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Study and Calibration of Electrical Discharge Machining (EDM)

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A B S T R A C T

With application to the repair of aerospace dies and moulds in mind, the near-net-shape material removal technique Electrical Discharge Machining is investigated. The paper tests electrode materials including graphite, copper, and tungsten carbide (WC), determining various machining performance parameters, such as the peak current and servo voltage, under ideal parameter settings. Results reveal that graphite electrodes have excelled among all the electrodes, as the relatively satisfactory surface roughness is 2.48 µm and the material removal rate is about 103%. Graphite electrode-based EDM technique requires more research for efficiency, controlled material removal, and surface finish. This aspect depicts the level of promise EDM can provide for accuracy-oriented high-quality industries in precision repairing processes. Tool wear in machining operations acts as the most critical factor influencing dimensional accuracy, tool life, cost of production, and product quality. These techniques have proven to be effective tools in predicting tool wear effects and optimising the management of wear, thereby minimizing errors in micro-EDM drilling. The data-driven regression models based on process monitoring data do show very satisfactory predictions for MRR and the TWR; thus, it significantly increases the accuracy. The Touch and Laser techniques micro-EDM milling methods are used to manage tool electrode wear, and have proven to be particularly effective for small-diameter tools and low wear rates. Periodic adjustments are necessary to maintain machining precision. Plunge milling has recently demonstrated advantages over the traditional milling method by improving productivity, achieving a balance between tool wear and extending tool life in a manner that is environmentally and economically favourable. Further, the modified tool design material with the application of copper and copper-tungsten alloys offered lower wear rates, higher removal rates, and the time to machine significantly reduced. Research in the area of LE-VMF studies the protective effect of certain material layering, which reduces wear and improves machining performance. Cermet material studies also show that EDM processing and surface finishing techniques can be used to enhance wear resistance and tribological performance. Therefore, these results highlight the dependence of tool material and design on wear rates, improvement in MRR, and better surface integrity. In general, the value of EDM in precision repair and machining in industry is underlined. This paper gives practical insight into how to improve EDM processes, particularly for graphite electrodes, yet presenting sound thinking behind the development of tools for advanced wear management strategies through advanced tools, predictive models, and novel electrode designs. Additional research should focus on improving dimensional accuracy and surface integrity as EDM continues to progress as an art and science for efficient and versatile machining.

Keywords: Electrical Discharge Machining (EDM), Graphite Electrodes, Material Removal Rate (MRR), Tool Wear Rate (TWR), Precision Machining, Surface Integrity, Tool Electrode Wear, Micro-EDM Drilling, Predictive Models, Machining Performance, Copper-Tungsten Alloys, Tool Design, Wear Management.

1. Introduction

Electrical discharge machining (EDM) is a nonconventional process, which is broadly applied in machining all sorts of hard conductive materials without any regard to their hardness. It is highly crucial for manufacturing accurate parts made up of complex hard materials such as composites, tool steels, and superalloys. This process works on the principle of erosion of the workpiece material using electrical discharges from the electrode commonly termed as the tool through high-frequency sparks. EDM provides excellent surface finish and accuracy, but process efficiency and product quality suffer with problems like tool wear and surface roughness.

Tool wear in EDM does not end there since it influences tool life, usability, surface finish, and machining accuracy. Mechanisms of wear are basically thermal, chemical, and mechanical wear. Each one contributes differently in varying proportions due to considerations such as the discharge energy, tool material, and dielectric properties. Thermal wear results from localized heating that causes melting, vaporization, and microcracking of the tool material. Chemical wear arises from interactions between the electrode and dielectric fluid, forming undesirable compounds, whereas mechanical wear is a result of physical abrasion during tool-workpiece interaction. We have to fight every mechanism with a target of making EDM more viable and effective.

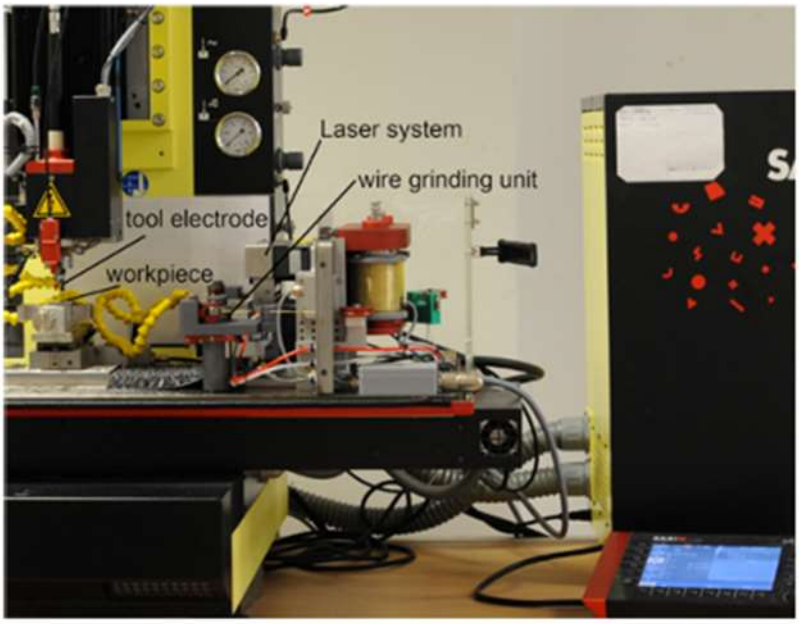

Fig.1 Machine setup

Many methods have been developed to decrease the tool wear. Such methods include the selection of advanced electrode materials, such as graphite, copper-tungsten, and copper, which give very good thermal and erosion resistances, and proper optimization of the process parameters concerning the discharge current, pulse frequency, and pulse duration. Innovations in dielectric fluid composition and circulation systems are also contributing to better cooling and lesser wear. Numerical simulations, experimental studies, and advanced diagnostic techniques provide the cutting tool wear interdependencies that help researchers analyse them for process refinement and extended lives.In parallel, sustainable alternatives such as vegetable oil-based dielectric fluids are currently being studied for EDM. Such fluids bring environmental benefits and generally promising performance improvements over conventional kerosene-based dielectrics. Higher viscosity assists debris flushing and recast layer prevention capabilities, improving surface finish and machining precision. For instance, MRR of dielectric fluids based on sunflower oil increased very significantly and reached even 55% improvement over kerosene in intensive regimes. Such a high increase in MRR was found for MRR in dielectric fluids in abrasive machining of materials having high thermal conductivity and low electrical resistivity - aluminium and magnesium alloys. The higher oxygen content in vegetable oils would naturally imply that the more intensified spark energy. However, problems persist here, as certain research studies reveal an increased surface roughness (Ra) with vegetable oil-based dielectrics in comparison to kerosene, primarily due to diversity in the dynamics of spark energy and debris removal. Despite these advancements, further research is required to optimize EDM processes with vegetable oil dielectrics. Key focus areas include refining dielectric properties to balance MRR and surface quality, and understanding the interplay of spark frequency, energy, and material characteristics. Apparently, efforts in tool-life reduction have been promising through the implementation of specific electrode designs, like laminated electrodes with protective material layers. These reduce wear rates, improve machining performance, and extend the life of the tool, thus improving the sustainability and efficiency of EDM operation.EDM's ability to machine complex precision parts makes it one of the pillars of modern manufacturing technology. This technology offers a potential for improved tool wear and surface quality when incorporating environmentally friendly vegetable oil dielectrics. EDM innovation in materials, optimization of the process, and sustainability will keep EDM at a performance level that is able to meet the demanding requirements of the industries like aerospace, automotive, and tooling.

2. Mechanisms of Tool Wear in EDM

2.1 Thermal Wear

The surface being machined gets overheated, softened and evaporated as the temperature generated in the machining process is hot enough to cause thermal wear. In operations such as EDM, both the workpiece and tool electrode melt and vaporize due to the high temperature generated by electrical discharges. Also, cyclic heating and cooling can damage the surface of the material or even create cracks. Since heat builds up faster in materials with low thermal conductivity, this type of wear is more pronounced. Proper cooling and material selection are two major requisites for minimizing thermal wear.

2.2 Electrochemical Wear

Electrochemical interactions at the contact between tool electrode and workpiece due to the presence of a dielectric or electrolyte cause electrochemical wear. Material loss from oxidation, corrosion, or dissolution results from this process. Electrochemical wear EDM is one of the mechanisms that causes the degradation of the electrode and workpiece. It becomes significant for machining electricity-carrying materials. This wear mechanism is chiefly governed by process parameters such as voltage and current; furthermore, electrolyte composition is also under its command.

2.3 Mechanical wear

There are three primary mechanisms for mechanical wear: abrasion, impact, and friction between the tool and the workpiece. This is not the predominant mechanism in EDM, but it might occur when machining debris particles get trapped between the electrode and the workpiece, thus causing abrasive wear. The causes of this wear include tool deterioration, surface roughness, and dimensional errors. Mechanical wear can be mitigated through proper cleaning out of debris and by optimizing machining settings.

2.4 Melting and Vaporization

The two primary methods of material removal in EDM are vaporization and melting, which are caused by intense electrical discharges. Tiny craters on the workpiece surface are created by the melting and vaporization of material because of the localized heat. These high-energy processes generate vapor and molten metal that are released by the dielectric fluid.

3. Strategy for minimising tool wear

3.1 Tool Material Selection

In EDM, selecting the appropriate tool material is essential to reducing tool wear. Tungsten, tungsten carbide, and copper-tungsten alloys are examples of high melting point materials that successfully withstand thermal erosion and wear. Such high conductivity materials as pure copper ensure adequate spark formation and reduce wear and energy losses. Due to the self-lubricating properties and good resistance to wear, graphite is often applied too. In some cases, the choice of a material should also consider the workpiece material and the machining task. The advantageous properties of coated electrodes or composite materials may lead to an additional improvement of wear resistance. Moreover, the selected material should withstand the mechanical and thermal stresses of prolonged EDM operations.

