Optimization of Nitriding Steel EN41 Responses by S/N Ratios Combined with Utility Methods

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CERTIFICATE

This is to certify that the Project Report entitled "**OPTIMIZATION OF NITRIDING STEEL EN41 RESPONSES BY S/N RATIOS COMBINED WITH UTILITY METHODS**" being submitted by SWARNAPUDI BHAVYASRI (317126520173), GUDE CHANDRA KANTH (317126520130), KUNDRAPU PRAVEEN (317126520146), YAMALA ANILREDDY (317126520179), SHAIK PEER AHMED (317126520170) in partial fulfillments for the award of degree of **BACHELOR OF TECHNOLOGY** in **MECHANICAL ENGINEERING, ANITS**. It is the work of bona-fide, carried out under the guidance and supervision of **MR.CH. MAHESWARA RAO**, Assistant Professor, Department Of Mechanical Engineering, ANITS during the academic year of 2017-2021.

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Abstract

The present work is to explore the influence of Wire EDM process parameters on the multiple performance characteristics of Material Removal Rate (MRR) and surface roughness characteristics (Ra and Rz). A number of controlled experiments were done on a Nitriding Steel EN41 using CNC Wire EDM machine. Taguchi's standard L18 orthogonal array (OA) has been planning for conducting the experiments. The optimal setting of process parameters was analyzed by Taguchi S/N ratios and Utility methods.

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CHAPTER-1

INTRODUCTION

The wire electrical discharge machining (WEDM) is currently one of the most well-known and applied electro thermal machining processes by which the material removal from the work piece occurs due to nonstationary electrical discharges developed between the traveling wire tool electrode and the work piece. The resulting waste is removed from the working gap due to the circulation of a dielectric fluid. The wire tool electrode must unwind on one coil wheel and wrap on another coil wheel to reduce or even avoid the influence of material loss due to electrical discharges that also contribute to the removal of material from the wire tool electrode. In the working gap, the traveling wire electrode has a rectilinear shape due to its low rigidity and the presence of a tension force and suitable guiding subsystems. If initially only ruled surfaces were obtained by WEDM, now there has been a certain diversification of the machining processes included in the general group of WEDM machining techniques, since it is possible to obtain other various categories of surfaces. As another limitation of use in industrial practice, at least the classic version of WEDM did not allow the machining of blind holes or cavities. To some extent, this limitation is currently being eliminated using the WEDM milling process. The chapter includes a characterization and evaluation of the main current achievements in the field of a WEDM process. The steps that led to the emergence and the promotion of the WEDM process were considered in more detail. A systematic presentation of the main ways of approaching and optimizing the different aspects specific to the WEDM process.

1.1 Essential Aspects of the WEDM Processes

In the initially promoted version, the WEDM process involved the use of a traveling wire electrode (v_{TE} = 0.1–10 m/min) vertically positioned and supported in the machining zone on two guide subsystems. There was movement between the wire tool electrode and the plate-type work piece (2–6 mm/min) in a horizontal coordinate system. The working gap usually has values of 0.02–0.05 mm. As the other conditions for carrying out a process of electrical discharge machining were also fulfilled, from the plate type work piece, it was possible to gradually separate a part characterized by simpler or more complex contours. In this version, it was possible only to obtain ruled surfaces in which the right line generatrix remained permanently parallel to the vertical direction.

The wire tool electrode’s upper guide support can achieve a controlled movement, also in the horizontal plane (Figure1). Thus, for example, this allows the approach of machining some conical surfaces. The addition of other possibilities for moving the wire electrode and the work piece has significantly increased WEDM process versatility.

The diameter of the wire electrode was 0.01–0.3 mm. It must first be flexible enough to take the form of guide rollers or coin wheels on which it is stored. A second necessary condition that the wire electrode material must meet that it has a high tensile and bending strength. The wire had to be as long as possible (7–12 km), to allow machining without the interruption of the contours, themselves of long length, and in work pieces whose thickness has increased over the years.

As a working fluid, deionized water is usually preferred since it has high fluidity and allows, as such, the relatively simple removal of particles detached by the electro erosive process by the action of gravity. A less convenient aspect is the possible development of an electrolysis process. The electrolysis could generate micro explosions by igniting hydrogen from bubbles formed due to the electrolysis process, with undesirable consequences on the wire's integrity, but also on the quality of the machined surface. For this reason, other liquids usable for processing by wire EDM have been investigated and promoted.

The speed of movement of the wire along its axis must be high enough to avoid affecting the precision of processing by possible thinning of the wire due to electrical erosion, which also affects the wire electrode. For a long time, the traveling speed was about 1.5–80 mm/min. WEDM processes use very high speeds of traveling movement in high-speed WEDM processes. It is necessary to exert a tension on the wire under the action of forces of about 0.04–0.7 daN, to ensure its recti-linearity in the machining zone.

The main benefits of WEDM are the following:

- efficient production capabilities
- production reliability
- difficulties or even impossibility to obtain surfaces by other machining methods • low costs
- stress-free and burr-free cutting
- tight tolerances and excellent finishes
- CNC (Computer Numerical Control) downloadable program files.

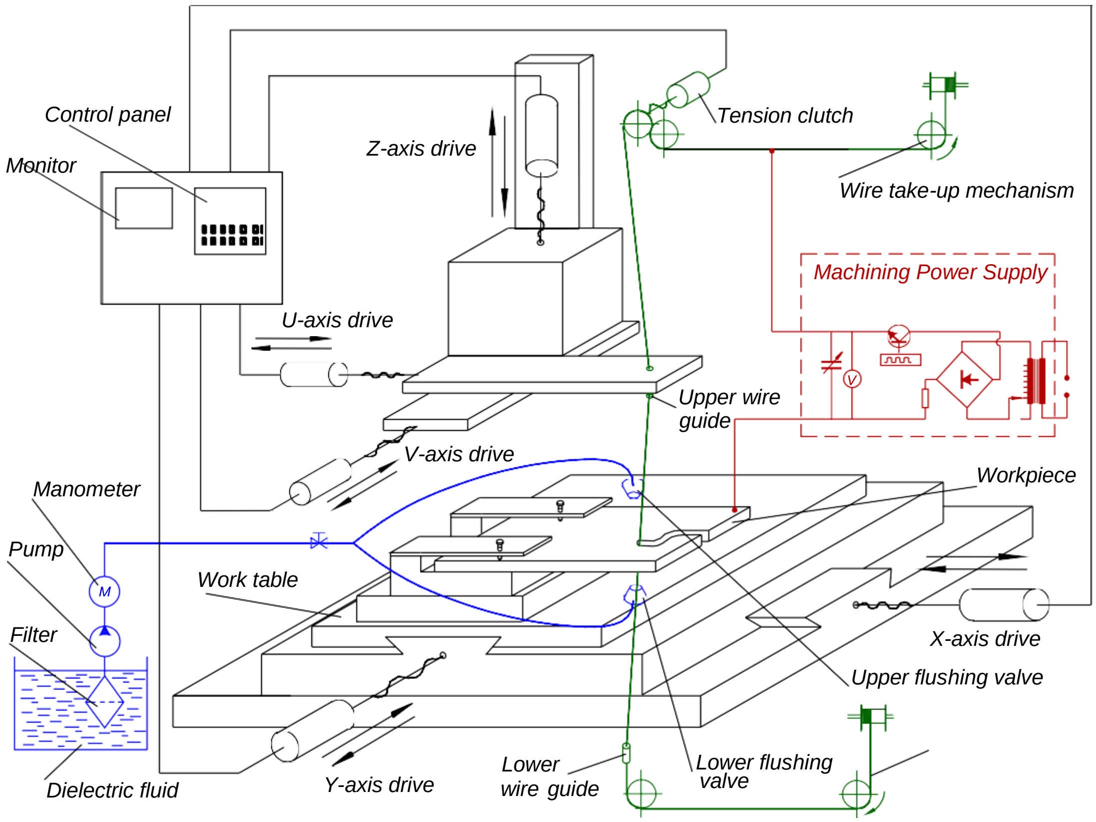

Figure 1: Schematic representation of the machining zone in WEDM Process.

1.2. Evolution of WEDM

The first proposals for the use of electric discharges for cutting metallic work pieces were formulated by Tilghman ("Cutting metal by electricity"), towards the end of the 19th century (1889). A fuller outline of a field that would refer to electrical discharge machining took place once with the patent application elaborated by Boris and Natalia Lazarenko (1943). They aimed to develop a method of machining the electro conductive materials. Almost two decades later, real electrical discharge machines were to be built and used. Gradually, these machines became more and more complex. They were equipped with subsystems for machining process optimization and benefited greatly from the emergence and development of numerical control subsystems. Some of the moments considered decisive for developing the equipment currently used for WEDM were highlighted in Figure2. These moments were mentioned according to the information identified in the literature.

Table 1.1. Evolution of Knowledge about WEDM Processes and Equipment

1	1889	Benjamin Chew Tilghman obtained a patent for the invention “Cutting metal by electricity.
2	1943	Boris and Natalia Lazarenko proposed a method for machining electroconductive materials.
3	1947	In the UK, D.W.A.F. Rudorff probably wrote the first patent application for “Improvements in methods and apparatus for cutting electrically conductive materials” (Patent GB637872), which used a so-called “endless wire or band”.
4	1960	The team coordinated by David H. Dulebohn finalized an optical line following system, which later formed the basis for the development of CNC equipment.
5	1960	Patent application concerning “Method of guiding the wire EDM or ultrasonic wire tool” proposed by V.Iu.Veroman (SU Patent SU142138A1).
6	1964	In a book published in 1967, Livshits presented a wire EDM machine used in 1964 and based on the precise Leitz measurement machine.
7	1967	A company in the former Soviet Union seems to have introduced the first WEDM machine (displayed at a machine exposition in Montreal, Quebec, Canada), (stepper motors, machining accuracy of 0.02 mm.
8	1969	At the European Machine Tool Exbihition in Paris, the Swiss company Agie promoted a WEDM machine (AGIEcut DEM15).
9	1970	The early 1970s. Pure copper wire electrodes are used.
10	1974	As a consequence of the use of the results obtained by the team coordinated by Dulebohn, a wire-cut EDM machine controlled by the optical-line following system was achieved.
11	1970	Second half of the 1970s: brass wire used instead of pure copper wire.
12	1980	Copper wire electrodes coated with zinc.
14	1985	Tsuchiya et al. have proposed and investigated a hybrid process later called travelling wire electrochemical spark micro-machining (TWECSMM), to machine nonconductive workpiece.
15	1985	Masuzawa proposed the wire electrical discharge grinding (WEDG) process.
16	1989	Wire vibration.
17	1990	Brass wire electrodes coated with zinc for high-precision cutting and coated Cu-50 mass % Zn for high-speed were used.
18	1990	Wire electrode including core materials of stainless wire coated with copper.

19	1994	A control subsystem to monitor and control the spark frequency to estimate the workpiece height proposed by Rajurkar et al.
20	1997	Studies concerning the ultrasonic aided wire electrical discharge machining were made.
21	2001	A subsystem for online estimation of the workpiece height based on using neural networks and hierarchical adaptive control.
22	2006	An electrostatic induction feeding method, mainly applicable to micro WEDM process.
23	2009	Plastic deformation of the surface's intersections characterized by small value angles under the action of the attraction or repulsion forces were reported.
24	2009	At Nanjing Univerity, a high-speed WEDM (HSWEDM) process was proposed and investigated.
25	2010	Twin-wire electrical discharge grinding proposed by Sheu.
26	2012	Cryogenic treatment cooling to -110oC or to -184oC applied to the brass wire filiform tool electrode.
27	2013	Gotoh et al. have proposed a wire electrical discharge milling process.
28	2015	Zhang proposed the use of polyvinyl alcohol in distilled water as a machining fluid when applying WEDM to nanocomposite ceramic.
29	2015	Tangential feed WEDG process proposed by Zhao et al.
30	2015	Method for the online monitoring of discharge pulse in WEDM middle speed based on digital image processing and machine learning.
31	2018	A high-precision constant wire tension control subsystem to improve the workpiece surface quality and geometric accuracy.
32	2019	Active supplying wire-electrical discharge grinding (AS-WEDG) proposed by Li et al. to diminish the wire fluctuation and improve the aspect ratio of the microelectrode.

1.3. WEDM Equipment

The WEDM mechanical system involves the CNC controlled worktable (X–Y) on which the work piece is clamped and an electrode wire driving mechanism for continuous motion through the work piece with a mechanical tension between a pair of wire guides (Figure1). According to the work piece's height, the lower wire guide is stationary, and the upper guide could be repositioned along the Z axis. The mechanism involves moving the upper guide in Cartesian coordinates (U–V) by driven servo motors to obtain tapered surfaces. The spark generator enables various forms of electric pulses. It allows the variation of electrical parameters to adapt the sparks to the working conditions to generate a series of electrical discharges between the work piece and the continuous wire electrode. If how the dielectric fluid reaches the working zone is taken into account, the following categories of WEDM processes can be highlighted:

- **Submerged type WEDM,** when the wire electrode and the work piece are immersed in the dielectric fluid;
- **Non-submerged (co-axial flushing) type WEDM,** when the dielectric fluid reaches the space around the wire electrode in the machining zone from the top and the bottom nozzles;
- **Dry and near dry WEDM,** when the dielectric liquid is replaced with a minimum amount of atmospheric gas or other gas. In this case, the ecological requirements are better fulfilled.

In recent decades, the development and improvement of numerical control subsystems have generated a strong impetus for designing and developing new WEDM equipment. Such equipment has made it possible to solve a broad set of problems required by the WEDM process in a short time. If the first software for the numerical control of WEDM equipment was quite complicated, it gradually came to simpler software, which allows the development of CNC programs even by specialists who do not have indepth knowledge in this field.

1.4. Improvements in the WEDM Processes and Equipment

General Classification

A possible grouping of improvements applied to the WEDM process could consider:

- Improvements regarding the machining equipment and its operation:
  The emergence of hybrid machining processes, with the adaptation of machining equipment to the requirements of such processes;
- Improvements of the geometric wire shape and chemical compositions of the wire materials:
  The use of the WEDM process for new materials and including the improvement of the characteristics of the surfaces processed as a result of the application of WEDM;
- Identifying the optimal conditions for the development of the WEDM process:
  These improvements will be briefly addressed below, with a separate chapter covering some key ways to optimize WEDM processes.

1.4.1. Improvements Regarding the Machining Equipment and Its Operation

Improved solutions for the pulse generator. The improvement of the WEDM process results acting on the characteristics of electric discharges characteristics was implicitly connected with some improved pulse generators or at least of the generators capable of ensuring the variation between certain limits of the machining pulse characteristics. A particular objective of the research regarding the improvement of pulse generators was to ensure better environmental protection. This led to the effective shaping of “clean-cut” type generators. Intending to eliminate the influence of stray capacitance in the pulse generator circuit and at the same time, the wear of the wire electrode connection brushes in the pulse generator circuit, methods aiming to use electrostatic induction feeding method were investigated.

Subsystems for the estimation of work piece height. The use of WEDM in the case of a work piece that presents components with different thicknesses highlighted an unstable process in the transition zone. The research developed to avoid or reduce such a negative effect aimed at using information during the processing process to assess the thickness of the work piece thickness and change continuously. As such, the values of process input factors so that an optimal process occurs. The information regarding the spark frequency, the abnormal ratio defined by the proportion of abnormal sparks in a sampling period, variable gap error (considered as a combination of ionization-time and servo voltage) were used. New subsystems were proposed to be part of the WEDM machining equipment.

