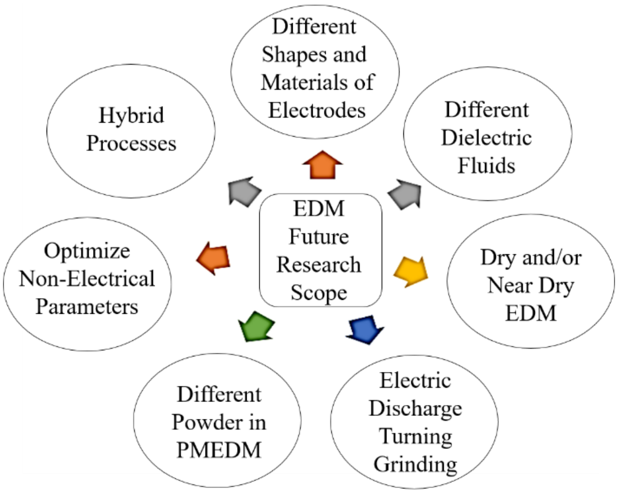

Figure 8 Future scope of work

- It can be observed that by adding suitable powders to the dielectric media enhances the process performance specifically MRR.
- Electrode or workpiece rotation also enhances the MRR though it also increases R_a.

6. Future research trends

The pictorial representation of the future research directions is shown in Figure 8.

- More emphasis is required on research of machining different grades of Inconel by EDM and its variants as compared to Inconel 718.
- Investigation on influence of different powder materials in PMEDM needs to be carried out.
- Very few literature is available on assisted machining like magnetic, ultrasonic etc. Therefore, this is an emerging area and yet to be explored.
- Other hybrid processes can be explored to attain enhanced response parameters i.e. combining two processes e.g. EDM with Ultrasonic machining (USM).
- Little work was available on modelling and simulation of parameters while machining these superalloys.
- Non-electrical parameters optimization has been done by few researchers. So, this is also an emerging field and can be explored more extensively.
- Tool materials processed by powder metallurgy can be trial and explored to machine these superalloys through EDM and its variants.

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