3.2 Machining Parameters

Tool wear is significantly reduced by appropriately optimizing machining parameters such as pulse current, pulse on-time, and pulse off-time. A balance needs to be found because high pulse energy accelerates tool wear as well as increases the rate of material removal. Shorter pulse durations and reduced currents reduce thermal stresses in the electrode, ensuring it maintains its lifetime and shape. Adjustment of spark gap voltage ensures that the discharge will be efficient without excessive degradation of the tool. By making fine-tuned adjustments to flushing pressure and flow rates, debris is removed more effectively and deleterious secondary discharges that would wear down the tool are avoided. Machining processes like rough and finish machining with parameter settings aid effective wear management for some applications, which can be optimized through simulation tools or data-driven techniques such as the Taguchi or ANFIS methodologies.

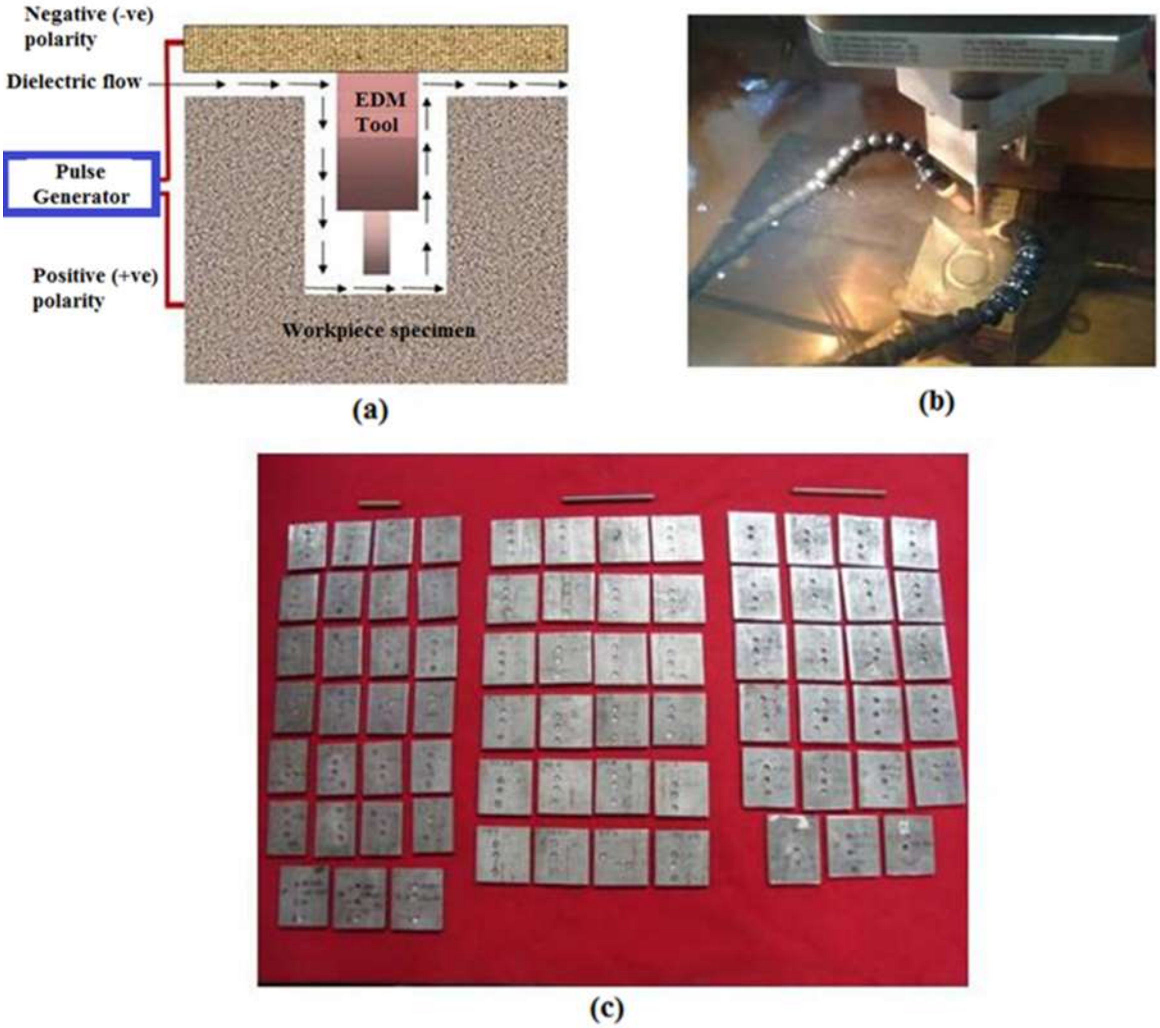

Fig.2 Schematic representation of Experimental setup (a) Schematic die-sinking EDM (b) Experimental arrangement (c) Machined specimens

Effective Management of Dielectric Fluid

Tool wear directly depends on EDM when it cools, removes debris and conditions the spark environment. Excellent dielectrics, such as deionized water or specific oils, cool better and reduce stress on the tool. Effective flushing will clear dirt from the spark gap and prevent those secondary discharges that cause the material to wear down. Optimization of dielectric viscosity and flow rate will ensure uniform machining and energy distribution. Additives in the dielectric fluid may reduce the chemical erosion of the tool or improve the cooling ability of the tool. The dielectric system must be filtered regularly and maintained to minimize contamination that may cause unpredictable machining conditions and accelerate wear. Emerging methods, like powder-mixed dielectrics or vibration-assisted flushing, could be used to enhance particle removal and minimize erosion on the tool.

Advanced designs of tool

Advanced Tool Designs Multi-layered or segmented electrodes are some of the advanced tool designs that facilitate longer tool life and improved resistance to wear. The machining cycles can become extended with layered electrodes which preserve the core structure as wear occurs uniformly. Segmented tools allow for better dissipation of heat and prevent less thermal damage. Tools with hollow electrodes or internal cooling systems improve heat management and minimize thermal wear. This is achieved by designing certain tool forms to reduce stress concentration spots and foster wear consistency.

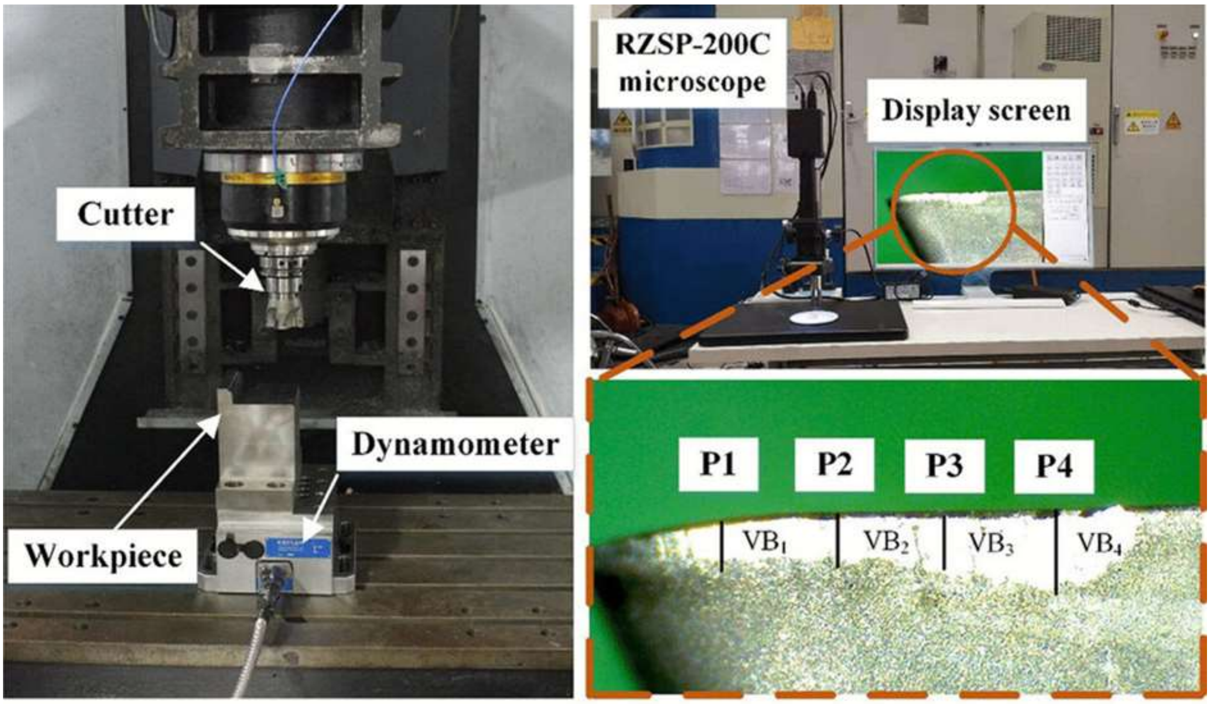

Fig 3. (a) Experiment setup (b) Tool wear measurement Optimized Machining

Adaptive Control Systems

The tools are adapted in terms of cutting parameters dynamically to minimize the amount of wear. Sensors in the EDM system monitor energy distribution, electrode shape, and the conditions of spark gap. The system adjusts parameters such as flushing pressure, on-time, and pulse energy as part of this process, maximizing performance based on feedback. Advanced algorithms such as fuzzy logic and machine learning enhance the ability to anticipate and prevent excessive wear. Elimination of the requirement for operator-controlled adjustments has opened up adaptive control systems that make increased productivity coupled with low error rates by the operator. Moreover, wear compensation techniques such as electrode redressing or automatic tool repositioning may be included in these systems. Adaptive controls provide consistent quality and also extended tool life because they maintain constant machining conditions. Real-time wear management in these systems is enhanced through the integration with on-machine measurement tools.

Environment for Controlled Machining

External variables reduce tool wear when the machining environment is stable. Controlling the temperature and humidity prevents the tool and workpiece from oxidizing or expanding thermally. Isolating the machining area from external interferences or vibrations provides a stable spark and material removal. A well-grounded machine reduces electrical noise and energy distribution. A clean environment reduces the chances of debris contamination, which may lead to secondary discharges or uneven wear. Optimal performance is guaranteed if machine parts, including power supply units and dielectric systems, are maintained in routine. Machining in vacuum or in an inert gas atmosphere can reduce chemical wear and oxidation even further in some cases.