Near-Dry WEDM. Near-Dry WEDM is a machining process involving a minimum amount of liquid with a mixture of gases to the working gap. This process’s main advantages are a possible better quality of the resulting surface, more stable development of electric discharges, and a reduced negative impact on the environment. In recent decades, this latest argument has led to a real intensification of the research in near-dry WEDM.

Use of an additional indexing axis of rotation. Better knowledge of how the WEDM process was used to separate parts with different contours from the plate-type work piece, suggested machining revolutionary surfaces. This led to the addition of an indexable rotation axis of the work piece that allowed the development of effectively distinct WEDM grinding and turning processes, but also to the machining of slots in secured positions using an indexable positioning subsystem of the work piece by its controlled rotation around an axis.

Wire electrical discharge grinding. The initial version of the wire electrical discharge grinding (WEDG) was proposed by Masuzawa in 1985 and applied to produce high accuracy micro shafts repeatedly. The WEDG process has certain similarities with the wire electrical discharge turning (WEDT) process. Both processes were used to remove material from a rotating axially work piece against the wire’s traveling electrode. In the opinion of some researchers, the difference among the two machining methods is the fact that WEDG is used, like the classic grinding, to obtain a lower roughness of the machined surfaces and sometimes a higher accuracy of these surfaces (a high accuracy also being accessible to some WEDT processes).

There are currently several machining processes that are known under the more general name of WEDG. The process called twin-wire WEDG allowed the simultaneous development of rough and finish machining, thus reducing two-thirds of the machining time (Figure3a). Subsequently, there was a process which was promoted in which instead of the radial feed motion; a tangential feed motion was used. This method was called tangential feed WEDG (TF-WEDG) (Figure3b). The method was reducing the effect of the work piece positioning error in the conventional radial feed WEDG version (Figure3a). The twinmirroring-wire tangential feed electrical discharge grinding (TMTF-WEDG) (Figure3c) was then promoted. It was considered as a combination of twin-wire WEDG with tangential feed WEDG. Using a novel active supplying wire-electro discharge (AS-WEDG) device, a microelectrode of 40.3 µm in average diameter and 49.6 in aspect ratio was obtained.

WEDM Milling. In wire electric machining process, it can be seen that a traveling wire electrode was used (Figure4). The wire electrode is active and has a circular arc shape due to its winding on hemispherical wire support and on which there is placed a semicircular groove. This groove determines the diameter of the circular arc of the wire arrangement. The wire support still has the possibility of achieving a reciprocating rotation characterized by a certain angle. Using such a tool it becomes possible to apply three-dimensional machining, similar to a certain extent to those in traditional milling with a ball-end mill.

As there is currently milling equipment with multiple possibilities of moving a hemispherical milling cutter to the work piece, especially for roughing or finishing complex surfaces of high precision, it is expected to be investigated in the future similar milling techniques with wire electrode. Such techniques could provide a considerable extension of the possibilities of using WEDM, taking into account that initially the WEDM process was used only to obtain ruled surfaces.

Wire cutting of the twist drill cone flank. A method based on the WEDM process was proposed starting from the conventional grinding wheel-sharpening process of the conical flank face or twist drills. A wire-cutting and forming device was used after a preliminary simulation of the machining conditions using UG NX software.

Wire cutting of the noncircular gears. The high precision and the good quality of the surfaces made by WEDM led to the idea of cutting noncircular gear teeth in a single operation. CAD/CAM software was used to determine the trajectory of the wire electrode relative to the work piece.

Micro WEDM. The micromachining concept was defined by considering the possibilities of obtaining parts with dimensions between 1 and 999 µm. It was appreciated that the versatility proved by the WEDM applications led to the adaptation of this machining process, including for the micromachining processes.

In principle, micro WEDM does not generate additional problems than those generally known in WEDM. However, the maximum pulse energy must be limited to avoid breaking the wire. Some characteristics of the micro-WEDM process can be considered the small values of the roughness of the processed surfaces (Ra < 0.1 µm), machining accuracy (<±0.2 µm), the thickness of the white layer (<2 µm), and gap size (<4 µm).

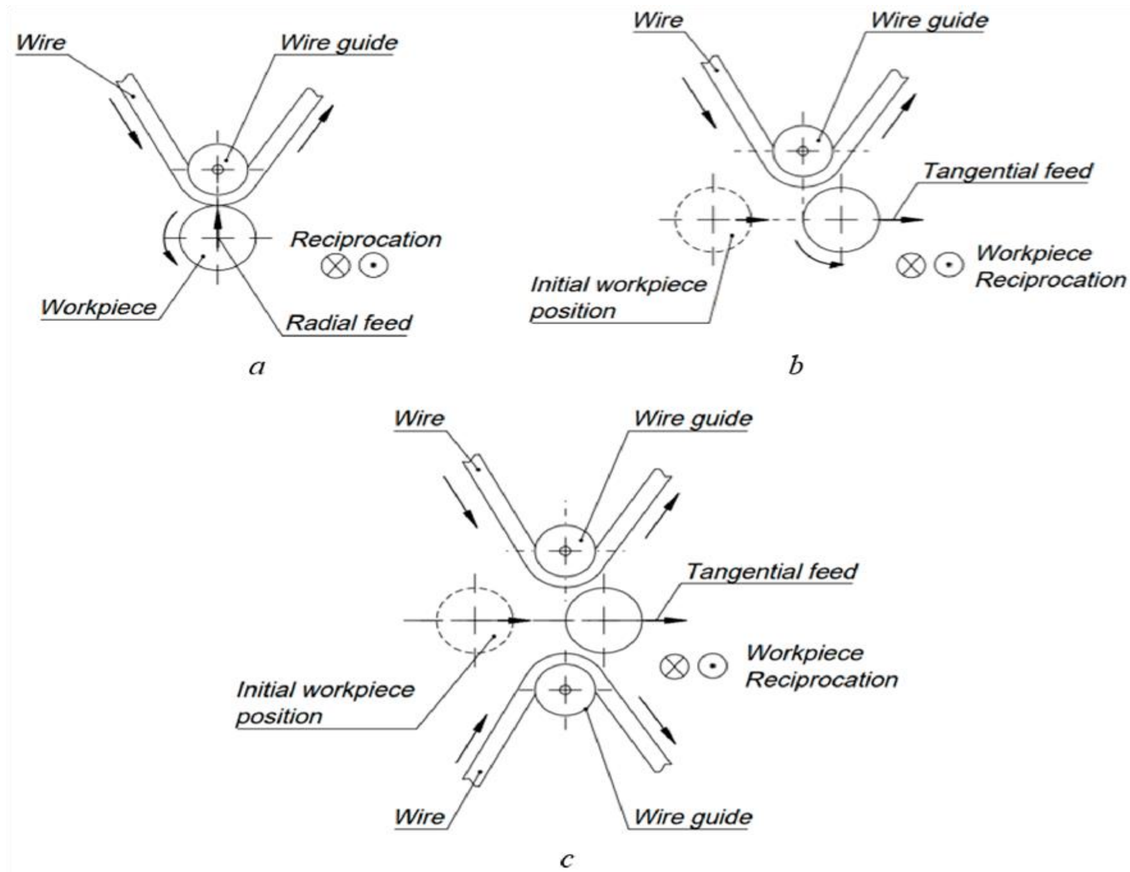

Figure 3. Redrawn figure of the schematic representations of different WEDG processes: (a)—conventional WEDG; (b)—tangential feed WEDG; and (c)—twin-wire WEDG.

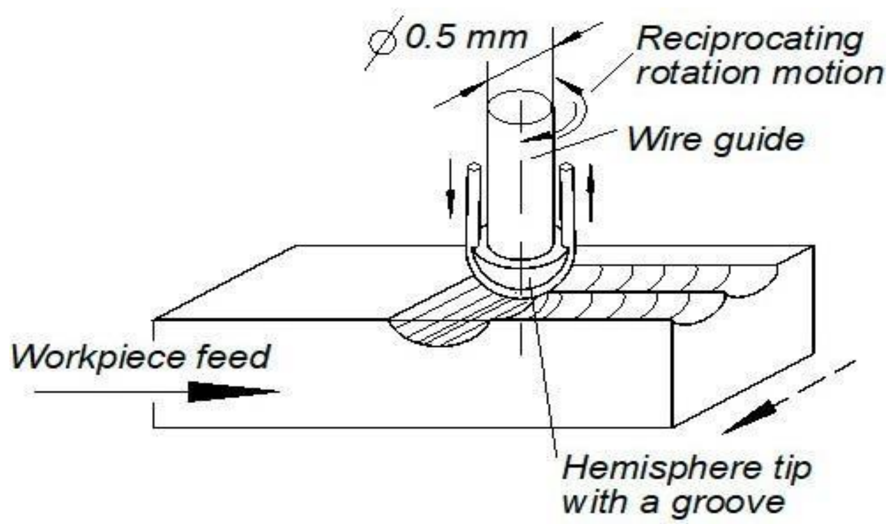

Figure 4. Wire Electrical Discharge (WED) Milling

WEDM Turning: Wire electrical discharge turning (WEDT) is considered an adaptation of the WEDM process that allows the machining of revolutionary surfaces of difficult-to-machine electro conductive materials. The existence of almost insignificant forces in size generated by the WEDM process ensured conditions for machining the parts with revolution surfaces characterized by a high aspect ratio. An illustration of a WEDT process can be seen in Figure5. Over the last decade, studies have considered the effects of input factors on the values of output parameters (including roundness and the cylindricity of turned surfaces), optimizing the development of the WEDT process.

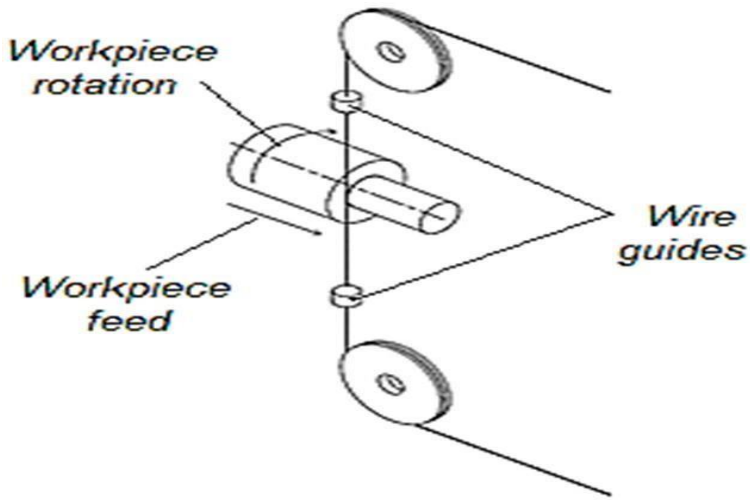

Figure 5. Wire Electrical Discharge Turning (WEDT) Process

Monitoring of the WEDM process: Monitoring a process refers to a set of actions designed to identify changes in some characteristic sizes of the process, but without using the interruption of the process and the existing possibility of a rapid response to the stochastic events, to ensure process development in better conditions. In the case of the WEDM process, the sensors could collect information about the integrity of the wire electrode, working gap size, level of vibrations, mechanical stresses, discharge pulse characteristics, amount of heat released, temperatures reached in the machining zone, energy consumption, integrity of the machined surface, etc. Currently, such information can be obtained inclusively by taking images from the processing area. It was considered that one of the first uses of monitoring subsystems in the field of nonconventional technologies was aimed at preventing the breakage of the wire tool electrode or even launching appropriate commands if such breakage of the wire electrode occurred.

Fabricating Micro-Texture on the Work Piece Surface. An interesting application of the WEDM process is the one that allows the generation of micro textures on the surfaces of different categories of cutting tools. Small width slots can be made into the work piece by controlled short working strokes of the wire electrode or the work piece. Grooves with a depth of 250 µm and width of 100 and 200 µm were achieved by a WEDM process to process the cutting edges of a turning tool used to generate a micro square structure.

Powder mixed WEDM. One of the possibilities to improve the WEDM process's performance is the introduction in the dielectric liquid of some powder particles that modify, to a certain extent, the mechanism of material removal from the work piece. Usually, the mixed powder particles in the dielectric are electrically charged and arranged in chain formation, which facilitates the earlier generation of electric discharges. These effects result in an increase in material removal rate and improved machined surface roughness in these surfaces' texture. Tungsten carbide, cobalt, boron carbide, silicon, silicon carbide, and aluminum can be used as powder material.

Combined electrical wire discharge-electrochemical machining in sequential use. To obtain specific benefits, both the EDM process (machining accuracy) and ECM process (quality of the surface integrity), a successive machining by wire electrical erosion and, respectively, by wire electrochemical erosion on the same machining equipment, using the same wire tool electrode, have been identified and investigated. Tap water was used as the dielectric liquid for WEDM, while aqueous sodium chloride solution was preferred for wire ECM.

Hybrid WEDM Processes

There are also improvements to the WEDM process which consider combining the WEDM process with other unconventional processes or by assisting the WEDM process with other conventional or unconventional processes. It is worth mentioning that the WEDM process is assisted by vibrations in the sonic or ultrasonic field, wire electrochemical discharge machining, and abrasive wire electrical discharge machining. A possible direction for the future development of the WEDM process could be determined by examining the possibilities of combining WEDM with aspects specific to one or more conventional or unconventional processing processes.

Wire electrochemical discharge machining. It is mainly applied to nonconductive brittle materials such as quartz glass or ceramics. The machining process can occur either by immersing the machining area in the electrolyte or by introducing the electrolyte in the form of droplets. The drops also contribute to a material removal of the products resulting from the process in the working gap. The tool electrode is connected to the cathode, using another additional electrode (Figure6a), connected to the direct current source's anode, and located near the work piece. It is necessary to ensure a certain pressure between the wire electrode and the work piece. In essence, the electrolysis process contributes to the appearance of oxygen and hydrogen bubbles. The electric discharges passing through the hydrogen bubbles gradually remove material from the work piece. The electrolyte may be, for example, an aqueous solution of sodium chloride. In Figure 6b, an illustration of the electrochemical discharge-assisted diamond wire cutting can be observed. The diamond wire was obtained by bonding diamond particles onto the steel wire. The process ensures a material removal rate higher than that of the case using the conventional diamond wire cutting process.

High-speed WEDM (HSWEDM). In principle, the high-speed WEDM (HSWEDM) process is a WEDM process in which high speeds of wire movement in both directions along its axis are used, much higher (10–12 m/s) than those in the case of ordinary WEDM processes (1.5–80 mm/min). It is estimated that the removal of material from the work piece results from both electrical discharges and the anodic dissolution of the work piece material, which would include this process in the category of hybrid processes. The HSWEDM ensures a 200–600% increase in the material cutting rate. The process involves using a new wire winding subsystem, hybrid electrolyte, and high-efficiency pulse generator.

External magnetic field-assisted WEDM. It was found that the presence of a magnetic field at the working zone contributes to an increase in the density and stability of the plasma channel, to the

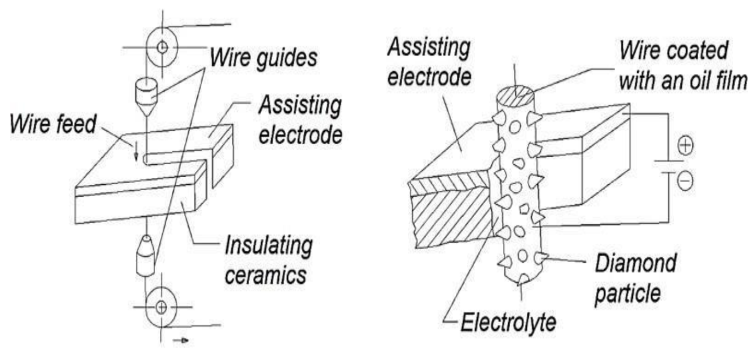

Figure 6. (a)simple version (b)electrochemical discharge-assisted diamond wire cutting.

intensification of the debris removal from the work piece surface, to an improvement of machining efficiency and quality. The magnetic field's influence on the WEDM process was investigated when the magnetic field lines are perpendicular to the direction of the wire electrode's movement.

Improvements Concerning the Wire Tool Electrode Material and Geometrical Characteristics

When selecting the wire electrode's material and dimensions, properties such as conductivity, tensile strength, elongation, melting point, straightness, flush ability, cleanliness, geometric properties (diameter, shape, coating, and surface layer structure) are considered Trying to achieve high-speed and high-precision WEDM. Various versions of wire electrodes have also been proposed and to some extent, investigated and even used in practice. Thus, there were proposed wire electrodes with cross-sections that revealed the presence of a core coated with a single layer (for example, the brass core coated with a layer of copper alloy) or with two layers (a low boiling temperature will characterize the outer layer), with an oxide layer (to diminish the process of developing electrical discharges on the side of the wire electrode), with a layer formed by twisting thin wires of brass characterized by high mechanical strength and an external layer of zinc or zinc alloy). The possibilities of using electrodes with a cross-section different from the circular one (rectangular, square, trapezoidal section, with triangular channels or other shapes) and possibly obtained by twisting, as well as wire electrodes on which diamond particles were attached to outer surfaces. *The* cryogenic treatment of the brass wire tool electrode (cooling to very low temperatures) was one of the researcher's solutions to improve the wire electrode's behavior. As a result of the application of a cryogenic treatment, the structure of the wire electrode material (brass) was refined, and the electrical conductivity of the material was improved, thus facilitating an increase in the material removal rate and an improvement of the surface roughness. Filiform electrodes made of brass and zinc-coated diffused brass were subjected to cryogenic treatments.

Wire deflection and deviation from the prescribed path of the wire electrode. Although the tension force acts on the wire electrode and it should ensure a rectilinear shape of its axis, the wire electrode does not behave like a rigid bar. Under the action of forces quite small in value generated by the electro erosive process, the dielectric liquid circulation in the working gap and feed motion along the established path, the electrode wire deforms, and its axis is no longer rectilinear in the machining zone (Figure7) . There is also a vibration of the tool electrode between the upper wire guide and lower wire guide, and this usually generates a larger kerf width in the middle zone of the work piece.

Research methodologies and simulations of errors generated by the wire electrode's deflection and its vibration have been proposed.

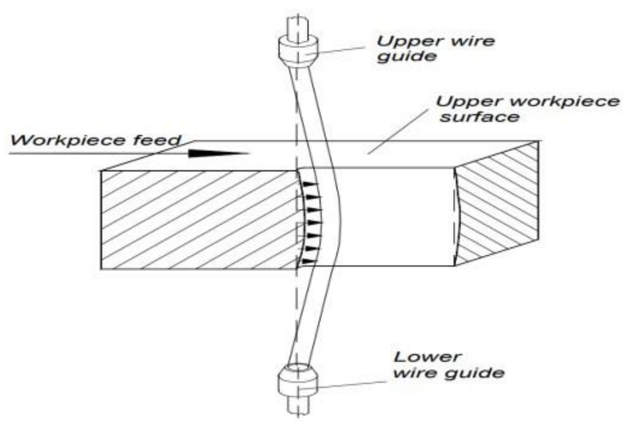

Figure 7. Wire tool deflection in the work zone during the WEDM process

Another error refers to the deviation from the prescribed path in trajectories that include sharp angles or radii of small values. This error can be determined by the accuracy of the relative feed movement subsystems between the wire and workpiece, by the use of certain commands for the CNC subsystem, but also by the previously mentioned wire deflection, or plastic deformation of thin tips, to the diamagnetic or paramagnetic character of the work piece. Wire tension control subsystems were proposed and experimented with, improving the machined surface's quality and geometric accuracy.

Improvements of the Usage Properties of the Parts Obtained by WEDM, Including by Using New Parts Materials

Expanding the range of materials processed by WEDM. As a result of the development of car manufacturing fields, increasingly diversified materials could be observed. A consequence of this fact has been the research efforts aimed at investigating the various materials' behavior during the WEDM process and, respectively, to optimize the machining of work pieces made of such materials. Thus, it was found, first of all, that the use of WEDM for very different groups of electro conductive materials and some of the studies in this direction took into account:

- Various steels
- Nickel–chromium-based alloys and super alloys type Inconel, nickel-based alloys
- Aluminium alloys, Tungsten, copper
- Titanium and titanium alloys
- Aerospace alloys
- Shape memory alloys
- Carbide type materials
- Polycrystalline diamond
- Semiconductor materials: silicon, germanium
- Some categories of composite materials
- Ceramics

Improving the use of properties of surfaces obtained by WEDM. Mechanisms specific to the WEDM process led to the generation of specific geometric characteristics of the processed surface and structural changes in the machined surface layer. Some of these consequences of using the WEDM process can determine the improvement in the part of the operating behavior.

Improvement in mechanical properties and especially fatigue strength has also been noticed in the use of WEDM for the manufacture of highly loaded titanium parts for space applications. In other situations, it was appreciated that the topography of the obtained surface has more convenient tribological characteristics, allowing increasing the load-carrying and the duration of use of the gears whose flanks that to be processed by WEDM, the materials must have a certain electrical conductivity. From this point of view, ceramics can be divided into the following categories:
Conductive ceramics, characterized by electrical conductivity of at least 10–ohms.cm (titanium nitride Tin, titanium diboride TiN2) and which, with some small difficulties, can be processed by WEDM; were obtained by WEDM.

- **WEDM of Ceramics**. The concept of ceramics refers to a wide range of hard, brittle and corrosion resistant materials, made by shaping and then firing a non-metallic material. In principle, it is known
- Nonconductive ceramics: for such materials, a so-called assisting electrode method was considered. There must be at least a thin conductive layer on the work piece's surface

or immediately near this surface. Under the action of high temperature developed by the electric discharges between the wire electrode and the conductive layer, cracks are developed, and this effect can contribute to the removal of material from the work piece. The dielectric hydrocarbons can also be cracked. Some of the resulting conductive carbon compounds could adhere to the surface of the work piece, ensuring a certain continuity of the conductive layer. Another WEDM way of non-conductive ceramics was based on an electrolyte in a hybrid WEDM process;

- Semi conductive ceramics, whose WEDM process can take into account the version applicable in the case of conductive ceramics (with lower machining performance) or the one usable in nonconductive ceramics.
- In recent years, it is found that that fluid machining is the main influencing factor of MRR and surface integrity quality when applying WEDM to ceramic nano composites.

Input Factors and Output Parameters for WEDM

The wire electrical discharge machining system (Figure1), as any other system, was defined by the input factors, by the output parameters which measure the process performance, the intermediate process factors (parameters whose values are continuously changing during the process), and the disturbing factors or system noise. Depending on the possibility of choosing their values, the input factors are classified into adjustable factors and imposed factors, which are, in general, those related to the workpiece or some devices of the WEDM machine. The WEDM process performance is decided by the values of the following input factors:

- *Characteristics of the wire electrode tool*: material, the chemical composition of wire electrode tool, resistivity, specific heat, thermal conductivity, melting temperature, latent heat of melting, vaporization temperature, latent heat of vaporization, specific mass, tensile strength, wire diameter, the shape of the wire (cross-section, structure), positioning accuracy of EF (angular positioning, coordinate error in the horizontal plane, etc.).

- *Characteristics of the work piece*: thickness, material, chemical composition, electrical conductivity, specific heat, thermal conductivity, melting temperature, the accuracy of work piece positioning, etc.

- *Characteristics of the positioning-clamping device*: positioning-clamping accuracy, clamping force, etc.;

- *Characteristics of the dielectric circulation subsystem*: electrical conductivity of the dielectric liquid, chemical composition, impurities concentration, liquid viscosity, surface tension, specific heat, temperature, flow direction through the working gap, dielectric pressure, inlet flow, relative position of the electrodes pair to dielectric flow;

- *Characteristics of the electric pulses*: voltage pulses shape, frequency and filling factor, pulse on-time, pulse off-time, cycle time, discharge frequency, peak or average voltage, peak or average current, pulse energy, electrodes polarity;

- *Characteristics of the mechanical conditions*: stability of the wire electrode feed subsystem, sensitivity and reaction speed, the adjustment range of the wire electrode feed subsystem, running speed of wire electrode, axial tension of the wire electrode, distance between the guides of the wire electrode, the initial inclination of the wire electrode;

- *Characteristics of the process control and optimization subsystem*: possibilities for the monitoring, adaptation, and optimization of parameters.

- *Intermediate factors* or so-called *process-dependent* parameters are dependent on the characteristic of the fundamental phenomena in the working gap, and their values change during the process. The following intermediate parameters can be considered,

- *Characteristics of the material removal processes*: the working gap size (front and lateral), kerf width, technological gap shape (kerf size in the upper work piece zone, at the of work piece bottom, at mid-height of work piece, convexity, taper angle), length of the free path of particles expelled from the crater, percentage of pulse energy received by the working environment, by the work piece material, the volume of removed material from the wire electrode tool by a single discharge, average depth of the crater in the electrode tool surface and in the work piece surface, local average density of spurious pulses, and short-circuited pulses, local, average current intensity;

- *Characteristics of the evacuation processes*: flow rate of solid waste and of gaseous waste from the gap, local density of erosive particles, average speed and pressure of shock waves, flow rate of erosive particles formation;

- *Forces that act on the wire electrode*: electrostatic forces, electromagnetic forces, hydrostatic forces, hydrodynamic forces, forces due to the pressure in the plasma column, forces due to the pressure of the gas bubble;

- *Wire electrode deformations*: dimensional deformation, vibration, position in the two directions, properties, structure.

- The performance of the WEDM process is evaluated using *the following output parameters*:
- *Characteristics of process productivity*: productivity, cutting speed evaluated in mm/min or mm2/min, totally removed volume, the total length of the machined kerf;

- *Characteristics of the machined surface of the work piece*: the physicochemical appearance of the machined surface (chemical composition, structure, properties), geometric appearance (dimensional accuracy, shape and position accuracy, maximum shape deviation, the roughness of rounding radii of the edges of the machined surfaces);

- *Wire electrode wear characteristics*: wire electrode wear rate, relative volume wear, specific consumption wire electrode;

- -Degree of process stability;

- *Processing time*: total working time, specific working time;

- *Processing cost*: specific cost of used wire electrode, total specific machining cost.

The analysis of the presented system (Figure8) suggests the complexity of the WEDM process and the fact that establishing the optimal processing conditions must be the result of analyzing the effects of as many factors as possible and the interactions between them.

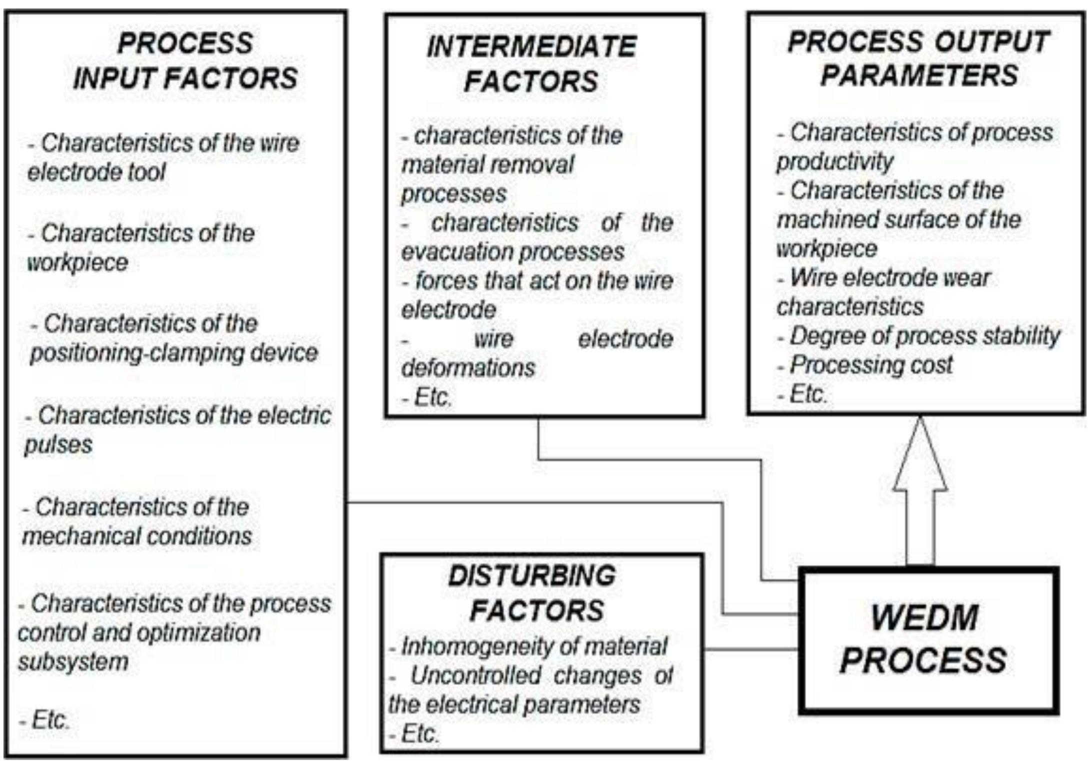

Figure 8. Several factors and groups of factors highlighted when analysing WEDM as a system.

Sometimes, highlighting the input factors in the WEDM process was done using Ishikawa diagrams and grouping the factors considering the dielectric medium, the wire tool, the machine, and the work piece.

1.3.1. Modelling and optimizing the WEDM Process

The need to use some models appears especially when the problem of optimizing the process arises. The empirical models (first-degree polynomial, second-degree polynomial, power type function, etc.), established using regression analysis, are well known and applied even for the WEDM process. The constants and exponents are present in the empirical models, but most often graphical representations made based on the models provide information about the intensity of the influence exerted by the input factors in the WEDM process or the interactions of these factors on the values of some output parameters. Extensive research has been undertaken to outline and use more complex mathematical models, the matrix type, and the Taguchi method.