Periodic Tool Maintenance and Replacement

Both regular tool replacement and maintenance guarantee consistent operation and prevent extreme wear of the electrode. Tools can be easily serviced or replaced by inspecting them for signs of wear such as cracks, distortion, or material buildup. Cleaning frequently removes residues or debris that might impair spark performance. Tools can be reshaped to restore its original geometry and working condition by polishing or grinding them. Regular inspections of the cooling and lubrication prevent overheating, which in turn enhances wear rate. A tool replacement schedule reduces the possibility of sudden breakdowns and ensures that machining is continuous. Forecasting wear patterns is possible by using data-driven insights from the earlier operations and planning for maintenance in advance. Maintenance procedures conserve the lengthy lives of costly electrodes, thereby saving total operating costs.

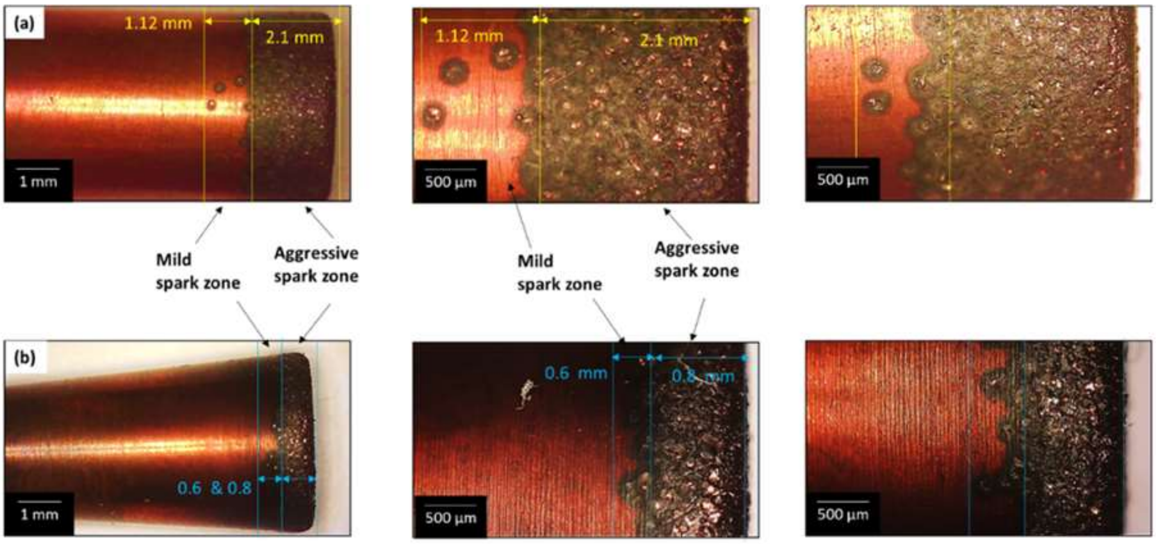

Fig. 4. Microscopic analysis of tool wear for the following cases: (a) conventional design at different magnifications and different tool positions and (b) relief angle design tool at different magnifications and tool positions.

Development methodology

1. **Overview of the Problem**

Tool wear is the focus of the study, important in micro EDM milling as a component that impacts machining precision. To maintain accuracy, adjustment for both linear and volumetric wear is necessary. The possibility of wear assessment is provided by regular measurements with on-machine techniques like Touch and Laser. Compensating variables must be adjusted continuously due to the stochastic nature of the EDM process. For better machining performance, the study aims at lowering uncertainty contributed by wear.

2. Experiment Setup

In the experiments, a Sarix SX-200 micro EDM milling machine, with 300 µm diameter tungsten carbide electrodes, and martensitic stainless steel (AISI 420) were used as workpieces. HEDMA 111 is also referred to as hydrocarbon oil, which was adopted as dielectric fluid. Touch technique utilized electrical contact to find the positions of the tool tips.

3. Methods for Measuring Tool Wear

Both linear and volumetric metrics were used to measure tool wear. In particular for lower wear values, the laser technique produced more accurate linear wear, that is referred to as the before and after machining length difference. Volumetric wear was calculated from the 3D profile of the electrode, and the Laser technique provided the higher level of accuracy by including the edge rounding. Since Touch technique assumed the homogeneous cylindrical forms; it is not effective.

4. Uncertainty Analysis

Measurement uncertainties were investigated in the study to find out the errors causing sources. In Touch approach, electrical erosion and contact variability led to errors but high resolution scanning in Laser method had caused only very few errors. Laser method has consistently shown a reduced uncertainty for linear and volumetric wear.

5. Optimization of Wear Compensation

Control intervals and electrode measurements were meant to be balanced for the best wear compensation. While increased intervals consumed extra time and errors, lower intervals reduced uncertainty but exposed a possibility to miss minute wear patterns. Edge wear started appearing for electrodes with dimensions less than 20 µm; hence changes like reshaping tips or increasing electrode stepover were required. Since the laser approach delivered good precision in volumetric wear and compensating factor, it was recommended.

3 Literature Review

EDM is a non-traditional machining process in which electrical discharges remove material from a workpiece; however, it has been indicated as an area of high negative environmental and health impacts. Under the concept of "green machining," much research focuses on reducing adverse effects or impacts such as energy consumption and exhaust emissions while EDM is being carried out. One possible way to achieve these is by using sustainable dielectric fluids. Promising choices include vegetable oils and biodiesel.

3.1 Advantages of Vegetable Oil-Based Dielecrics

1) Higher MRR: Vegetable oil, particularly sunflower oil, has proven to become a better substitute in machining vis-a-vis the conventional mineral oils with numerous advantages which they provide toward performance, quality, and an environment-friendly aspect as well. One of the prime merits they hold in store is their capability of permitting their users to achieve far higher Material Removal Rates (MRR). This means that the rate of material removal from the workpiece is much increased when vegetable oils are used as dielectrics, and the operations are faster and more efficient in machining. However, further savings-more than 55% improvement in MRR-were also observed under heavy machining conditions. Besides productivity improvement, this would save the total time consumed in machining activities as well, thus rendering the solution extremely economical for an industry seeking optimization of manufacturing processes.

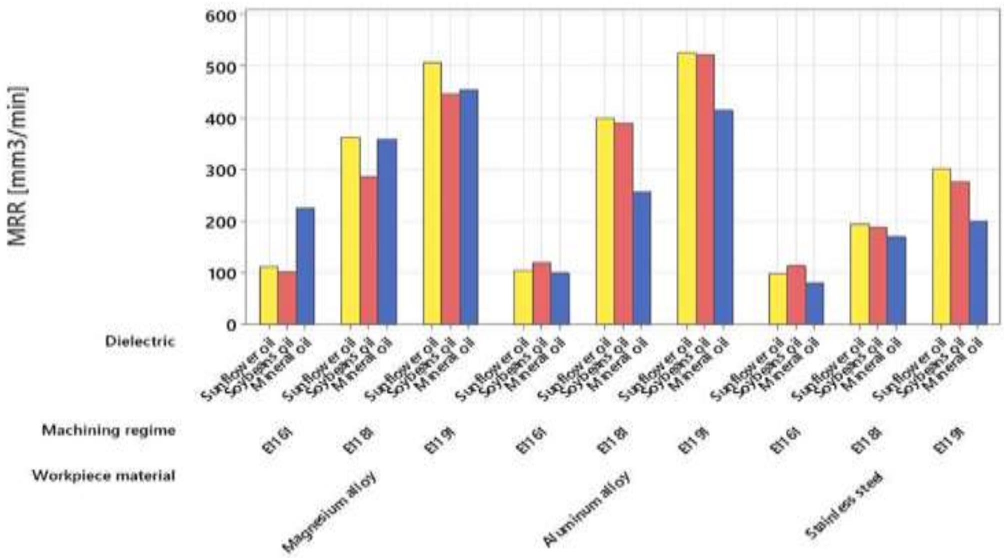

Fig 3: Comparative analysis of the results MRR

2) Quality of Surface Improved: Surface roughness-the macro- and microscopic views-remains an essential parameter for determining the functionality and strength of machined components. Generally, a surface finish of finer grains indicates less wear and tear and superior performance with better application compatibility where high precision and smooth interfaces are critical. This further saves time and resources in terms of post-machining finishing work. Besides these performance and quality advantages, vegetable oils are exceptionally environmentally benign, thus a bright, sustainable alternative against conventional hydrocarbon-based dielectrics.

3) Environmental benefits: Vegetable oils are bio-based products derived from renewable raw materials that are completely biodegradable, thus they would spontaneously degrade in the environment without posing a risk to it. This is sharply in contrast with the mineral oils, which are non-renewable and, if not handled cautiously, become a significant source of environmental risks. Using vegetable oils decreases the ecological footprint of industries, enables higher conformity to stricter environmental regulations, and supports the general aspiration worldwide toward sustainability.

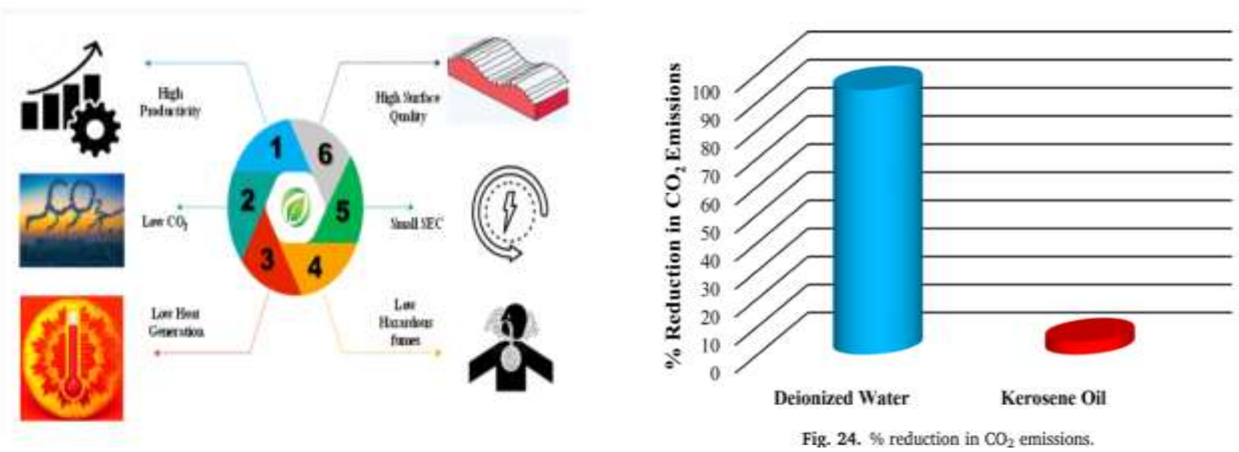

Fig 4: Sustainability in EDM

3.2 Challenges and Considerations

Electrical Discharge Machining is entirely dependent on dielectric fluids. It has caused problems to the EDM process. Traditionally, hydrocarbon-based dielectrics such as kerosene have been used for several reasons associated with its properties. Electrical Discharge Machining is entirely dependent on dielectric fluids. It has caused problems to the EDM process. Traditionally, hydrocarbon-based dielectrics such as kerosene have been used for several reasons associated with its properties. However, these fluids are hazardous to the environment and also hazardous to health. They give off harmful by-products and emissions while in the machining operation, which is contributing to the pollution and health hazards to the operators. Their prolonged contact leads to respiratory illness and skin problems, and their disposal necessitates very stringent environmental conditions for the prevention of contamination. Dielectric fluids are indispensable for EDM.