The methods used over time to model the WEDM process and its results can be highlighted as regression analysis and response surface methodology, the Taguchi method, and the least squares method. As previously mentioned, using specialized software for processing experimental results, empirical mathematical models were identified for the output parameters of the WEDM process, with the inclusion of independent variables of a greater or lesser number of the input factors of the process

Some of the models proposed over time to characterize some of the specific aspects of the WEDM process can be seen in Figure9. *Optimization* refers to identifying one or more solutions appreciated as the most convenient from several available solutions. Optimal solutions are sought in many areas of human activity, and it was normal, as such, to formulate *the*

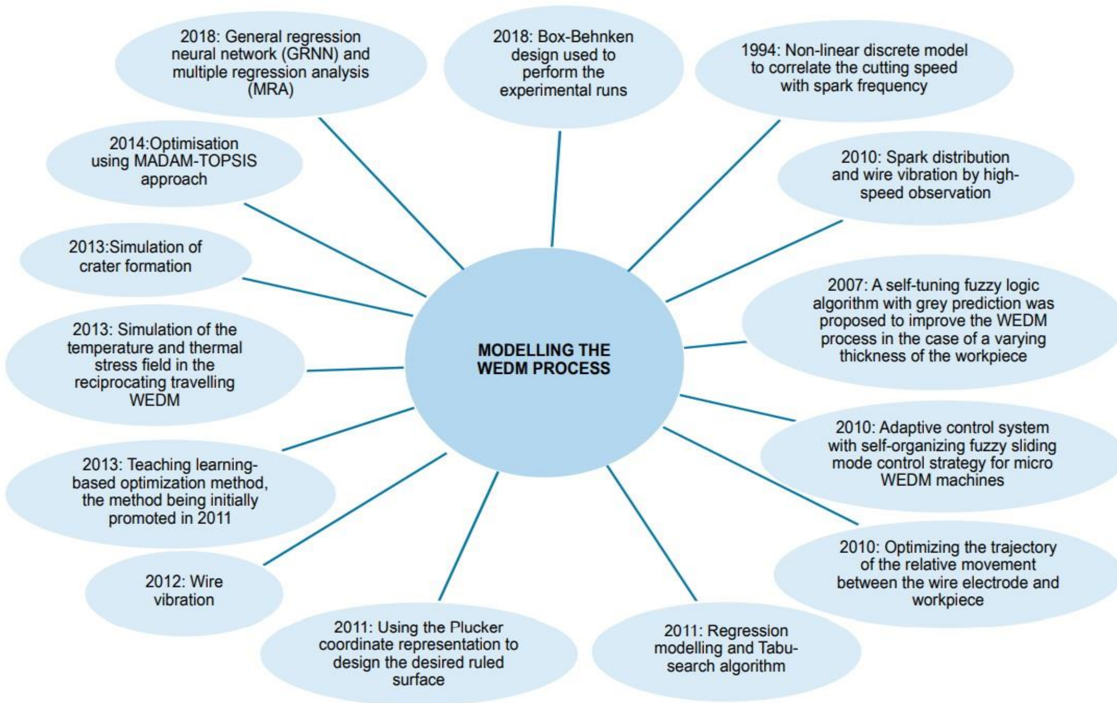

Figure 9. Some of the proposed models for the WEDM process.

Considering this process as a system, its optimization can be approached from several points of view. Thus, by optimizing the process, it can follow the identification of that combination of the input factors values that contributes to the maximization or minimization of an output parameter (mono criteria or mono objective optimization) or of many output parameters (multi-criteria or multi objective optimization). In this sense, the problem of maximizing the cutting speed within the WEDM process (for example, in the case of the need to ensure high productivity), of minimizing the height of the machined surface asperities, and of maximizing the machining accuracy (in case of a high accuracy cutting) were all addressed.

A problem of interest for optimizing the WEDM process was the one in which it was necessary to identify the path of the relative movement between the wire and work piece to ensure a high machining accuracy in the case of small width grooves in the work piece. Such a problem has been addressed, for example, in the situation of the manufacture of graphite discs with thin circular grooves, the WEDM process was selected to be used.

To date, in the field of WEDM processes, researchers have addressed to a lesser extent mono criteria optimization problem however, they have more frequently addressed multi criteria/multi objective optimization problems, applied in this sense as different methods, such as:

-Taguchi method;

-Taguchi and analysis of variance;

-Taguchi and grey relational analysis;

- Box-Behnken design (considered a type of response surface methodology (RSM) designs) method, showing that it is possible to reduce the number of experiments aimed at optimizing the WEDM process; *problem of optimization in the WEDM process*.

-Grey-based response surface methodology;
-Grey relational analysis;
-Grey-fuzzy methodology;
-Response surface methodology;
-Response surface methodology coupled with grey relational analysis–Taguchi technique;

-Desirability function analysis (DFA) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods;
-Genetic algorithms;
-Non-dominated sorting genetic algorithm approach and Pareto method;
-Artificial neural networks;
-Teaching learning-based optimization;
-Analysis of the fractal dimension of the surface obtained by WEDM, etc.
Analysis of variance (ANOVA) has been used relatively often to highlight the significance of the factors found concerning one or more of the objectives considered functions.

CHAPTER-2

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LITERATURE SURVEY

Electric discharge machining (EDM) is one of the most efficient manufacturing technologies used in highly accurate processing of all electrically conductive materials irrespective of their mechanical properties. It is a non-contact thermal energy process applied to a wide range of applications, such as in the aerospace, automotive, tools, molds and dies, and surgical implements, especially for the hard-to-cut materials with simple or complex shapes and geometries. Applications to molds, tools, and dies are among the large-scale initial applications of this process. Machining these items is especially difficult as they are made of hard-to-machine materials, they have very complex shapes of high accuracy, and their surface characteristics are sensitive to machining conditions. The review of this kind with an emphasis on tool and die materials is extremely useful to relevant professions, practitioners, and researchers. This review provides an overview of the studies related to EDM with regard to selection of the process, material, and operating parameters, the effect on responses, various process variants, and new techniques adopted to enhance process performance. This chapter reviews research studies on the EDM of different grades of tool steel materials. This chapter (i) pans out the reported literature in a modular manner with a focus on experimental and theoretical studies aimed at improving process performance, including material removal rate, surface quality, and tool wear rate, among others, (ii) examines evaluation models and techniques used to determine process conditions, and (iii) discusses the developments in EDM and outlines the trends for future research.

In recent years, rapid developments in aerospace, medical instruments, transportation, and many other industrial sectors increased the need for new materials with favorable characteristics. In addition to unique characteristics, most modern materials need special manufacturing processes to enable them to be machined with ease [1,2]. Most of these materials are usually difficult to cut by conventional manufacturing processes [3–7]. The unique characteristics of these hard-to-cut materials increase their applications, which further drive manufacturers to explore new machining processes with reasonable cost and high precision [8,9].

Tool steels and other tool materials (e.g., carbides) are such widely used hard-to-cut materials because of their high hardness and abrasion wear resistance, in addition to their ability to withstand high load and to operate in rapidly changing temperatures [6]. Tool steels have a wide range of applications, including stamping and metal-working dies, cutting tools, hammers, and machine parts [10]. Applications of these tools in the manufacturing sector is very large; thus, there exists huge machining requirements of tools, tooling, dies, and molds [11]. Before being put to use, these steels are subjected to heat treatment to meet the required properties for specific application [12,13]. In addition to iron and carbon, tool steels have in them other elements (e.g., Cr, W, V, Mo, etc.) to increase their strength, hardness, hot strength and hot hardness, and wear resistance. Although these steels can be machined by conventional methods, they come with serious concerns with regard to very poor tool life and part accuracy [14].

Electric discharge machining (EDM) is one of the most advanced manufacturing methods used to successfully machine conductive hard-to-cut materials [8,15–19]. EDM is the process of choice to machine hard-to-cut materials widely used in modern industries to facilitate accurate machining [20–25], complex shape machining, and better surface integrity. The process is utilized to machine electrically conductive materials by applying repetitive sparks between electrode and workpiece. Unlike in mechanical machining, no deforming force is required
between the electrode and the workpiece, and the machining takes place without actual contact between them [23,26–28]. There are a large number of variants of the EDM process such as sinking EDM, wire EDM, micro-EDM, powder-mixed EDM, and dry EDM; all of these possess work on the same mechanism of material removal. Developments of variants make the process more versatile and suitable for relatively big and micro-scale machining areas. Several review papers related to EDM were published in recent years such as references [29–35], among others. Furthermore, some other articles presented a discussion of specific objectives; for example, Barenji et al. [36] developed a model for prediction of material removal rate (MRR) and tool wear rate (TWR) for the EDM of AISI D6 tool steel. They reported that higher values of pulse-on time resulted in higher MRR and lesser TWR. Long et al. [37] used powder-mixed EDM for machining die steels. Titanium powder was used for mixing, and surface quality was analyzed. It was revealed that the quality of surface layer was improved at optimal parameters. Shabgard et al. [38] studied the e*ff*ects of the key input variables of wire EDM of ASP30 tool steel. The output responses under consideration were MRR and surface roughness. The results revealed that an increase in spraying pressure of dielectric fluid led to a higher MRR and surface roughness. EDM of AISI M42 high-speed tool steel alloy was conducted to study the e*ff*ect of major input parameters on MRR. It was revealed that tool polarity was the most influential factor and, at negative polarity, maximum MRR was achieved. P20 tool steel was machined using wire EDM, and pulse-on time, pulse-o*ff* time, peak current, and spark gap voltage were varied. The output responses under study were kerf width and MRR. The best combination of parameters was reported to achieve maximum MRR [39]. Sharma and Sinha [40] applied rotary-EDM to machine AISI D2 tool steel using a copper electrode. MRR, TWR, and machining rate were studied by varying input parameters (peak current, voltage, duty cycle, and electrode rotation speed). Bahgat et al. [41] conducted experiments to study the e*ff*ect of major input variables on MRR, electrode wear ratio, and surface roughness while machining H13 die steel. It was reported that higher MRR and lower electrode wear rate were achieved using a copper electrode, whereas lower surface roughness was attained with a brass electrode. Gopal et al. [42] compared the performance of unprocessed and equal channel angular pressing (ECAP)-processed copper electrode while machining AISI H13 tool steel using EDM. It was reported that the triple-ECAP-passed electrode gave better machining quality. Despite many existing

review papers, to the best of authors’ knowledge, there is no study that reviewed the EDM process specifically for tool and die steels. Since tool and die steels have usage in a wide range of applications and they are difficult to cut with the conventional manufacturing processes, non-conventional processes such as EDM are becoming prevalent for their machining. Generally, one of the largest uses of the EDM process is in tool-, die-, and mold-making. All these industries mostly use various kinds of tool steels. EDM remains one of the most popular processes used for their fabrication.

1.Various Grades of Tool Steels

Steels can be categorized into four groups, namely, stainless steel, tool steel, carbon steel, and alloy steel. Each of these groups has its own characteristics which make it suitable for specific applications. Tool steels are mainly employed for making cutting and metal-working tools [12]. In order to meet the required conditions these tools encounter under service conditions, tool steels must have many properties such as the ability to withstand high load, the ability to operate in rapidly changing temperatures, high abrasive resistance, etc. Normally, the tool steels are used in hardened conditions by heat treatment, and they are subsequently tempered to meet the required properties for specific application [12]. Tool steels are high-hardness and abrasion-resistant alloy steels. In addition to iron and carbon, tool steels include many other elements to increase hardness and wear resistance and hot strength and hot hardness. Furthermore, they also possess adequate toughness which can be achieved by tempering, which is performed subsequent to hardening. Applications of tool steels include stamping and extrusion dies, cutting tools, hammers, and machine parts [10]. Properties of widely and recently used different grades of tool steels, as well as the EDM processes considered for each grade, are summarized in Table2.1.

Figure 2.1 shows the EDM processes and their main process parameters and output (performance) measures.

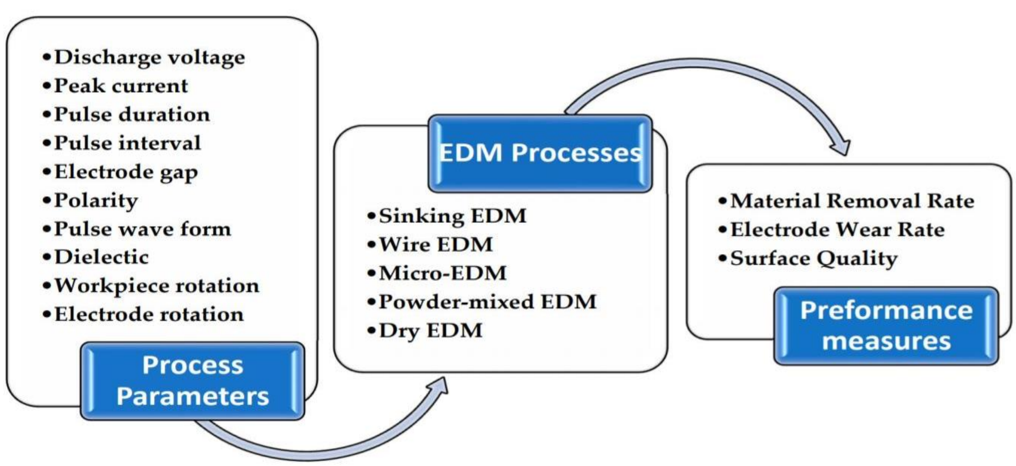

Figure 2.1. The processes of electric discharge machining (EDM) and their process parameters and performance measures.

Table 2.1. Details of various EDM processes used by researchers for different grades of tool steels

Different Grades and Corresponding Machining Operations	**Composition (Weight %)**	**Properties**
AISI D2 Die sinking EDM [85,104–110]. Wire EDM [111–113] Powder-mixed EDM [114–116].	C 1.5, Si 0.3, Mn 0.3, Mo 1.0, Cr 12.0, Ni 0.3, V 0.8, Co 1.0.	High-carbon and high-chromium tool steel. It has high resistance to wear and abrasion. D2 grade is heat-treatable steel with hardness in the range 55–62 HRC. Its corrosion resistance depends on the percentage of chromium [117].
AISI D3 Die sinking EDM [118]. Wire EDM [119].	C 2.00, Si 0.30, Mn 0.30, Cr 12.00	High-carbon, high-chromium tool steel. It has excellent resistance to wear and abrasion and has good dimensional stability and high compressive strength. Its hardness is in the range of 58–64 HRC [120].
AISI D5 Wire EDM [121,122].	C 1.53, Si 0.89, Mn 0.46, Cr 12.00, Mo 1.00, Ni 0.384	Similar to other grades in group D, D5 has high carbon and high chromium content; it is the most commonly used steel among the group D steels [123].
AISI D6 Die sinking EDM [124].	Cr 12.5, C 2.05, W 1.3, Mn 0.8, Si 0.3	In addition to high carbon and high chromium contents, D6 tool steel is alloyed with tungsten. D6 steel has high compressive strength, high wear resistance, high surface hardness, and good hardening stability [125].