They also remove debris from the machining area to avoid possible short circuits besides increased machining accuracy. Dielectric fluids are also coolants that conduct heat developed during the operation to prevent thermal damage to the electrodes and the workpiece. They also regulate the discharge phenomenon and thus are able to achieve uniform and efficient spark generation. To overcome the environmental problems of the traditional dielectrics, alternative solutions are now being considered. Dry EDM is one such example wherein a gaseous medium is used replacing liquid dielectric.

Although it is eco-friendly, it has several disadvantages. MRR reduces while removal of debris also becomes difficult. Near-dry EDM, which integrates a spray of dielectric fluid and gas, is also a more balanced method. Deionized water is also an attractive alternative that is known to provide sustainability and performance benefits. The powder-mixed dielectrics in which nano-particles are added to the fluid has also shown enhanced machining outcomes like higher MRR and better surface finish. Bio-dielectrics comprised of vegetable oils such as sunflower oil and palm oil are gaining progressively increased popularity as environmentally friendly, renewable substitutes to the standard fluids. Properties of EDM dielectric fluids have a direct relation with performance. Fluids with high viscosities can help in high material removal rates but spoil the surface finish. Fluids having higher values of breakdown voltage tend to improve sparking efficiency. Higher thermal conductivity and specific heat enhance cooling effectiveness, and thus fluids are responsible for stable machining conditions. A higher value of dielectric constant assures stabilization of electric field which is crucial for precision machining. Differet dielectrics have different influence effects on EDM. For example, bio-dielectrics, such as sunflower oil, achieved high MRR with some cases overcoming standard dielectric fluids. However, some bio-dielectrics surface roughness is much higher and requires more processing. Furthermore, nano-powders are mixed with the dielectrics that improve the machining efficiency in both MRR and surface finish. It holds a great promise for future work.Thesefluids are hazardous to the environment and also hazardous to health. They give off harmful by-products and emissions while in the machining operation, which is contributing to the pollution and health hazards to the operators. Their prolonged contact leads to respiratory illness and skin problems, and their disposal necessitates very stringent environmental conditions for the prevention of contamination. Nonetheless, dielectric fluids are indispensable for EDM.

They serve several important purposes, such as electrode and workpiece insulation, to maintain a well-regulated gap. They also remove debris from the machining area to avoid possible short circuits besides increased machining accuracy. Dielectric fluids are also coolants that conduct heat developed during the operation to prevent thermal damage to the electrodes and the workpiece. They also regulate the discharge phenomenon and thus are able to achieve uniform and efficient spark generation. To overcome the environmental problems of the traditional dielectrics, alternative solutions are now being considered. Dry EDM is one such example wherein a gaseous medium is used replacing liquid dielectric.

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3.3 Research on Specific Oils

- Sunflower Oil: Sunflower oil is one of the most studied vegetable oils for EDM applications, showing excellent performance metrics. Study shows that sunflower oil can improve MRR considerably; in fact, a report shows an 80.25% increase in MRR as compared with standard EDM oil. Moreover, with the help of sunflower oil, surface finish properties are superior because the cracks' number and size on machined surfaces are lower compared with others. For example, one study found that sunflower oil enhances the surface finish by up to 17.05% in comparison with other dielectrics. Nonetheless, the performances could represent a slight increase in the TWR that was noticed when using this oil. Therefore, potential tool material selection should be done carefully when employing sunflower oil.

Machining regime	Workpiece material	Dielectric comparison	Δ_{MRR} (%)	Δ_{Sa} (%)
E1161	AZ31B magnesium alloy	SfO vs MO	−49.73	−1.60
		SoyO vs MO	−54.03	6.87
	7075-T7351 aluminum alloy	SfO vs MO	5.15	4.03
		SoyO vs MO	19.97	−6.99
	17-4 PH stainless steel	SfO vs MO	21.72	16.88
		SoyO vs MO	39.46	34.94
E1181	AZ31B magnesium alloy	SfO vs MO	1.20	−10.31
		SoyO vs MO	−20.18	−11.66
	7075-T7351 aluminum alloy	SfO vs MO	55.15	−8.97
		SoyO vs MO	51.96	−2.15
	17-4 PH stainless steel	SfO vs MO	14.22	107.33
		SoyO vs MO	10.40	104.55
E1191	AZ31B magnesium alloy	SfO vs MO	11.58	−19.70
		SoyO vs MO	−1.95	−14.87
	7075-T7351 aluminum alloy	SfO vs MO	26.89	7.16
		SoyO vs MO	26.03	12.58
	17-4 PH stainless steel	SfO vs MO	50.83	74.73
		SoyO vs MO	38.62	38.55

SfO – Sunflower oil, SoyO – Soybean oil, MO – mineral oil.

Bio-based fluid that is gaining much attention due to the advantages in EDM is canola oil. Its MRR has been improved at various energy settings and is strongest at both low and high values of discharge energy.

Jatropha Oil: Jatropha oil has unique properties, which will help enhance EDM performance. The bio-dielectric fluid increases both MRR and Surface Hardness (SH), while keeping TWR and surface roughness values lower than those with conventional fluids. This balance between material removal efficiency and surface integrity makes it a strong candidate for sustainable EDM processes. Moreover, the non-edible nature of jatropha oil adds to its appeal because it does not compete with food resources.

- Palm oil: Palm oil, in particular, its refinery version known as RBD palm oil, has shown promise as a dielectric fluid for EDM. Palm oil, from observations, is seen to outperform kerosene in terms of MRR and EWR while offering acceptable levels of surface roughness. Moreover, users would experience higher TWR and average surface roughness compared with kerosene. Despite these drawbacks, palm oil is still a promising bio-dielectric because it is easily accessible and relatively inexpensive.

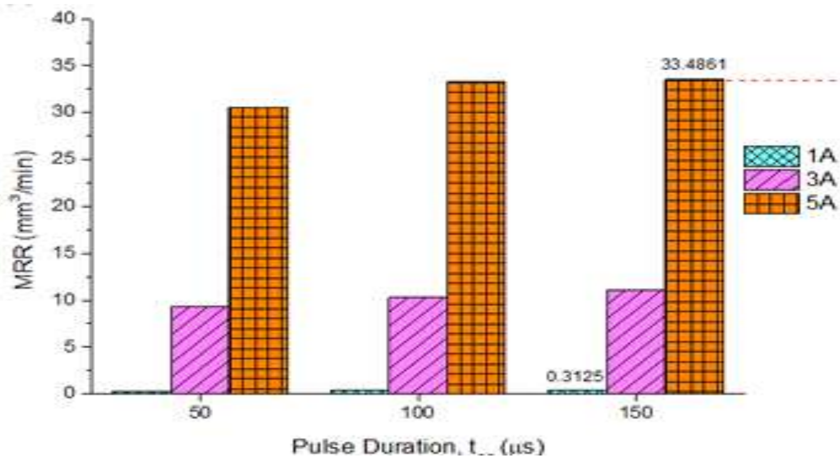


Fig 6: Material removal rate of palm oil

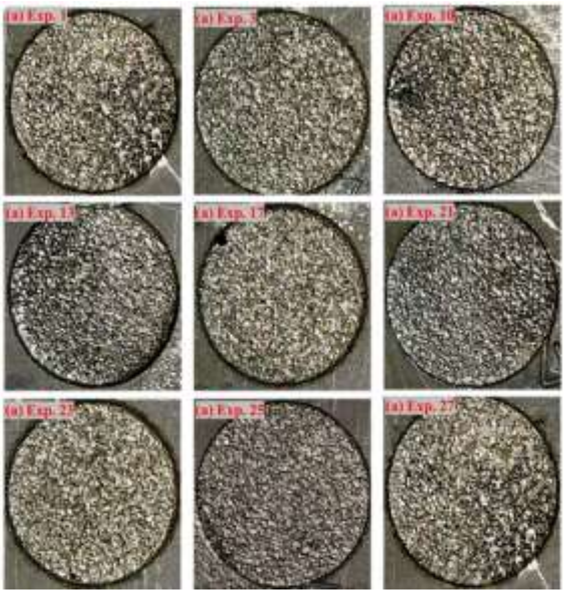
- Neem oil: Neem oil biodiesel was proved to be superior to kerosene in MRR and surface finish, hence it is an ideal "green" machining fluid. Mustard oil-based dielectric stands out for its low thermal conductivity, imparting better quality surfaces and lesser surface roughness. These niche oils, meanwhile, establish the versatility of vegetable-based dielectric fluids as adaptive in various machining requirements.