AISI H11 Die sinking EDM [109,126]. Dry EDM [78,127]. Powder-mixed EDM [116,128–131]. Micro-EDM [132].	Cr 4.75–5.50, Mo 1.10–1.75, Si 0.80–1.20, V 0.80–1.20, C 0.32–0.45, Ni 0.3, Cu 0.25, Mn 0.20–0.50, P 0.03, S 0.03	H11 grade is one of the most commonly used chromium hot-work steels. It has low carbon content and has good toughness and deep hardness due to air quenching from heat treatment [133].
AISI O1 Die sinking EDM [76]. Wire EDM [134]. Powder-mixed EDM [135,136].	C 0.85–1.00, Mn 1.00–1.40, Si 0.50, Cr 0.40–0.60, Ni 0.30, W 0.40–0.60, V 0.30, Cu 0.25, P 0.0, S 0.03	O1 is oil-hardening tool steel. It has good machinability and dimensional stability in hardening. It also has a good combination of high surface hardness and toughness after hardening and tempering. O1 grade has good resistance to wear and abrasion due to its content of tungsten and chromium [137].
AISI O2 Powder-mixed EDM [116].	OHNS: C 0.82, Si 0.18, Mn 0.52, Cr 0.49, V 0.19, Mo 0.13, Ni 0.05;	O2 grade is oil-hardening tool steel. It has good durability, excellent wear resistance, and an ability to hold a good cutting edge [138].
AISI M2 Die sinking EDM [139– 141]. Wire EDM [142].	C 0.78–1.05, Cr 3.75–4.50, W 5.50–6.75, Mo 4.50–5.50, V 1.75–2.20.	M2 grade is molybdenum-based high speed steel (HSS). It is a medium alloyed HSS. It has good machinability, well-balanced toughness, wear resistance, and red hardiness properties [143].
SKD11 Die sinking EDM [144– 147]. Wire EDM [148–151]. Dry EDM [103,152]. Powder-mixed EDM [54,136,153–155].	C 1.40–1.60, Si Max 0.40, Mn Max 0.60, P Max 0.030, S Max 0.030, Cr 11.0–13.0, Mo 0.80–1.20, V 0.20–0.50.	SKD 11 is high-carbon and highchromium alloy steel. It has high hardness and a tempering hardening effect. It also has good resistance to wear, quenching, and less deformation. Currently, it has the best wear resistance of alloy tool steel [156].
SKD61 Die sinking EDM [157]. Powdermixed EDM [136,158,159].	C 0.35–0.42, Si 0.80–1.20, Mn 0.25–0.50, P Max 0.030, S Max 0.020, Cr 4.80–5.50, Mo 1.00–1.50, V 0.80–1.15	KSD61 is hot-work steel; it has high creep, temperature fatigue resistance, and high toughness. It also has a good ability to be polished and good thermal conductivity [160].

P20 Die sinking EDM [161–164]. Dry EDM [165]. Powder-mixed EDM [166].	C 0.28–0.40, Si 0.20–0.80, Mn 0.60–1.00, P Max. 0.030, S Max. 0.030, Cr 1.40–2.00, Mo 0.30–0.55.	P20 tool steel is a chrome-moly alloy steel with a carbon content of approximately 0.35 to 0.40. P20 has good mirror-polish ability and less texture, making finishing easier. It distributes a uniform hardness level even across large blocks [167].
BÖHLER W300 Die sinking EDM [168– 170].	C 0.36, Si 1.1, Cr 5.0, Mo 1.3, V 0.4	BÖHLER W300 is hot-work tool steel and it has high impact strength and excellent hot tensile properties.
EN 31 Die sinking EDM [23]. Powder-mixed EDM [61].	C 0.9–1.2, Si 0.1–0.3, Mn 0.3–0.7, Cr 1–1.6, S Max 0.025 and P Max 0.025.	EN 31 is a high-carbon alloy steel. It has high hardness with compressive strength. Moreover, it has high resistance against wear and abrasion.
ASP 2023 Die sinking EDM [171]. Wire EDM [172].	C 1.28, Cr 4.1, Mo 5.0, W 6.4, V 3.1	ASP 2023 is a high-alloy high-speed steel. It has dimension and shape stability during heat treatment. It has good toughness even for large dimensions. ASP 2023 has high hardness and good wear resistance [173].
C45 Die sinking EDM [174]. Wire EDM [175].	C 0.43–0.50, Si 0.17–0.4, Mn 0.50–0.8	C45 is a medium carbon steel. It has high strength and hardness. It features extreme size accuracy, straightness, and concentricity combined with minimal wear in high-speed applications [176].
DC 53 Wire EDM [177,178].	C 0.95, Si 1.0, Mn 0.4, Cr 8.0, Mo 2.0, V 0.3	DC53 has exceptional toughness, wear resistance, compressive strength, and temper resistance. It also has excellent machining characteristics [179].
DIN 1.2379 Die sinking EDM [180– 182].	C 1.50, Si 0.30, Cr 12.0, Mo 0.80, V 0.80	This grade has high abrasive resistance, adhesive wear resistance, and compressive strength. It also has good toughness and good dimensional stability [183].

DIN 1.2738 Die sinking EDM [184]. Micro-EDM [185].	C 0.4, Mn 1.5, Cr 1.9, Ni 1.0, Mo 0.22	This grade has good toughness, wear resistance, stability in hardness, and high hardenability
DIN 1.2714 Die sinking EDM [186].	C 0.50–0.60, Si 0.10–0.40, Mn 0.65–0.95, Cr 1.0–1.2, P max. 0.03, S max. 0.03,	DIN 1.2714 has good hardenability and uniform hardness over sections with big dimensions. Furthermore, it has good
	V 0.07–0.12, Ni 1.50–1.80, Mo 0.45–0.55	strength and toughness in addition to its tempering resistance and dimensional stability [187].
DIN 1.2080 Die sinking EDM [182].	C 2.00–2.35, Mn 0.60, Si 0.60, Cr 11.00–13.50, Ni 0.30, W 1.00, V 1.00, Cu 0.25, P 0.03, S 0.03	DIN 1.2080 is high-carbon/chromium tool steel. It has very high wear resistance and compressive strength. It can be hardened with a very slight change in size.
AISI 4340 Die sinking EDM [188].	C 0.38–0.43, Si 0.15–0.35, Mn 0.6–0.8, P 0.035, S 0.04, Cr 0.7–0.9, Ni 1.65–2.0, Mo 0.2–0.3	AISI 4340 is a heat-treatable and lowalloy steel containing chromium, nickel, and molybdenum. It has high toughness and strength in the heat-treated conditions [189].
S390 Wire EDM [148].	C 1.64, Cr 4.80, W 10.40, Co 8.00, V 4.80, Mo 2.00, Si 0.60, Mn 0.30	This material has the ability to maintain its strength and hardness level under extremely high cutting temperatures.
M238 HH Die sinking EDM [74].	C 0.36 0, Si 0.28, Mn 1.52, P 0.008, S 0.001, Cr 1.88, Mo 0.22, Ni 0.95, Al 0.021	It is hardened and tempered plastic mold steel. There is reduction of hardness in the center of large sizes due to the Ni-addition.
Vanadis-4E Wire EDM [190].	C 1.4, Si 0.4, Mn 0.4, Cr 4.7, Mo 3.5, Va 3.5	This grade has very good ductility, high abrasive/adhesive wear resistance, and high compressive strength. Moreover, it has good dimensional stability during heat treatment, good through-hardening properties, and temper back resistance [191].

Earlier studies were also conducted to investigate the relationship between processes and performance parameters [54,142]. The main researches in optimizing process parameters of EDM machining are summarized in Table 2.2.

S.no.	Authors	Process	Process parameters	Machining performance	Remarks
1	(Younis et al., 2015) [182]	EDM	Is, EM, and MC	CR and RS	SR was higher when using Dura graphite than when using Poco graphite. As pulse current increases, micro-cracks increase; soft machining exhibited higher residual stresses than medium and rough machining. Poco graphite exhibited higher residual stresses compared with Dura graphite electrode.
2	(Valaki and Rathod 2015) [74]	Die sinking EDM machine	Is, Vg, Ton, and Tof	MRR, EWR, and TWR	The waste vegetable oil-based biodielectric fluid can be used as an alternate to hydrocarbon-, water-, and synthetic-based dielectric fluids for EDM.
3	(Zhang et al. 2014) [197]	EDM	PD and PoW	RE, D_plas, and RE	The MRR and energy efficiency were much higher with short pulse durations than with long pulse durations. The depth–diameter ratio of the crater was higher when the workpiece was positive.

4	(Sudhakara and Prasanthi 2014) [190]	W EDM	Ton Toff, Vs, Ip, WT, and DP	SR	The ranges of process parameters for wire EDM were established as follows: pulse-on time 108–128 µs, pulse-off time 47–63 µs, peak current 11–13 A, voltage 18–68 V, wire tension 2–8 g, water pressure 8–14.
5	(Aich and Banerjee 2014) [139]	EDM	I, Ton, and Toff	MRR and SR	The optimal parameters (I, Ton, and Toff) to maximize the MRR were 12.0 A, 153.9865 µs, and 50.0000 µs, respectively, and those to achieve the best SR were 3.0 A, 200.000 µs, and 126.8332 µs, respectively.
6	(Balasubramanian and Senthilvelan 2014) [118]	EDM	Ip, Ton, DP and D_tool	MRR, TWR, and SR	For EN-8 material, the mean MRR value was (72.4 mm3 /min), it was higher for the cast electrode than for the sintered electrode. The TWR was (12.73 mm3 /min); it was lower for the cast electrode than for the sintered electrode. For die steel D3, the mean value of MRR was higher for the cast electrode than for the sintered electrode. The TWR was marginally lower for the cast electrode than for the sintered electrode. The mean value of SR was marginally lower for the sintered electrode than for the cast electrode.

7	(Sahu, Mohanty et al. 2013) [107]	EDM	Ip, Ton, τ, and Dp	MRR, TWR, SR, and r1 /r2	The values of discharge current (Ip), pulse-on time (Ton), duty factor(τ), and flushing pressure (Fp) that achieved the best quality were 7 A, 200 µs, 90%, and 0.4 kg/m2 , respectively. The optimal obtained response parameters were MRR = 13.9600 mm3 /min, TWR = 0.0201 mm3 /min, Ra = 4.9300 µm, and circularity = 0.8401.
8	(Klocke et al. 2013) [170]	EDM	I, PD, and GG	MRR and TWR	The discharge current was the main parameter effect on the MRR and the discharge duration was the main parameter effect on the TWR. There was no direct link between the grain size and the two response parameters MRR and TWR. MRR increases as the current increases and it decreases as the pulse duration and electrical conductivity of graphite grade increase. Relative TWR slightly decreases as the current increase and slightly increases as the electrical conductivity of graphite grade increase, whereas it sharply decreases as pulse duration increases.

9	(Shabgard et al. 2013) [126]	EDM	Is and Ton	PFE	Plasma flushing efficiency increases as pulse current increases and it decreases as pulse-on time increases. Recast layer thickness increases as pulse-on time increases.
10	(Fan, Bai et al. 2013) [198]	W EDM-HS	C	T and SR	Best surface roughness and the minimum achievable maximum processing thickness were obtained upon selecting a capacitance that achieved triple the charging time constant equal to pulse duration.
11	(Srivastava and Pandey, 2012) [141]	EDM	Is, Ton, τ, and Vg	MRR, EWR, and SR	EWR and surface roughness were significantly lower in the ultrasonic assisted cryogenically cooled copper electrode (UACEDM) process than in the conventional EDM process and MRR was approximately the same as for conventional EDM. Surface integrity of the workpiece machined by UACEDM was better than that machined by the conventional EDM process. In UACEDM, the density of cracks increases as the discharge current increases. Induced stress increases as pulse-on duration and crack formation increase.

12	(Teimouri and Baseri 2012) [196]	EDM	DE, H, and w	MRR and SR	The rotary tool electrode improved the machining performance. The magnetic field reduced the inactive pulses and helped the ionization. As rotational speed increases, Ra decreases.
13	(Kumar and Batra 2012) [116]	EDM	Ip, Ton, and Tof	µH	Machining conditions allowing material transfer (of tungsten and carbon to the workpiece surface) by EDM were at a discharge current less than 5 A, shorter pulse-on time less than 10 µs, and longer pulseoff time more than 50 µs with negative polarity of the tool electrode. The most significant factor for surface modification was peak current.
14	(Sivapira et al. 2011) [194]	EDM	Ip, PD, DL, and DF	S_green	The optimal machining performance for green EDM was with peak current = 4.5 A, pulse duration = 261 µs, dielectric level = 40 mm, and flushing pressure = 0.5 kg/cm2 .
15	(Çayda¸s et al. 2009) [121]	Wire EDM	PD, V, DP, and S-wire	TWL and Avr_SR	The developed approach greatly improved the surface roughness and white layer thickness in wire EDM.

16	(Lin et al. 2009) [157]	EDM	P, Ip, PD, IH, V, and Vs	MRR and SR	The MRR of magnetic forceassisted EDM was almost three times as large as the value for standard EDM. Employing magnetic force-assisted EDM improved the lower relative electrode wear ratio (REWR) from 1.03% to 0.33% and reduced the SR from Ra 3.15 to 3.04 µm on average. Discharge craters were bigger and deeper, and microcracks were more common in standard EDM than that magnetic force-assisted EDM. In the magnetic force-assisted EDM process, MRR was significantly affected by polarity and peak current and SR was significantly affected by peak current. The optimal parameters which maximized MRR were negative polarity, peak current = 5 A, auxiliary current = 1.2 A, pulse duration = 460 µs, no-load voltage = 120 V, and servo reference voltage = 10 V. The optimal parameters which achieved minimum SR were positive polarity, peak current = 20 A, auxiliary current = 0.8 A, pulse duration = 460 µs, no-load voltage = 200 V, and servo reference voltage = 10 V.

17	(Wu et al. 2009) [159]	EDM	Ip, PD, V, and Vg	MRR and SR	Adding 30 g/L of Span 20 to kerosene increased the MRR by 40%. Selecting proper working parameters improved MRR by 85%. SR was not deteriorated even at MRR. Adding Span 20 (30 g/L) decreases both the concentrated discharge energy and the unstable discharge phenomenon. The thickness of recast layer on the workpiece of kerosene was less than the thickness of pure kerosene. The surfactant increased the conductivity of kerosene and shorted the delay time, thus improved the machining efficiency
18	(Matoorian et al. 2008) [193]	EDM	IN, Ton, Toff, V, S, and W	MRR	The factors most influencing the cost-effectiveness of the EDT process were intensity, spindle speed, servo, and pulse-on time in the following combination: 6 A, 50 µs, 20 µs, 120 V, 30 V, and 40 rpm, respectively. The actual and predicted values of MRR were 0.023 and 0.021, respectively.

19	(Haron et al. 2008) [192]	EDM	I, EM, and D_tool	MRR	The copper electrode achieved higher MRR than the graphite electrode. It was recommended to use the copper electrode for rough cutting and the graphite electrode for finish

					cutting
20	(Haddad and Tehrani 2008) [119]	Wire EDM	P, Toff, V, and w	MRR	The only influential design factors and interaction effects of machining parameters on the MRR in the cylindrical wire electrical discharge turning process were power, voltage, pulse-off time, and spindle rotational speed.
21	(Kansal et al. 2008) [114]	Powdermixed electric discharge machining (PMEDM)	I, Ton, Toff, DE, and PCH	TD	The simulation results showed that PMEDM produced smaller and shallower craters than EDM under the same set of machining conditions.
22	(Kanlayasiri and Boonmung 2007) [177,178]	Wire EDM	Ton, Toff, Ip, and WT	SR	The main parameters of wire EDM affecting the SR of DC53 die steel were pulse-on time and pulse-peak current. The SR increases as the pulse-on time and pulse-peak current increase.