Machine Performance	Unit	Value of Machining Performance for EDM oil	Type of Bio-dielectric fluids	Value of Machining Performance for bio-oil	% Change in machining performance
MRR	g/min	0.032395	Jatropha	0.0491975	51.85 (increase)
TWR	g/min	0.00616		0.002439	60.39 (decrease)
SR	µm	12.98173		14.56565	12.20 (increase)
MRR	g/min	0.036135	Sunflower	0.0651343	80.25 (increase)
TWR	g/min	0.0038225		0.003902	02.09 (increase)
SR	µm	13.315335		14.04271	05.46 (increase)
MRR	g/min	0.0322575	Palm	0.053625	66.24 (increase)
TWR	g/min	0.0063525		0.0029181	50.16 (decrease)
SR	µm	11.1887325		13.676025	22.23 (increase)
MRR	g/min	0.0326975	Mixed	0.05555	69.89 (increase)
TWR	g/min	0.01397	vegetable	0.003667	73.75 (decrease)
SR	µm	12.38966	oil	13.081667	05.58 (increase)

3.4 Experimental Results

Machine Performance	Unit	Value for EDM Oil	Value for Bio-Oil
MRR	mm^3/min	0.0416	0.0463
SR	µm	1.4658	1.1881
TWR	Mm^3/min	0.0020	0.0017

Table 1. Comparison of Machining Performance between Different Dielectrics



Sr. No.	Process Parameters			
	I_p (A)	S_v (V)	S_t (µs)	C_p (g/100 ml)
1	5	2	7	0.5
2	25	2	3	0.5
3	15	6	5	1
4	25	6	3	1.5
5	15	4	7	1
6	15	4	5	0.5
7	25	6	7	0.5
8	25	6	7	1.5
9	5	6	3	0.5
10	5	2	3	0.5
11	5	6	7	0.5
12	15	4	3	1
13	5	2	7	1.5
14	5	2	3	1.5
15	25	2	3	1.5
16	25	2	7	0.5
17	15	4	5	1
18	5	6	3	1.5
19	25	6	3	0.5
20	15	2	5	1
21	25	2	7	1.5
22	5	4	5	1
23	5	6	7	1.5
24	15	4	5	1
25	25	4	5	1
26	15	4	5	1
27	15	4	5	1.5

Fig7: Machined cavities of different experiments.

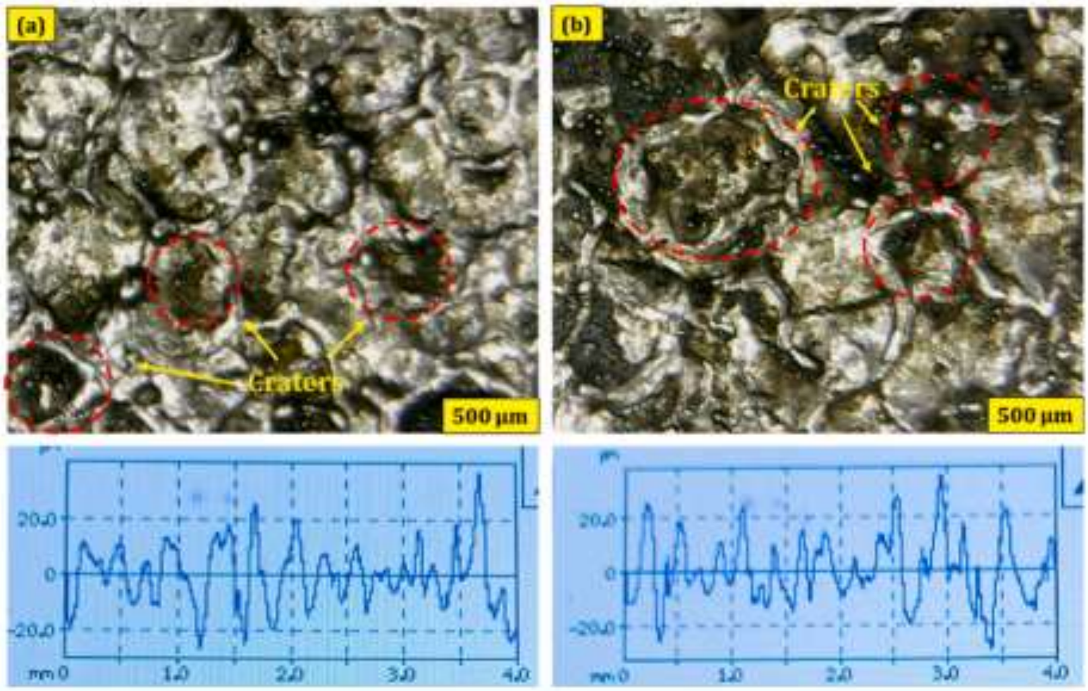


Figure 8: Micrograph of machined profile of IN600 using; (a) Amla oil at 1.0 g/100 ml Cp of Cu; (b) Amla oil at 0.5 g/100 ml Cp of Cu.

4 Methodology

4.1 Experimental Setup:

1) Machining Parameters: In EDM, the machining parameters must be controlled precisely for optimum result. The following parameters were selected, and their variation was done systematically in the experimentation: peak current (Ip), pulse duration (Ton), voltage (V), and depth of cut. The energy level of each spark depends on the peak current that directly affects MRR as well as surface finish. Pulse duration affects the energy per spark, and longer pulse durations lead to more material removal but may also result in heat damage. It controls the strength as well as the stability of the electric field of the creation of sparks, which directly affects the machinability efficiency. The depth of cut determines the vertical distance the electrode has to travel to remove material; hence, it is an important factor in the detailing of the operation as well as its duration. Systematic alteration of such parameters would indeed allow for a wide analysis of their machining effects.

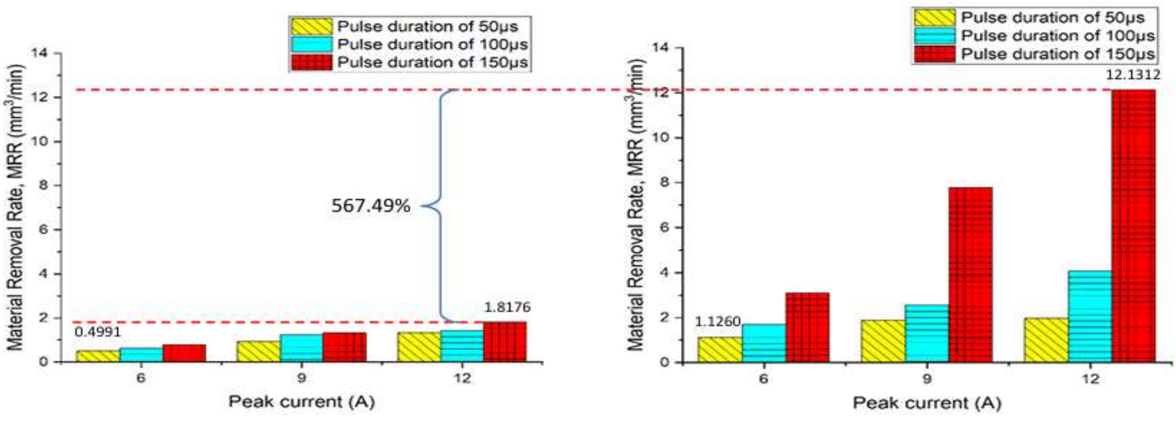


Fig10: The Effect of Peak Current, Ip and Pulse Duration, ton on MRR for (a) Kerosene (b) RBD Palm Oil

1) Dielectric Fluids: Dielectric fluids have a number of roles during the EDM process. First, dielectric fluids act as an insulator between the electrode and the workpiece. The other role is to flush away debris from the spark zone. In such a manner, it provides cooling to the sparking site. It basically varies from any conventional dielectric fluid such as kerosene and EDM oil to environmentally friendly alternatives. The sustainability and machining performance of bio-based fluids, such as sunflower oil, palm oil, canola oil, and jatropha oil, were evaluated. UCOB from used cooking oil was also considered, being cost-effective and environmental-friendly. Several properties of the fluids, such as viscosity, flash point, breakdown voltage, and thermal conductivity, were studied for their suitability in application. These experiments focus on getting greener solutions without compromising the quality and performance of the EDM process.

Dielectric fluids	Sunflower oil	Jatropha curcas oil	Palm oil	Mixed vegetable oil
Viscosity (mm^2/sec)	35	39.6	34	28.70
Density (g/cm^3)	0.912	0.93292	0.885	0.9160–0.9210
Flash point (°C)	316	229	314	278–282
Fire point °C	341	235.2	341	344
Thermal conductivity W/mK	0.168	4.25	0.1717	-
Smoke point (°C)	227	-	223	213

Table 2: Physical properties of the bio-dielectric fluids

2) Workpiece and Electrode Materials: Workpiece and electrode material assumed significant importance in EDM efficiency and performance. Titanium alloys, Ti-6Al-4V, are popular because of the exceptional strength to weight and corrosion resistance due to its vast application for aerospace parts. Other materials used for testing to expand the scope of applicability of these findings are AISI D2 steel, AZ31B magnesium alloy, and 7075-T7351 aluminium alloy. The electrodes consisted primarily of copper because of its superior thermal and electrical conductivity needed to create effective sparks. Graphite and tungsten-copper alloys were used in particular cases for the electrode materials in order to address specific needs for, for example, wear resistance combined with thermal stability. Such diversity in material ensures thorough examination of the machining behaviour in numerous cases.

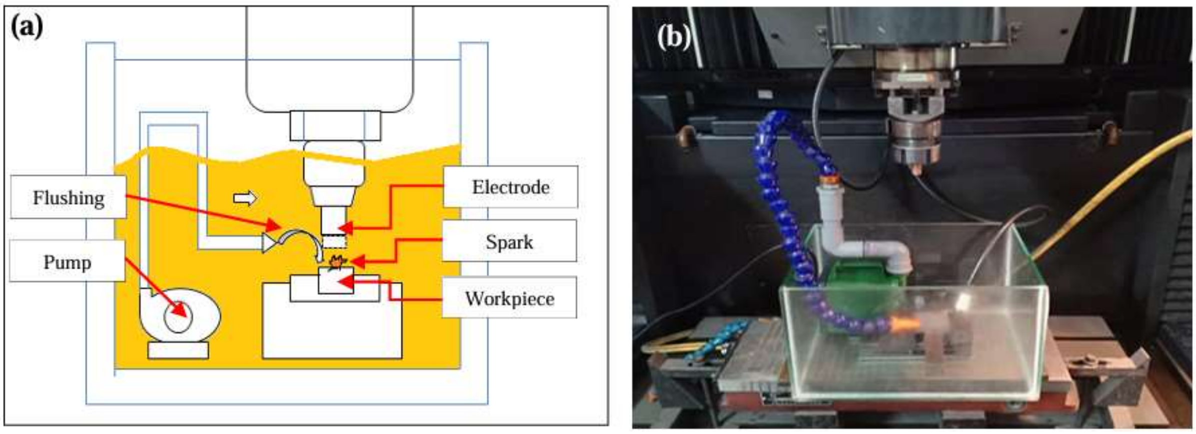


Fig 11: The custom-made glass tank of the machine is set up in (a) Schematic diagram (b) Actual diagram

4.2 Performance Measurement

1) The Tool Wear Rate (TWR): It is measured for the strength of the electrode used in the EDM process. It gives a measurement of the endurance of the tool, besides the power that is withstood by it towards repeated spark discharges. The TWR is computed by taking the weight of the tool before machining subtracting this from the weight of the tool after machining and then dividing the result by the time taken during machining. A lower TWR would mean that a stiffer tool will produce a less expensive cost because of electrode replacement and associated downtime. TWR is rather sensitive to the nature of electrode material used, for example, copper, graphite, or tungsten-copper alloys and other machining parameters such as peak current and pulse duration. Low TWR is very critical for an efficient EDM process, as even average values of TWR may degrade precision in case of considerable electrode wear, especially in high-precision applications.