23	(Kansal et al. 2007) [115]	Powdermixed EDM	Ip, Ton, Toff, PCON, GN, and NF	MRR	MRR in powder-mixed EDM was significantly affected by peak current, concentration of the silicon powder, pulse-on time, pulse-off time, and gain. Among all, peak current and concentration of silicon powder were the parameters most influencing MRR. The optimum c parameters were peak current = 10 A, powder concentration = 4 g/L, pulse-on time = 100 µs, pulse-off time = 15 µs, and gain = 1 mm/s.
24	(Kiyak and Cakır 2007) [164]	EDM	Is, Ton, and Tof	SR	The SR increases as pulsed current and pulse time increase. SR decreases as current and pulse time decrease and pulse pause time increases. For rough EDM machining, the machine power should be 25% of the produced power with current, pulse time, and pulse pause time of 16 A, 6 µs, and 3 µs, respectively. For finish machining, the machine had 50% of produced power with current, pulse time, and pulse pause time of 8 A, 6 µs, and 3 µs, respectively.

25	(Tzeng and Chen 2007) [154]	EDM	V, Pd, τ, Ip, PCON, regular distance for electrode lift, time interval for electrode lift, and powder size	Precision and accuracy of the highspeed EDM	81.5% of the high-speed EDM process variance was due to pulse time, duty cycle, and peak value of discharge current. The best parameter combinations achieving precision and accuracy of the highspeed EDM process were opencircuit voltage of 120 V, pulse duration of 12 µs, duty cycle of 66%, pulse-peak current of 12 A, powder concentration of 0.5 cm3 /L, regular distance for electrode lift of 12 mm, time interval for electrode lift of 0.6 s, and powder size of 40 µm
26	(Zarepour et al. 2007) [186	EDM	Ton, I, and V	TWR	Pulse-on time, current, and preEDM roughing as factors, along with pulse-on time/current, pulseon time/pre-EDM roughing, and current/pre-EDM roughing as interactions, were found to have significant effects on electrode wear of the EDM process of DIN 1.2714.
27	(Yilmaz et al. 2006) [188]	EDM	Is, PD, PI, FR, and GC	EWR, better SR, and ER	Providing a selection tool enables an unskilled user to select necessary parameters which achieve less electrode wear, better surface quality, and high erosion rate for both finish and rough machining.

28	(Wu et al. 2005) [158]	EDM	P, PD, V, Vg, PCON, and SCON	SR	The surface roughness of the workpiece in the EDM process was improved by adding surfactant and aluminum powder to the dielectric fluid. The EDM parameters which achieved optimal surface roughness (0.172 μm) were Al powder concentration of 0.1 g/L, positive polarity, peak current of 0.3 A, peak duration of 1.5 μs, and surfactant concentration of 0.25 g/L. The gap distance was increased by adding aluminum powder or surfactant to the EDM dielectric fluid. Dielectric mixed with both aluminum powder and surfactant achieved an optimally thin recast layer. The mixture also improved the SR by 60% compared to the SR under normal dielectric.

29	(Kansal et al. 2005) [61]	Powdermixed EDM	Ton, τ, Ip, and PCON	MRR and SR	MRR increases as the concentration of the silicon powder increases. SR decreases as the concentration of the silicon powder increases. Peak current and concentration of the silicon powder were the parameters most affecting MRR and SR. MRR increases and SR decreases as the combination of peak current and concentration increase.
30	(Amorim and Weingaertner 2005) [161]	EDM	Is, PD, PI, V, P, and G_mod	MRR, WWR, and SR	The maximum MRR of 8 mm3 /min was obtained at a discharge current of 8 A and a discharge duration of 50 µs, with positive electrode polarity and a generator under iso-energetic mode. The minimum average SR of 0.6 µm was obtained at a discharge current of 3 A, discharge duration of 12.8 µs, negative electrode polarity, and generator under iso-energetic mode. The volumetric relative wear for

					EDM with a negative electrode polarity was much higher than that with positive electrode polarity

31	(Hasçalýk and Çayda¸s 2004) [122]	W EDM	PD, V, Swire, and DP	SR and MS	The thickness white layer was proportional to the magnitude of the energy impinging on that surface. The density of cracks in the white layer and SR increase as the pulse duration and open-circuit voltage increase. Dielectric fluid pressure and wire speed did not have much of an influence on SR. The surface of all workpieces was harder than the bulk material, while the heat-affected zone was softer in quenched and tempered workpieces

32	(Kunieda et al. 2004) [103]	Dry EDM	G and Gain	MRR	The monotonous oscillation using a piezoelectric actuator was not useful in dry EDM.
33	(Singh et al. 2004) [23]	EDM	Is and EM	MRR, D_over, EWR, and SR	Among copper, copper tungsten, brass, and aluminum, copper and aluminum electrodes offered higher MRR and SR during machining of En-31 work material in EDM, where the electrodes of these two materials produced low diametrical overcut. The copper– tungsten electrode offered low values of SR at high discharge currents. Copper and copper–tungsten electrodes offered low EWR. In contrast, brass resulted in the highest EWR. Among the four electrode materials, copper was the best to machine En-31 material.

34	(Lin et al. 2000) [54]; Puri and Bhattacharyya 2003) [142]	W EDM	Ton, Toff, Ip, τ, Vp, Swire, WT, Vs, DP, and F	Avg_CS and G-InI	The parameters most affecting the average cutting speed during rough cutting were pulse-on time, pulseoff time, and pulse-peak current, and those during trim cutting were pulse-on time and constant cutting. The parameter most affecting the SR during rough cutting was pulse-peak current, and those during trim cutting were pulse-on time, pulse-peak voltage, servo spark gap set voltage, dielectric flow rate, wire tool offset, and
					constant cutting speed. The factors most affecting geometrical inaccuracy due to wire lag during rough cutting were pulse-on time, pulse-off time, pulse-peak current, and pulse-peak voltage, and those during trim cutting were wire tension, servo spark gap set voltage, wire tool offset, and constant cutting speed.

35	(Guu et al. 2003) [105]	EDM	Is, Ton, and Tof	T_RL, SR, and σ_{res}	The recast layer becomes thicker as the pulse current and pulse-on duration increase. As the peak current is achieved, the melting of the material and damage of the surface and subsurface area increase.
36	(Ghoreishi and Atkinson 2002) [135]	EDM	A, w, LF, and HF	MRR, TWR, and SR	High-frequency vibration had a notable effect on the MRR. The combination of low-frequency vibration and electrode rotation did not give a satisfactory effect on MRR. The combination of ultrasonic vibration and electrode rotation led to an increase in MRR. The combination frequency vibration and electrode rotation was the best for the finishing cut. In the semi-finishing cut, the vibro-rotary EDM increased MRR by 35% and 100% compared to vibratory and rotary EDM, respectively.
37	(Kunieda and Furudate 2001) [152]	Dry EDM			The MRR and waviness could be improved by increasing the wire

					winding speed and decreasing the actual depth of cut.

After reviewing the research work related to tool steel machining using the EDM process, it can be found that the majority of studies investigated the e*ff*ect of the operating parameters on the performance parameters of MRR, EWR, and surface quality. Other bodies of research were conducted to investigate, solve, or study other issues, such as the electrode shape and its movement, the e*ff*ect of the EDM process on the tool steel properties and machined surface, as well as combined and hybrid processes, and the e*ff*ect of various dielectric fluid used in the process, among others.

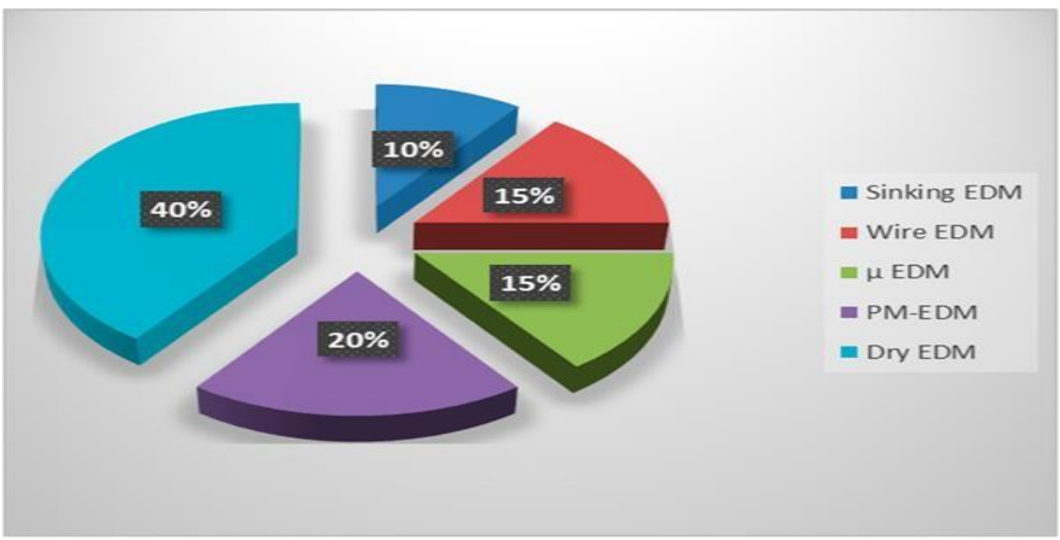

Figure 2.2 shows the percentages of the EDM processes utilized for studying tool steel machining

This review on the state-of-the-art studies of the EDM processes of tool steel led to the following conclusions:

- According to the general agreement of the results, the main factors influencing the MRR of di*ff*erent tool steel grades in EDM are the discharge current and the pulse-on time. The gas pressure and electrode rotation speed also have a significant influence on the MRR. Furthermore, the MRR can be improved by using an electrode material with high electrical conductivity. Using powder-mixed EDM significantly a*ff*ects the MRR.

- According to major observations by the researchers, low SR is achieved at lower peak current and pulse-on duration. Furthermore, the medium value of peak current, along with minimum possible pulse-on time, can minimize surface crack density. The review revealed that the SR is increased with higher values of pulsed current and pulse-on time, whereas better surface finish is achieved with lower current, lower pulse-on time, and relatively higher pulse-o*ff* time. Long-duration pulses cannot meet the machining requirements during finish machining with high requirements in SR. Furthermore, applying a magnetic field leads to an improvement in surface quality.
- The review revealed that surface cracks are influenced by the pulse current. Furthermore, a reduction in pulse-on duration suppresses the formation of surface cracks.
- The review revealed that waste vegetable oil-based bio-dielectric fluid can be used as an alternate to hydrocarbon-, water-, and synthetic-based dielectric fluids for EDM. Furthermore, the use of a powder-mixed dielectric in EDM reduces the SR, crater diameter, crater depth, and the white-layer thickness; it also significantly reduces the surface heterogeneity.

Table 2.3. General e*ff*ect of major operating parameters on key performance measures.

↑ ↑ **Time** **Speed**

Discharge Current

Pulse-Off

Pulse-On Time

Voltage **Electrode Rotation**

MRR			↑	↓	↗↘	↑
EWR	↓	↓	↓	↓	↓	↓
SR	↓	↓	↓	↑	↓	↑

- The studies also divulged that a significant amount of material is transferred from the powder suspended in the dielectric medium to the work material. The most significant factor for this phenomenon of surface modification is the peak current.
- The review also revealed that ultrasonic action has a significant influence on the performance of the EDM process. The surface integrity is better in an ultrasonic-assisted process than in conventional EDM.
- Applying a magnetic field reduces inactive pulses, including arcing, short circuit, and open circuit, in addition to helping in the ionization. Using a magnetic field also leads to an improvement in surface quality.
- The review revealed that, for thermal profiling, the gauss heat source was closer to the actual EDM process than the point heat source, circular heat source, and other heat source types.
- The compositions of generated aerosol depend on the composition of the electrode materials and on the boiling points of its constituents.
- According to a general observation by the researchers, the particle size in the dielectric fluid affects the surface quality of the machined surface. More improvements in the SR can be achieved using a smaller particle size. However, particle size has the opposite effect on the recast layer, whereby a smaller particle size leads to a thicker recast layer in the EDM machined surface. Despite the existing studies on this topic, more studies are still needed to assess the effect of adding different available powder types in the EDM of different grades of tool steel.
- In the EDM process, particle agglomeration is reduced after surfactant molecules cover the surface of debris in the dielectric fluid. Adding a co-surfactant to the dielectric increases the conductivity of the dielectric and improves the machining efficiency. Furthermore, it improves the MRR of the EDM process.

CHAPTER 3

METHODOLOGY

In this present chapter methodology used for obtaining better response parameters is briefly discussed. In modern industrial environment a numerous kind of Investigations have been done for the improvement of product quality in the field of manufacturing. Some have few factors to be considered, some have many. While there are others, that demand factors to have mixed levels. A vast majority of experiments however fall in the category where all factors possess the same number of levels. In the conventional technique of varying one factor at a time, lot of experimental data can be obtained. This way of experimentation not only consumes lot of time but also poses a challenge to the investigator for deriving appropriate conclusion from the huge experimental data. Design of Experiments (DOE) is at ever rescue for planning systematic experimentation and arriving at meaningful conclusion without being inundated in huge set of experimental data. DOE is an experimental strategy in which effects of multiple factors are studied simultaneously by running tests at various levels of factors. There are number of statistical techniques available for engineering and scientific studies. In the present investigation Taguchi approach combined with Utility is used.

3.1. Design of Experiments (DOE)

Design of Experiments is a powerful statistical technique introduces by R.A**.** Fisher in England in the 1920's to study the effect of multiple variables simultaneously. The DOE using Taguchi approach can be economically satisfy the needs of problem solving and product/process design optimization projects. DOE is a technique of defining and investigating all possible combinations in an experiment involving multiple factors and to identify the best combination. In these different factors and their levels are identified. Design of Experiments is also useful to combine the factors at appropriate levels, each with the respective acceptable range, to produce the best results and yet exhibit minimum variation around the optimum results. Therefore, the objective of a carefully planned designed experiment is to understand which set of variables in a process affects the performance most and then determine the best levels for these variables to obtain satisfactory output functional performance in products.

Advantages of Design of Experiments (DOE)

- Number of trails is significantly reduced.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental errors can be estimated.
- The effect of parameters on the characteristics of the process can be found out.

The DOE techniques used for process parameter optimization

- Full factorial technique
- Fractional factorial technique
- Taguchi orthogonal array
- Response surface method (central composite design).

3.2. Taguchi Optimization Method

Taguchi techniques are statistical methods developed by Genichi Taguchi to improve the Quality of manufacturing goods. Basically, classical experimental design methods are to complex and not easy to use. A large number of experiments have to be carried out when the number of the process parameter increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach i.e., System design, parameter design and tolerance design. In system design the engineer applies scientific and engineering knowledge to produce a basic functional prototype design, this design including the product design stage and process design stage. In the product design stage, the selection of material components tentative product parameter values, etc., are involved as to the process design stage the analysis of processing sequences, the selection of production equipment, tentative process parameter values, etc., are involved. Since system design is an initial functional design it may be far from optimum in terms of quality and cost. Following on from system design is parameter design. The objective of parameter design is to optimize the settings of the process parameter values for improving quality characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variation in the environmental conditions and other noise factors. Finally, tolerance design is used to determine and analyze tolerances around the optimal settings recommend by parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not meet the required performance. However, based on above discussion parameter design is the key step in the Taguchi method to achieving high quality without increasing cost. To obtain high cutting performance, the parameter design proposed by Taguchi method is adopted in this project work.

The general steps involved in the Taguchi Method

- Selection of factors for the study
- Selection of the number of levels for the factors
- Selection of appropriate orthogonal array
- Assignment of factors to columns
- Conduct the test
- Analysis of the results.

Optimization of process parameters is the key step in the Taguchi method to achieve high quality without increasing cost. Originally Taguchi method was designed to optimize single performance characteristic. According to Taguchi method, the S/N ratio is the ratio of Signal to Noise where signal represents the desirable value and noise represents the undesirable value. For the experimental responses Signal-to-Noise Ratio(S/N) are calculated by using the Equations 3.1, 3.2 and 3.3. The experimental results are now transformed into a signal-to-noise (S/N) ratio. Since the Material Removal Rate is desired to be at maximum, so higher the better characteristic is used for S/N ratio calculation and similarly for Surface

Roughness is desired to be minimum, so lower the better characteristic is used for S/N ratio calculation. After calculating the S/N ratios of responses, the Mean values of S/N ratio for each response are calculated for different levels of process parameters and optimum conditions are found by taking the maximum value of mean S/N ratio.

Upper –bound effectiveness (i.e., higher-the-better)

$$\frac{S}{N}\text{ratio} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^2}\right) \quad \text{.............................. Eq (3.1)}$$

Where y_{ij}= i^{th} replicate of j^{th} response n

=number of replicates, i=1,2,3……n;

j=1,2,3……k.

Equation (3.1) is applied for problem where Maximization of the quality characteristic of interest is required.

$$= -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^2\right)$$

Lower-bound effectiveness (i.e., lower-the-better)

$$\frac{S}{N}\text{ratio} \quad \text{............................... Eq (3.2)}$$

Equation (3.2) is applied for the problem where minimization of the quality characteristic is required. **Moderate effectiveness (i.e., nominal-the –better)**

$$\frac{S}{N}\text{ratio} = 10\log\left(\frac{\bar{y}^2}{s^2}\right) \quad \text{....................................... Eq (3.3)}$$

Where, $\bar{y} = \frac{y_1+y_2+y_3...+y_n}{n}$ and $s^2 = \frac{\sum(y_i-\bar{y})^2}{n-1}$

Equation (3.3) is used where minimization of the mean squared error around a specific target value is desired.

3.3. Utility Method

The performance of any machining process is measured based on the number of output characteristics. Therefore, a combined measure is necessary to measure its overall performance, which must take into account the relative importance of all the quality characteristics. Such a composite index represents the overall utility of a product/process. Utility refers to the satisfaction that each attribute provides to the decision maker. Thus, utility theory assumes that any decision is made on the basis of the utility maximization principle, according to which the best choice is the one that provides the highest satisfaction to the decision maker. According to the utility theory, if x_i is the measure of effectiveness of an attribute (or quality characteristics) 'i' and there are *'n'* attributes evaluating the outcome space, then the joint utility function can be expressed as

$U\,(x_1, x_2 \dots \dots \dots \dots \dots, x_n) = f(U_1(x_1), U_2(x_2) \dots \dots \dots \dots \dots, U_n(x_n))$...............Eq (3.4)

Where, $U_i(x_i)$is the utility of the i^{th} attribute

The overall utility function is the sum of individual utilities. If the attributes are independent, then

$U(x_1, x_2, \dots \dots \dots \dots, x_n) = \sum_{i=1}^{n} U_i(x_i)$............................. Eq (3.5)

The attributes may be assigned weights depending upon the relative importance or priorities of the characteristics. The overall utility function after assigning weights to the attributes can be expressed as

$U(x_1, x_2, \dots \dots \dots \dots, x_n) = \sum_{i=1}^{n} W_i U_i(x_i)$........................ Eq (3.6)

Where, W_i is the weight assigned to the attribute i. The sum of the weights for all the attributes must be equal to 1. The overall utility computed is treated as a single objective function and it is optimized using Higher-the-Better (HB) characteristic.

CHAPTER-4

EXPERIMENTAL DETAILS

This chapter describes the experimental procedural steps, details of wire EDM machines, specifications, work piece properties and applications. Similarly, the selection of wire EDM process parameters and design of Orthogonal Array (OA) for conducting the experiments have been well explained.

4.1. WEDM Machine

The experiments were carried out on a Wire EDM machine (ELPULS-40ADLX) shown in the figure 4.1. The WEDM machine tool has the following specifications:

Design	:	Fixed column, moving table
Table size	:	440 x 650 mm
Max. work piece height	:	200 mm
Max. work piece weight	:	500 kg
Main table traverse (X, Y)	:	300, 400 mm
Auxiliary table traverse (u, v)	:	80, 80 mm
Wire electrode diameter	:	0.25 mm (Standard) 0.15, 0.20 mm (optional)
Generator	:	ELPULS-40 A DLX

Controlled axes	:	X Y, U, V simultaneous / independent
Interpolation	:	Linear & Circular
Least input increment	:	0.0001mm
Least command input (X, Y, u, v)	:	0.0005mm
Input Power supply	:	3 phase, AC 415 V, 50 Hz
Connected load	:	10 KVA
Average power consumption	:	6 to 7 KVA

Figure 4.1. WEDM Set Up

4.2. Work Piece Material

In the present work the Nitriding steel EN41 shown in figure 4.2 is considered as the work piece. EN41 is a chromium aluminium molybdenum-based steel specification usually supplied in the hardened and tempered. EN41 ‘R’ condition has a tensile of 700-850 N/mm². EN41’S’ condition has a tensile of 775-925 N/mm². It offers high wear resistant properties together with toughness and ductility. EN41 is supplied ready heat treated. If further heat treatment is required annealed EN41 should be heated slowly to 870-930°C and after adequate soaking at this temperature quench in oil/polymer or water. The chemical composition of EN41 steel is mentioned in table 4.1.

Figure 4.2. EN41 Steel

Table 4.1. Chemical Composition of EN41 Steel

S.No	Composition	Range
1	Carbon	0.35-0.45%
2	Silicon	0.10-0.45%
3	Manganese	0.65%
4	Sulphur	0.05%

5	Phosphorus	0.05%
6	Chromium	1.40-1.80%
7	Molybdenum	0.10-0.25%
8	Nickel	0.40%
9	Aluminium	0.90-1.30%

4.3. Range of Process Parameters

The pilot experiments were carried by varying the process parameters e.g., Pulse-On-Time (T_{on}), Pulse-Off-Time (T_{off}), Wire Feed (WF) and Wire Tension (WT) to study their effect on output parameters eg. Surface roughness and material removal rate etc. The ranges of these process parameters are given in Table 4.2. From these ranges of the process parameters, different levels of process parameters (Table 4.3) would be selected for the Taguchi experimental design and the experimental design using MINITAB is given in the table 4.4.

Table 4.2. Process Parameters with Their Ranges

S.No.	Parameter	Range	Units
1	Pulse-On-Time (T_{on})	115-131	µsec
2	Pulse-Off-Time (T_{off})	40-63	µsec

3	Peak Current (IP)	180-230	Ampere
4	Spark Gap Voltage	10-20	Volts
5	Wire Feed (WF)	0-10	m/min
6	Wire Tension (WT)	0-5	Kg-f
7	Flushing Pressure	3-15	Kg/cm2

Table 4.3. Process Parameters and Their Levels

Parameter	Level-1	Level-2	Level-3
Pulse-On-Time (T_{on})	115	123	131
Pulse-Off-Time (T_{off})	53	58	63
Wire Tension (WT)	2	3	4
Wire Feed (WF)	4	5	6

Table 4.4. L27 Orthogonal Array (OA)

S.No	T_{on}	T_{off}	WT	WF
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3

4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	2
11	2	1	2	3
12	2	1	3	1
13	2	2	1	3
14	2	2	2	1
15	2	2	3	2
16	2	3	1	1
17	2	3	2	2
18	2	3	3	3
19	3	1	1	3
20	3	1	2	1

21	3	1	3	2
22	3	2	1	1
23	3	2	2	2
24	3	2	3	3
25	3	3	1	2
26	3	3	2	3
27	3	3	3	1

4.4. Experimentation Procedure

A plate of 150mm x 25mm x 25mm size of EN41 steel is mounted on the ELPULS-40ADLX WEDM machine tool (Figure 4.1) and specimens of 25mm x 25mm x 25mm size are cut. The following steps were followed in the cutting operation:

- Measure the weight of work piece before machining.
- The wire was made vertical with the help of verticality block.
- The work piece was mounted and clamped on the work table.
- A reference point on the work piece was set for setting work co-ordinate system (WCS). The programming was done with the reference to the WCS. The reference point was defined by the ground edges of the work piece.
- Water is used as the dielectric fluid.
- The program was made for cutting operation of the work piece and a profile of 25 mm x 25 mm square was cut.
- After machining, measure the surface roughness by using tally-surf shown in fig 4.3.

While performing various experiments, the following precautionary measures were taken:

- Each set of experiments was performed at room temperature in a narrow temperature range (range 27ºC).
- Before taking measurements of surface roughness, the work piece was cleaned with acetone.

Figure 4.3. Tally surf

CHAPTER-5

RESULTS & DISCUSSIONS

In this chapter the experimental results of Material Removal Rate (MRR) and Surface Roughness
(R_a) are analysed using Taguchi utility-based Signal to Noise (S/N) Ratios approach. The focus of the work is to identify the optimal combination of process parameters that concurrently maximizes the material removal rate and minimizes the surface roughness characteristics.

5.1. Experimental Results

The experimental results of Material Removal Rate (MRR) and Surface Roughness (R_a) are given in the table 5.1. The material removal rate is expressed as the ratio of weight difference of the work piece before and after machining to the machining time and is measured in cm^3/min. The surface roughness is tested at three different points on each machined surface by Tally surf Surface tester and the average is taken as the final value.

Material Removal Rate (MRR) = $\frac{w_i - w_f}{\rho * t}$ in cm^3/min.

Where, w_i = Initial weight of the work piece in grams.

w_f = Final weight of the work

piece in grams

ρ = density of the work material in

gm/cm^3

t= machining time in minutes.

Table 5.1. Experimental Results of Quality Characteristics

S.No.	T_{on}	T_{off}	WT	WF	MRR (cm^3/min)	R_a (μm)
1	115	53	2	4	12.52	2.52
2	115	53	3	5	13.36	5.10
3	115	53	4	6	14.15	7.23
4	115	58	2	5	13.05	4.32
5	115	58	3	6	13.75	6.12
6	115	58	4	4	12.94	3.02
7	115	63	2	6	13.59	7.14
8	115	63	3	4	12.81	4.21
9	115	63	4	5	13.55	5.24
10	123	53	2	5	14.92	3.73
11	123	53	3	6	15.89	7.52
12	123	53	4	4	14.75	3.24
13	123	58	2	6	15.84	4.26
14	123	58	3	4	14.40	3.20
15	123	58	4	5	15.56	5.71

16	123	63	2	4	14.24	2.76
17	123	63	3	5	15.27	4.17
18	123	63	4	6	14.24	6.91
19	131	53	2	6	18.44	5.46
20	131	53	3	4	16.71	3.52
21	131	53	4	5	18.31	4.92
22	131	58	2	4	16.46	2.30
23	131	58	3	5	17.61	3.84
24	131	58	4	6	19.60	6.25
25	131	63	2	5	17.43	4.21
26	131	63	3	6	18.49	5.10
27	131	63	4	4	17.34	3.72

In Taguchi utility-based Signal-to-Noise (S/N) ratios method figures step is to find S/N ratios for the performance characteristics of Material Removal Rate (MRR) and Surface Roughness (Ra) using Higher-the-better and Lower-the-better characteristics as described in chapter-3. The calculated values of S/N ratios are given in table 5.2. From the individual utility (S/N) values the combined utility values for the responses of such experiments has to be calculated and obtained values were depicted in table 5.3.

Table 5.2 Signal-to-Noise(S/N) ratios of responses characteristics

S.No.	η_{mrr}	η_{ra}
1	21.9521	-8.0280
2	22.5161	-14.1514

3	23.0151	-17.1828
4	22.3122	-12.7097
5	22.7661	-15.7350
6	22.2387	-9.6001
7	22.6644	-17.0740
8	22.1510	-12.4856
9	22.6388	-14.3866
10	23.4754	-11.4342
11	24.0225	-17.5244
12	23.3758	-10.2109
13	23.9951	-12.5882
14	23.1672	-10.1030
15	23.8402	-15.1327
16	23.0702	-8.8182
17	23.6768	-12.4027
18	23.0702	-16.7896
19	25.3152	-14.7439
20	24.4595	-10.9309
21	25.2538	-13.8393
22	24.3286	-7.2346

23	24.9152	-11.6866
24	25.8451	-15.9176
25	24.8259	-12.4856
26	25.3387	-14.1514
27	24.7810	-11.4109

Table 5.3 Combined Utility (η_{obs}) of Responses

S.No.	η_{obs}	S/N of η_{obs}
1	6.9620	16.8547
2	4.1824	12.4285
3	2.9162	9.2963
4	4.8013	13.6272
5	3.5155	10.9197
6	6.3193	16.0134
7	2.7952	8.9283
8	4.8327	13.6838
9	4.1261	12.3108
10	6.0206	15.5928
11	3.2491	10.2353
12	6.5825	16.3678

13	5.7035	15.1228
14	6.5321	16.3011
15	4.3537	12.7772
16	7.1260	17.0569
17	5.6370	15.0210
18	3.1403	9.9394
19	5.2857	14.4621
20	6.7643	16.6045
21	5.7072	15.1285
22	8.5470	18.6363
23	6.6143	16.4097
24	4.9638	13.9163
25	6.1702	15.8060
26	5.5937	14.9540
27	6.6851	16.5022

Now, Taguchi Analysis is employed on the obtained /converted Multi-objectives to a Single response. Taguchi Response table obtained for means is given in the table 5.4.

Table 5.4 Response Table for Means of η_{obs}

Level	TON	TOFF	WT	WF
1	4.495	5.297	5.935	6.706

2	5.372	5.706	5.213	5.290
2	6.259	5.123	4.977	4.129
Delta	1.765	0.583	0.957	2.576
Rank	2	4	3	1

From the results it is observed that the Wire feed (WF) has highest influence on the multi-Response. The Main-Effect-Plots were drawn and shown in figures 5.1 and 5.2 and it is observed that Wire Feed has highest effect on Multi Response with the changes in its levels.