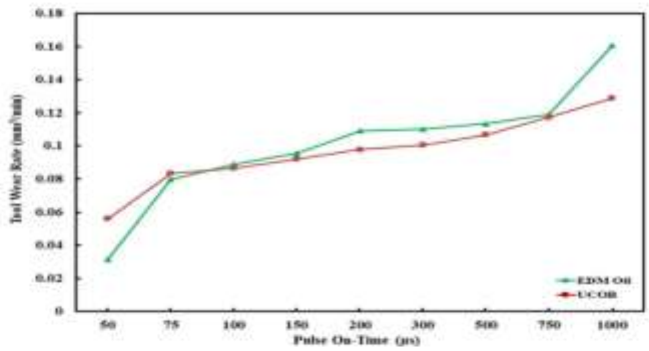


Fig 12: Effect of variation inpulse on-time on TWR at discharge current

2) Specific Energy Consumption (SEC): A new performance characteristic that was recently discussed for EDM is called Specific Energy Consumption (SEC), which focuses on energy efficiency and the environmental impact of the process. It is calculated as electrical energy consumed during machining, divided by the volume removed. The lower the SEC value, the lower the cost of operation and the environmental footprint of the process. This can also be very pertinent when using eco-friendly dielectric fluids because it would help in the appraisal

compared to kerosene-based fluids. The researchers target optimization of the EDM process for sustainability with regards to SEC without compromising productivity or quality.

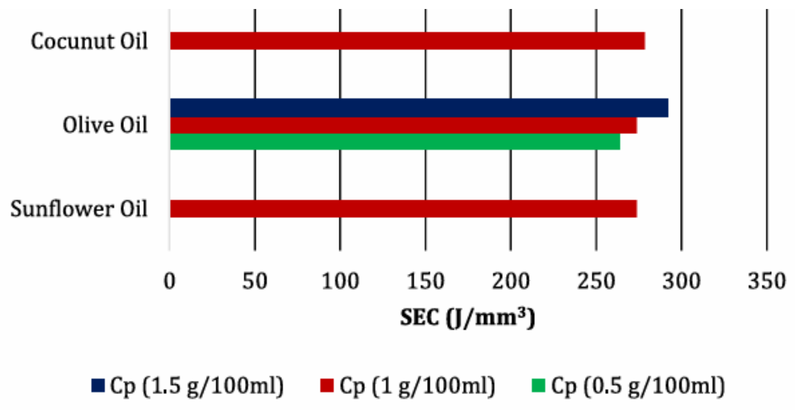


Fig 13: Overall comparison of SEC in different biodegradable dielectrics.

3) Surface Roughness (SR): It is an important parameter reflecting the quality of the surface machined. Some of the suitable scientific instruments measure SR by observing the microscopic level at which the surface profile is measured. A Talysurf surface roughness tester or a Taylor Hobson meter would be required for that. SR values that have higher values indicate a coarser surface finish. However, the fact is that smoother surfaces cost against other parameters like MRR. EDM is perhaps facing one of the maximum challenges in balancing SR with productivity. Hence this can be taken as one of the important parameters to evaluate the performance of the process.EDM Process The most significant performance parameter of EDM process is determined by the productivity which is attained directly by the machining operation. MRR Material Removal Rate: Volume of material being removed from work-piece in unit time during machining operation. The work piece can be weighed before and after machining using an electronic weighing machine highly sensitive to weigh the difference. It then gives differential weights divided by the time in totality of machining, thus yielding an accurate measure of material removal efficiency. A greater value of MRR will denote a more efficient process wherein the pieces can be machined in a shorter time and holds particular significance for high-throughput industrial applications.

4.3 Result Analysis:

The collected data is then subjected to different analysis techniques to draw meaningful conclusions. Some commonly used techniques include:

1) Statistical Analysis: The basic tool for interpreting results in EDM study is the statistical tools. The important technique involves ANOVA, which determines the role and percentage contribution of different machining variables like the peak current, voltage, and pulse duration in relating performance parameters such as Material Removal Rate (MRR) and Surface Roughness (SR). ANOVA enables researchers to highlight factors that contribute significantly and optimize parameters to enhance performance.

Another important statistical tool frequently employed is regression modelling, which finds mathematical relationships between input parameters and their output responses. Regression models serve, therefore, as predictive tools to help engineers compute some measurements, such as the wear rate of the tool, or energy efficiency for specific sets of machining parameters. Together, these statistical methods would form a strong framework for the optimization and control of the EDM process.

2) Grey Relational Analysis (GRA): Grey Relational Analysis has proven to be useful in EDM research, especially when usually a number of performance metrics have to be compromised. This technique transforms several response variables such as MRR, SR, Tool Wear Rate (TWR), and Specific Energy Consumption (SEC) into one common metric known as the Grey Relational Grade (GRG).

The GRG enables ranking of experimental trials and identification of the most optimal input parameter combination. For example, GRA can allow for better MRR while ensuring minimal surface roughness and tool wear. GRA alleviates the complexity of multiple-objective optimization challenges, thus making it easier to do better-informed decision-making and ensure effective trade-offs between several competing performance criteria.

Normalisation value			Deviation sequence value			Grey relational coefficient (GRC)		
MRR (g/min)	TWR (g/min)	SR (µm)	MRR (g/min)	TWR (g/min)	SR (µm)	MRR (g/min)	TWR (g/min)	SR (µm)
0.234527	0.699508	0.386306	0.765473	0.300492	0.613694	0.395109	0.624616	0.448956
0.084113	0	0	0.915887	1	1	0.353135	0.333333	0.333333
0.618753	1	0.542917	0.381247	0	0.457083	0.567378	1	0.522421
0.294097	0.719493	0.622902	0.705903	0.280507	0.377098	0.414627	0.640609	0.570062
0.605349	0.700734	0.581239	0.394651	0.299266	0.418761	0.558877	0.625574	0.544211
0	0.426528	0.352525	1	0.573472	0.647475	0.333333	0.465779	0.435739
0.934473	0.333588	0.458772	0.065527	0.666412	0.541228	0.884131	0.428665	0.480202
0.554715	0.688333	0.504958	0.445285	0.311667	0.495042	0.528941	0.616016	0.502491
0.809376	0.698595	0.652688	0.190624	0.301405	0.347312	0.723983	0.623904	0.590101
0.38643	0.184728	0.59486	0.61357	0.815272	0.40514	0.449006	0.380149	0.552401
0.09007	0.760504	0.377715	0.90993	0.239496	0.622285	0.354627	0.676136	0.44552
0.185382	0.686848	0.514402	0.814618	0.313152	0.485598	0.380338	0.614891	0.507306
1	0.685179	0.470033	0	0.314821	0.529967	1	0.613632	0.485452
0.206231	0.05812	0.317708	0.793769	0.94188	0.682292	0.386468	0.346769	0.422907
0.236016	0.746194	1	0.763984	0.253806	0	0.395575	0.663301	1
0.133258	0.702984	0.744461	0.866742	0.297016	0.255539	0.365833	0.62734	0.661779

Table 3:Normalisation, Deviation sequence and Grey Relational Co-efficient values from the experiments using bio-dielectric fluid.

3) Artificial Neural Networks (ANN): In highly nonlinear or complex relationships between input parameters and machining responses, the system relies on Artificial Neural Networks. ANNs are computational models that simulate the operation of a human brain. ANNs have been developed to learn patterns directly from experimental data. By training on input-output datasets, ANNs can predict machining outcomes for new parameter settings with very high accuracy.

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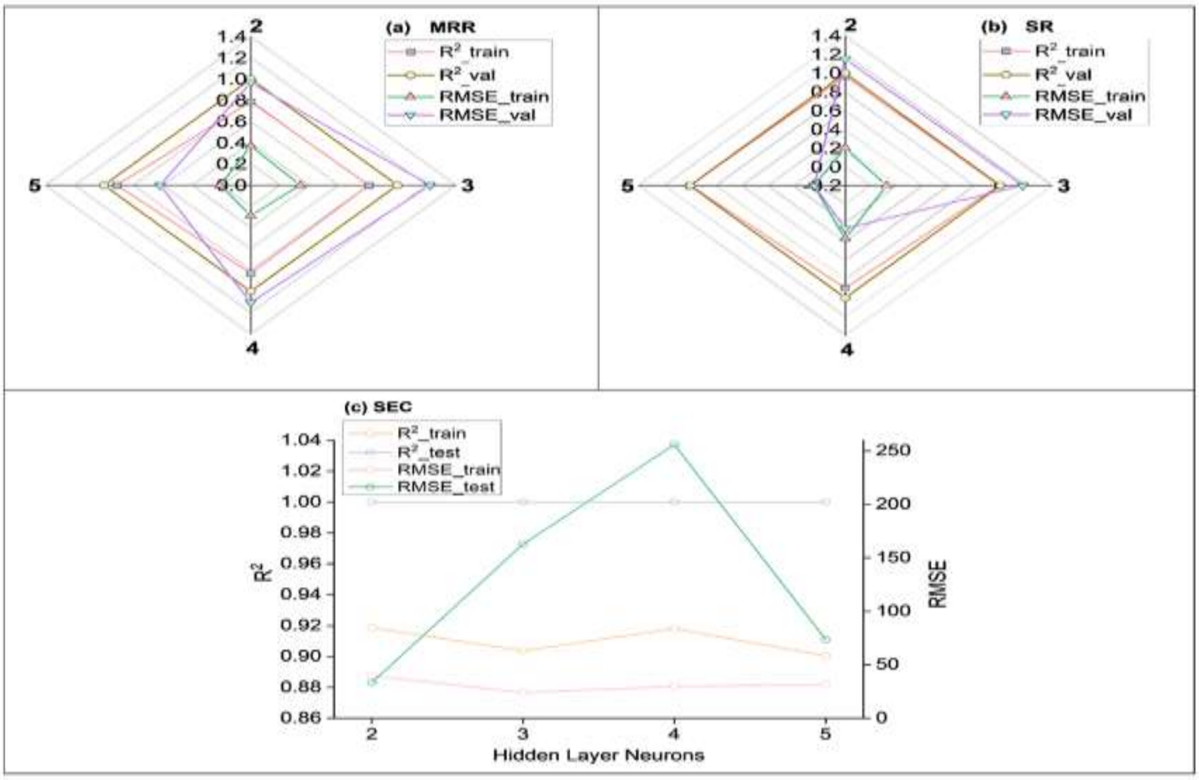

Fig 14:Development of ANN model on varying number of hidden layer neurons of (a) MRR, (b) SR, and (c) SEC. The performance matrix built on R2 and RMSE is computed during training and testing phase of the model.