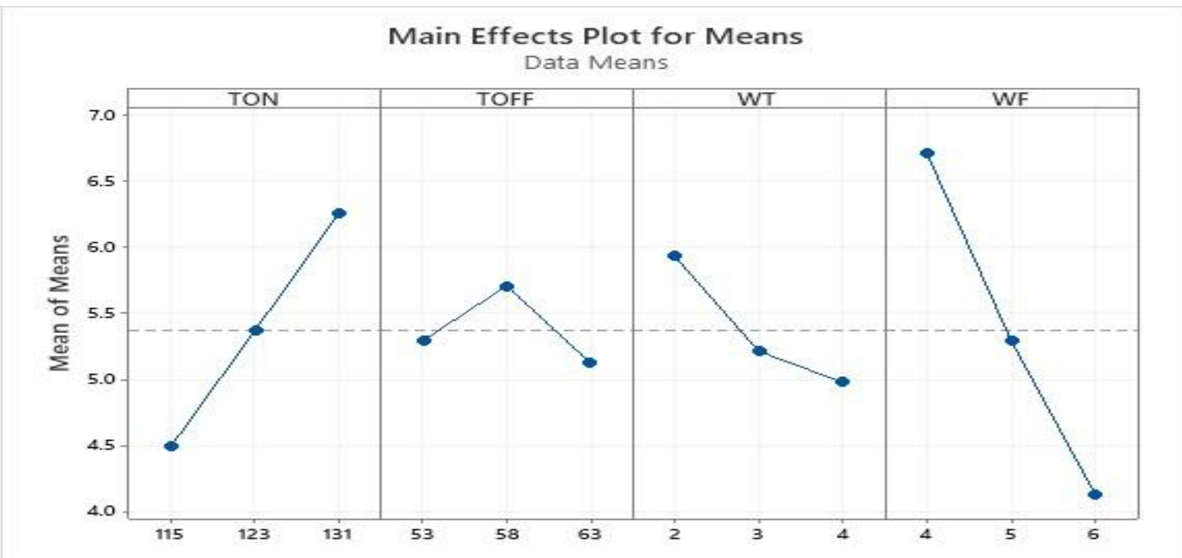

Fig 5.1 Main effect plots for means of overall utility(η_{obs})

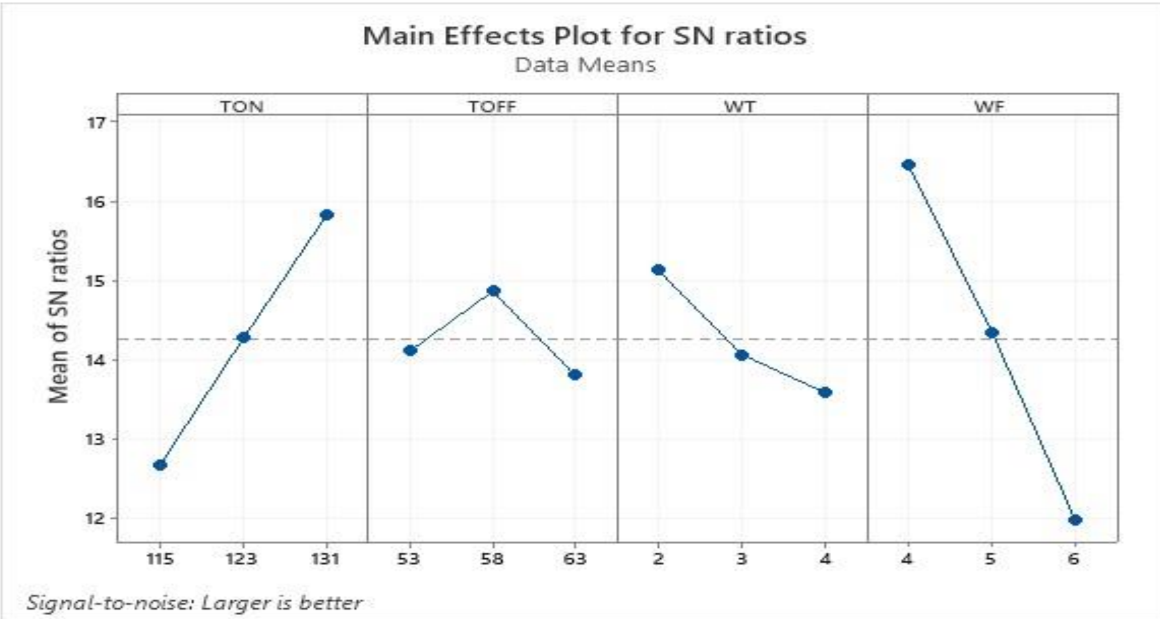

Fig 5.2 Main-Effect-Plot for S/N ratios of overall utility (η_{obs})

Table 10. Analysis of Variance (ANOVA) results of overall utility(η_{obs})

Regression & Analysis of Variance (ANOVA) has been conducted to study the influence of process parameters on the Multi response with 0.05 (95%) assumed significance. ANOVA results shown in table 5.5 it is observed that the wire feed has highest significance (F=42.61&p=0.0002005).

Regression Equation

nobs = 5.375 - 0.881 TON_115 - 0.003 TON_123 + 0.884 TON_131 -
0.078 TOFF_53
+ 0.331 TOFF_58
- 0.252 TOFF_63 + 0.560 WT_2 - 0.162 WT_3 - 0.398 WT_4
+ 1.331 WF_4 - 0.085 WF_5 - 1

The Regression model prepared (Eq.5.1) is tested for its adequacy with the Residual Analysis. The Residual plots for η_{obs} was shown in fig 5.3. From fig it is clear that the residuals are lie nearby the central line hence following the normality, the residuals are not showing any regular patterns. Either in versus Fits or verses order hence obey constant variance. Finally, the model prepared is best fit and can be use for the best prediction of Responses.

Source	DF	Adj SS	Adj MS	Fvalue	P-Value
TON	2	14.011	7.0055	19.92	0.000
TOFF	2	1.611	0.8054	2.29	0.130
WT	2	4.478	2.2390	6.37	0.008
WF	2	29.968	14.9841	42.61	0.000
Error	18	6.331	0.3517		
Total	26	56.399			

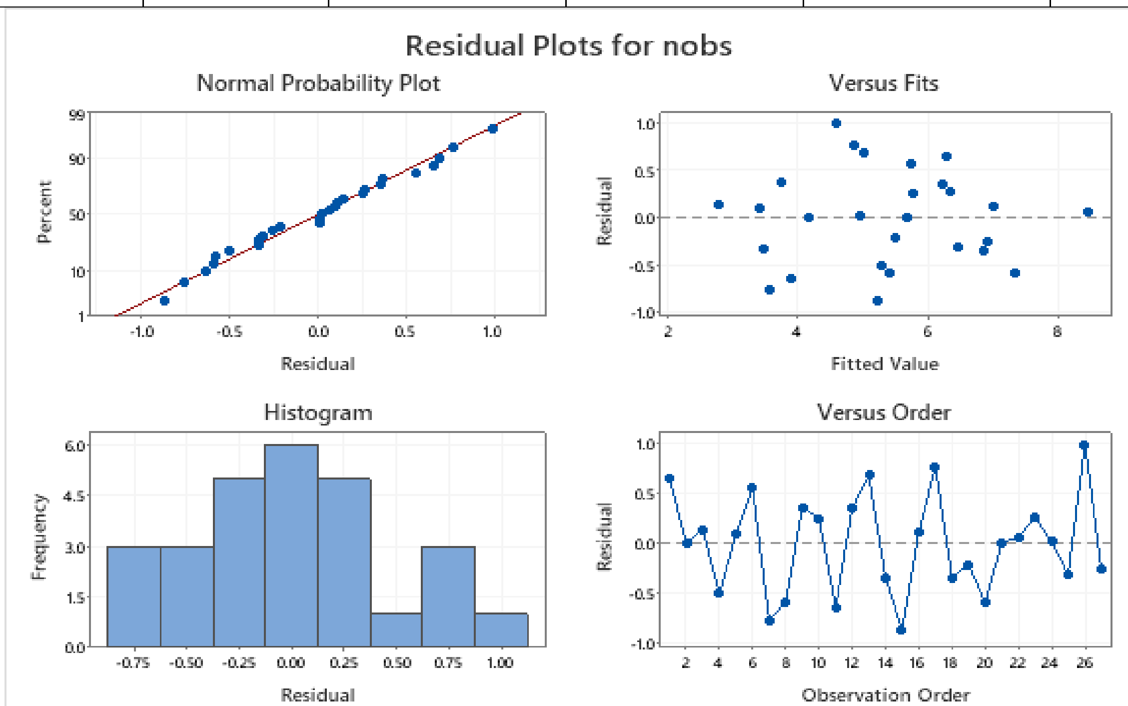

Figure 5.3. Residual plots for overall utility (η_{obs})

CHAPTER-6

CONCLUSIONS

The results of the multi objective optimization of responses using S/N ratios and utility are as follows:

1. Wire Tension (WT) is found as the most influencing factor.
2. The optimal condition of process parameters is obtained at,

   Pulse on Time: Level 3, 131 micro meters

   Pulse off Time: Level 2, 58 micro meters

   Wire Tension: Level 1, 2Kg-1

   Wire Feed: Level 1, 4m/min
3. The ANOVA results of Observed utility showed that the Wire Tension has the highest significance over the multi response.

CHAPTER-7

FUTURE SCOPE

Future Research Directions

Even though a high amount of work in the field of EDM was conducted, there are challenges left which still require more research, and these are listed below.

- Optimizing Process Parameters: The EDM process has a multifarious nature due to the complex discharge mechanisms, which hinders its optimization. Additionally, the introduction of new materials constantly complicates the optimization of parameters. Even in TS, many grades are introduced frequently; thus, more studies are required.
- Extending to a Wide Range of Workpiece Materials: EDM is primarily used for conductive materials; however, the current trend is to investigate the potential of EDM for machining nonconductive or semi-conductive materials, such as ceramics.
- Powder-Mix EDM: Powders of different materials are mixed with dielectrics to improve the machining process. This is another area which requires further attention. Researchers need to pay more attention to the machining of different tool steel grades in different EDM types under dielectric fluids with different material powders. There is a lack of studies covering this point.
- Use of Different Electrodes: Investigators can examine the performance of the EDM process by using various electrode materials, shapes, sizes, and geometries. The use of tubular electrodes is in the initial stages, and it requires further attention to deliver promising results.
- Hybrid or Assisted EDM: The EDM process hybridized with some other processes provides better results. Magnetic force-assisted EDM, laser with EDM, etc. are becoming commonly used methods to overcome process limitations. The great improvement in the performance revealed in the reviewed research was related to

EDM with ultrasonic action. Research trends may be directed toward the combination of these two processes.

- Electrode Cooling Methods: The electrode cooling mechanism represents another field of research. The cryogenic cooling of electrodes provided positive results in terms of a reduction in TWR.
- Electrical Discharge Turning (EDT) and Dry EDM: EDT is a very new concept and it requires more research. Dry EDM is also gaining interest in the research community.
- Miniaturization: More e*ff*orts are needed to extend the limits of miniaturization in micro-EDM. A smaller level of electric discharge energy is needed to overcome this limitation. Furthermore, new techniques to avoid the distortion of micro-workpieces are necessary in future research.
- Figure 5.4 shows a pictographic depiction of the future research directions.

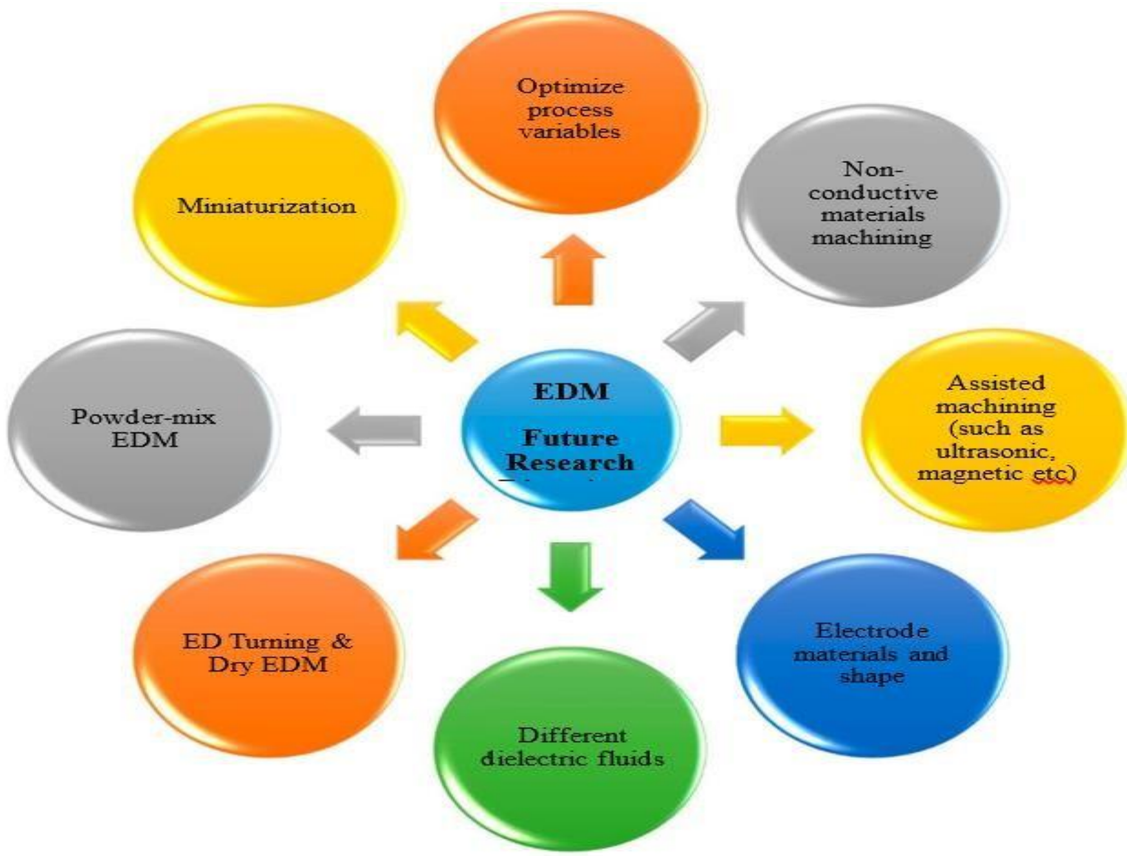

Figure 5.4. Future research areas in the EDM field

The research directions can be categorized into four broad classes, which can be further allocated into sub-groups, as shown in Figure5.5.

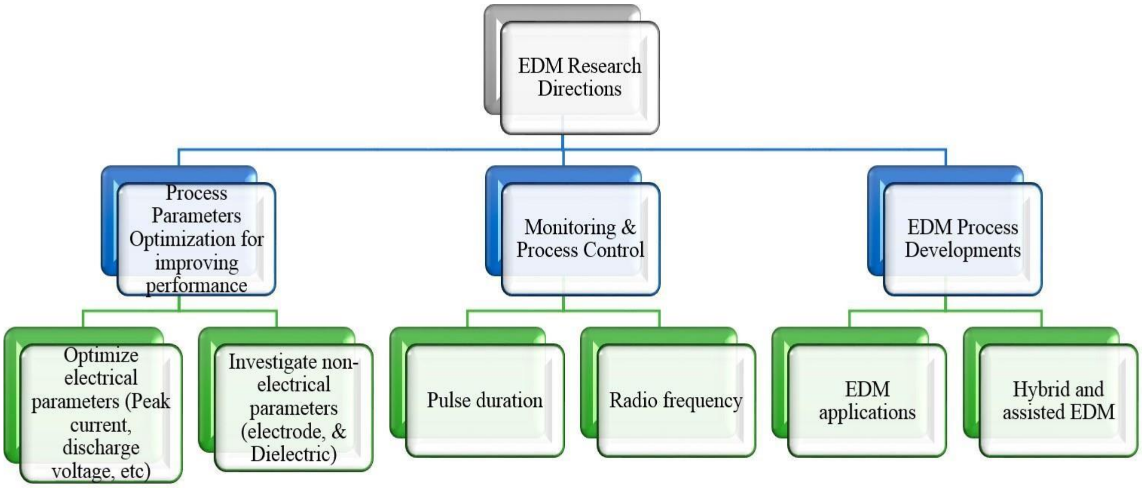

Figure 5.5. Classification of research directions.

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