4) Microscopy: Microscopic techniques offer essential contributions in the assessment of surface quality and behaviour of material in EDM. Techniques involving SEM and optical microscopy are typically made in analysing surface morphology and microstructural features of

samples machined out from the workpiece. These methods allow achieving high-resolution images with critical details that include cracks, recast layers, and zones affected by heat.

Microscopy also aids in determining the effects of varying different dielectric fluids on the quality of surfaces. A verdant dielectric material such as vegetable oils produce surfaces that are smother than those produced by the traditional kerosene. This helps microscopy observers see the differences. In depth analysis of surface features is used to provide insights on how machining parameters and dielectric fluids affect the final product.

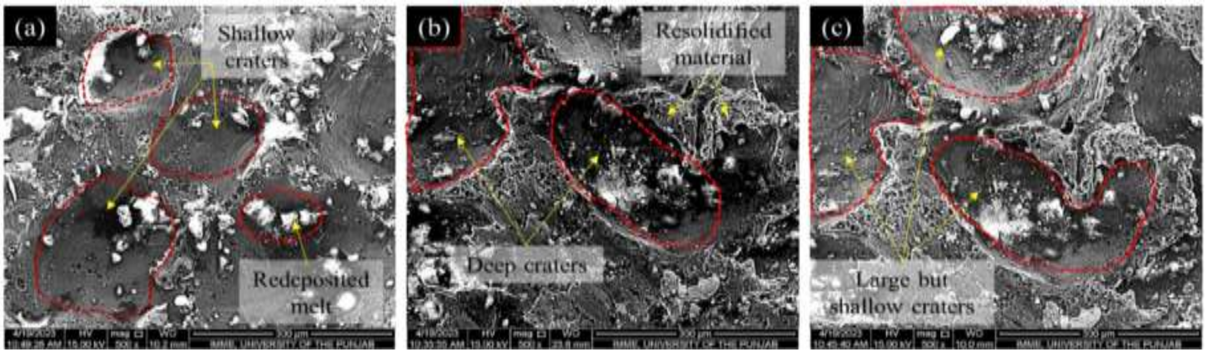

Fig 15: Surface morphology of machined cavities at various setting of Ip: (a) 5 A, (b) 15 A, (c) 25 A.

1.2 EDM DRILLING

This specialized EDM method is called electrical discharge drilling or EDM drilling. It applies for the machining of small, precise holes in hard or sensitive materials that cannot be machined easily using conventional methods. EDM drilling can produce deep, high-aspect-ratio holes with small diameters and good accuracy by employing a tubular electrode that produces controlled electrical discharges. This method is particularly advantageous in regions where conventional drilling would be futile or damaging- such as in medical equipment that require complex inner channels or microholes, fuel injectors, and aircraft components. EDM drilling reduces mechanical stress as it is non-contact which makes it ideal for high precision drilling in brittle and heat-resistant alloys.

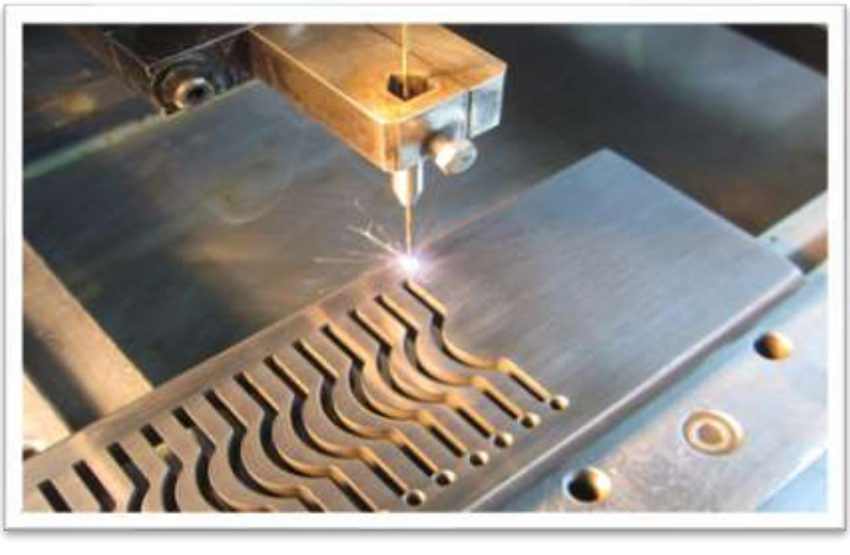

Fig 1.EDM drilling operation

1.3 EDM MILLING

EDM milling, also known as Electrical Discharge Milling or EDM contouring, removes material using electrical discharges with a rotating electrode tool for generating intricate forms and fine details on conductive workpieces. Because EDM milling does not require physical contact-a principle not present in conventional milling-the process can be used to machine complex shapes and hard materials without creating tool pressure or mechanical stress.This method is suitable for the generation of complex forms, cavities, and curves in hard metals-it's a major market for mold-and-die manufacturing, tooling manufacturing, and aerospace. EDM milling enables flexible high accuracy in machining tiny features and those areas that cannot be accessed. These are some of the advantages suitable for items requiring fine details and high accuracy.

1.4 EDM CUTTING

Wire-cut EDM or wire-cutting, in other words, is a precision machining wherein intricate features and complicated designs are cut into conductive materials using a thin wire charged with electricity. The wire acts as an electrode that cuts into the workpiece and it feeds repeatedly into it while it is submerged in a dielectric solution that would avoid overheating and the removal of eroded particles. EDM cutting would be extremely vital in very delicate feature works and complex geometries of parts which would hardly have been achieved by conventional cutting methods, as it provides high accuracy and the tightest of tolerances. It's best suited only for applications requiring intricate profiles and high precision like manufacturing surgical instruments, gears, dies, parts with tight corners, or tiny slots.

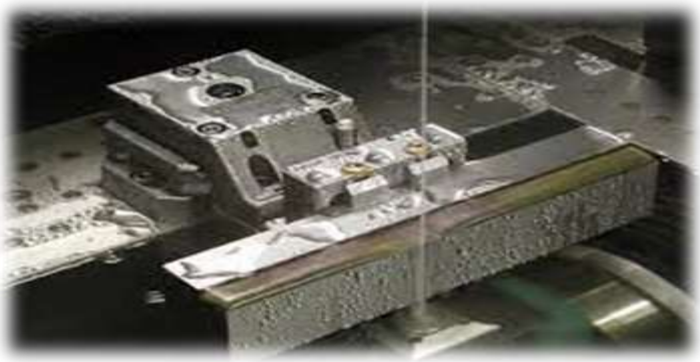

Fig 2. EDM cutting operation

1.5 PROCESS METRICS

Knowledge of a few basic concepts facilitates understanding and optimization of process in EDM operations. Many ideas are frequently mentioned to include:

1. MRR or material removal rate: the rate at which material is eroded from the workpiece, where this varies with discharge energy, pulse duration, and current.

2. TWR: Tool Wear Rate. The rate of wear of the EDM electrode during machining. Less is preferred for tool precision and economy.

3. Spark Gap: That small controlled gap between tool (electrode) and workpiece, through which electrical discharge occurs. Precise gap control is a prerequisite for precise and stable operation.

4. Pulse Length: The time of the electrical pulse. This affects the surface finish, MRR, and the amount of energy delivered to the workpiece.

5. Dielectric Fluid: A non-conductive liquid, such as deionized water or oil, acts to maintain the spark gap intact, cool, and flush away the debris,

6. Duty Cycle: The on-to-total pulse cycle time ratio, which impacts the amount of energy that could be delivered to a workpiece and increases efficiency in material removal.

7. Flushing: This operation is essential to maintain stability and prevent short circuits. It includes the circulation of dielectric liquid around the gap to remove the eroded particles.

8. Electrode Polarity: The polarity assigned to the workpiece or electrode, positive or negative, may influence tool wear, surface polish and material removal rate.

9. Surface Integrity: The integrity of the machined surface; that is, it considers the attributes of surface roughness, the thickness of the recast layer, and any micro-cracks.

10. Recast Layer: Because of the high temperature, due to resolidification, a thin layer of material may be formed on the work-piece surface. This layer's control is very important in applications where the surface area is large.

11. Arcing: if the electrical charge supplied to the gap is unable to be drained properly, a long disposal can result that may damage the work and precision.

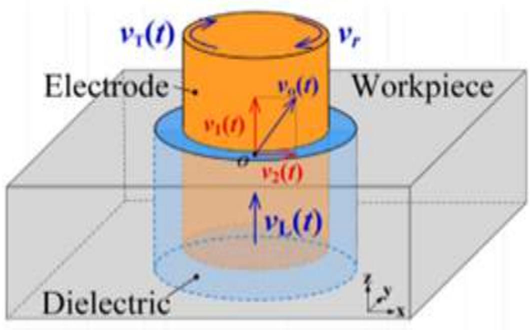

Fig3: Analysis of electrode motion during EDM of LTV electrodes

2. LITERATURE SURVEY

2.1 Examining the methods of debris removal in EDM drilling with ultrasonic vibration assistance.

Deep micro-holes provide difficulties for traditional EDM, particularly when working with durable materials like titanium, where debris buildup reduces quality and tool life. Through models and experimental testing, it examines ways to increase debris evacuation by introducing a longitudinal-torsional ultrasonic vibration.

2.2 Using an adaptive neuro fuzzy inference system to predict the depth of cut in vibration-assisted EDM cutting on titanium alloy.

In this case, the depth of cut in vibration-assisted electrical discharge machining on titanium alloy was predicted using the Adaptive Neuro-Fuzzy Inference System. The ANFIS model optimizes machining quality and efficiency due to its ability to function with significant prediction accuracy in relation to analyzing peak current, pulse-on time, and vibration frequency.

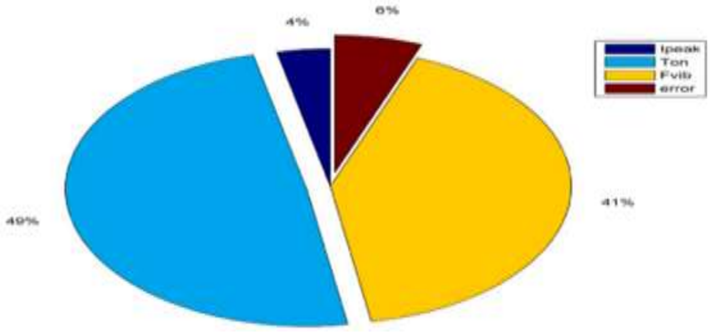

Fig4: Contribution of each process parameter

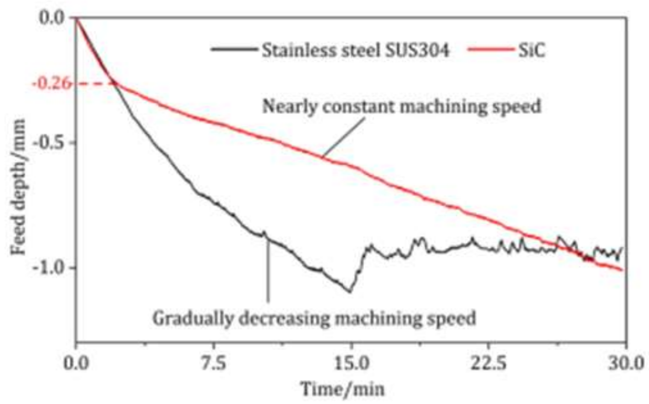

Fig 5: Contrast curves of the feed depth between the SiC workpiece and SS304

2.3 Relation between debris and the bubble flushing effect in micro EDM drilling

This paper discusses the examination of the bubble flushing effect in micro electrical discharge machining (EDM) drilling and its critical role in clearing debris that degrades deep-hole drilling machining quality.

2.4 Impact of tungsten carbide, copper, and tungsten copper tools on tie6Ale4V alloy micro-electric discharge drilling.

It discusses investigations on how micro-electric discharge drilling of the Ti-6Al-4V alloy is influenced by various tool materials, including copper, tungsten copper, and tungsten carbide. It points to how changing process variables, such as voltage and tool rotation speed, influence the machining efficiency.

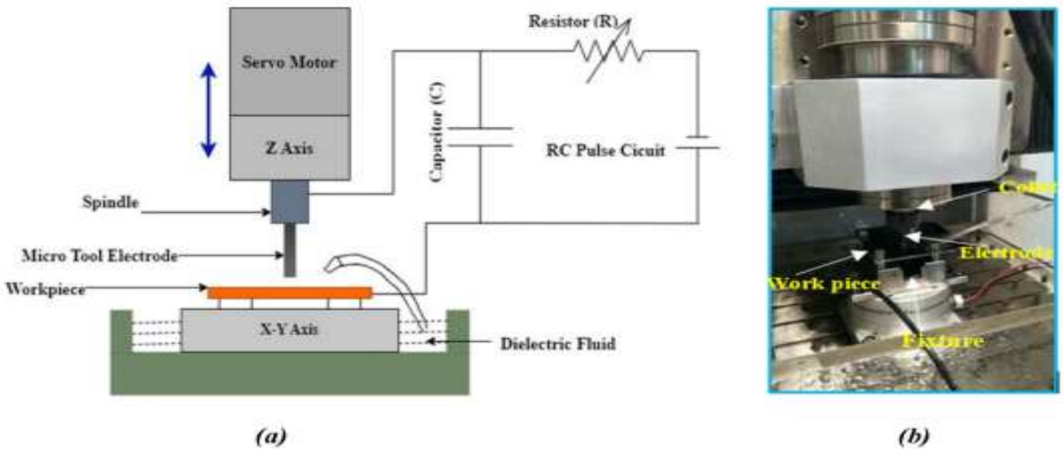

Fig6:(a) Schematic diagram (b) photograph of Micro-electro discharge drilling on DT110 machine tool.

2.5 Development of an EDM Operations Drowning Evaluation System

The research into sinking EDM stresses that due to interplay between variables such as material removal rates, flushing effectiveness, and electrode, time cannot be estimated precisely. Studies have shown the requirement for machine-specific calibration in controlled conditions, especially as reliance on generalized reference MRR values often leads to notably higher deviations in real-world applications. To increase accuracy, researchers have created prediction models that include correction factors for variations in operational conditions. Although there has been some investigation into integrating these models into CAD/CAM workflows, current solutions frequently lack real-time adaptation and flexibility. Recent developments imply that real-time feedback systems and machine learning can dynamically improve estimating models, resolving industrial issues. This framework, the proposed methodology is built on and incorporates future-focused aspects such as modular system design and calibration.

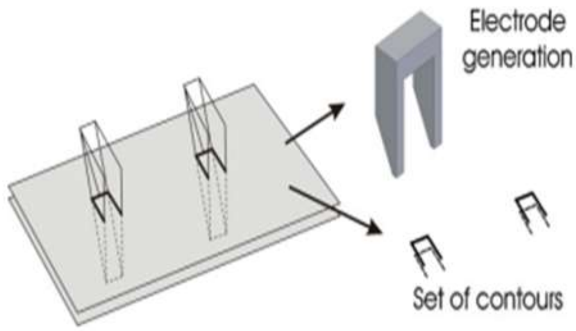

Fig7: Slicing of electrode geometry.

2.6 Chromatographic confocal measuring on-machine for micro-EDM milling and drilling

Both full-field and probe-scan on-machine measurement (OMM) systems are essential for precision production; probe-scan systems, particularly non-contact optical techniques like chromatic confocal probe measurement (CCPM), provide better accuracy and speed. CCPM is very successful for micro-component surfaces because it minimizes out-of-focus effects and vertical vibration influences by utilizing chromatic dispersion and confocal optics. CCPM has been demonstrated to be integrated in different machine tools, solving problems in steep surface inspections and attaining nanometre-scale resolution in ultra-precision machining. Some difficulties with scanning speed, surface gradients, and contamination have been identified but CCPM still has great promise in tracking tool wear while maintaining surface quality in electrical discharge machining. Comparative studies indicate that OMM based on CCPM maintains precision below the sub-micrometre range while cutting inspection times as much as 64% compared with offline techniques.

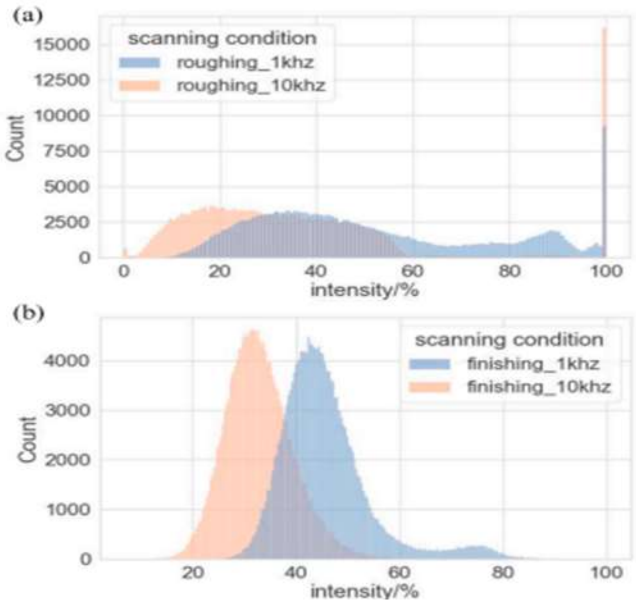

Fig8: Histogram of intensity distribution over (a) the rough surface and (b) the finished surface.

2.7 In micro EDM milling, the electrode wear on-machine measurements are uncertain.

Accurate electrode wear measurement and correction are essential for the precise creation of micro-scale features on conductive materials using micro-electrical discharge machining, or micro-EDM. On-machine measurement techniques are essential, such as Laser Scanning Micrometres (LSM) for volumetric wear and the Touch method for linear wear. Laser techniques offer high resolution 3D profiling and are therefore ideal for micromachining and small electrodes, but Touch is simple and practical for larger instruments. The latest improvements significantly enhance the accuracy and efficiency in micro-EDM operations as these techniques are combined with machine controls for real-time monitoring, reducing downtime, and increasing accuracy.

3. Conclusion

This work underlines the need for accurate measurements and adjustments of tool wear in attaining high precision in micro EDM milling. The Laser method proved to be better than the Touch method, not only in linear but also in volumetric wear measurements, due to its greater accuracy and noticeably reduced uncertainties. It works very well with tiny electrodes measuring less than 20 µm, where edge wear is more evident. The number of control intervals can also be maximized so that precision during machining can be further increased, and techniques such as the electrode stepover adjustments and frequent electrode reshaping can be put into use. For larger diameters, linear wear correction is usually enough, but volumetric wear considerations will be required for accuracy for smaller diameters.

Results indicated a higher consideration for volumetric wear, like edge rounding, in smaller tools, although linear measurements of wear would be sufficient for the larger electrodes. Long control intervals improve wear compensation but are best used sparingly to avoid increased uncertainty. Techniques such as redesigning electrodes, increasing electrode stepover, and compensating algorithms refinement were recommended for accuracy improvement. According to the findings of the study, Laser technique provides the precise information necessary for adaptive compensation systems and is very effective for linear and volumetric wear. It supports its use when high precision is necessary, such as in micro-machining activities.

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