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Tool Wear Rate Prediction by using Optimization Techniques

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Abstract: Electro discharge machining is a non-traditional machining process used for machining hard-to-machine materials, such as various grades of titanium alloys, heat-treated alloy steels, composites, tungsten carbides, and so forth. These materials are hard to machine with customary machining procedures like drilling, milling and hence electro-discharge machining is used to machine such materials to get better quality and efficiency. These materials are generally utilized in current industries like die making industries, aeronautics, nuclear industries, and medical fields. This type of machining is thermal-based, and machining takes place due to repetitive electric sparks that generate between workpiece and tool. Both tools and workpieces are inundated in a dielectric liquid, which has two primary functions. In the first place, it behaves like a medium between the work metal and the tool. Second, it is a flushing agent to expel the machined metal from the machined zone.

Machining parameters like a pulse on time, current, wire feed the tool and gap voltage affect the output responses like surface roughness and material removal rate. The material removal rate is a significant parameter that determines machining efficiency. Surface roughness is also a vital parameter that decides machining quality.

A lot of research has been conducted to determine the optimum parameters for obtaining the best results. In the present work, a comprehensive review of different types of EDM and the effect of various machining parameters on the surface roughness, material removal rate, and other response parameters has been done.

Keywords: Machining quality, TWR, surface roughness, parameter optimization, material removal rate

I. INTRODUCTION

Non-traditional machining processes were developed since the 1930s. Due to industrialization and as a result of war, processes that include less manpower and that give high precision were the need of the hour. Also, conventional machining processes had less efficiency, they were not robust enough for machining complex shapes and machining hard materials was extremely difficult. To cater to these needs, electro discharge machining was first developed in the 1940s.

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This process is capable of producing high precision, highly accurate shapes, and sizes and can machine extremely hard materials such as Inconel alloys, tungsten alloys, metal matrix composites, heat-treated alloys.

EDM is very efficient due to its high MRR. Softer metals like mild steel, stainless steel, and aluminum are also machining using this process due to the added advantage of machining efficiency. However, parameter optimization is required to get the best qualities, post-machining.

Output factors like tool wear, material removal, and surface roughness are major indicators of machining performance. Highly extensive research is taking place in the recently regarding the optimization of parameters. Materials like Inconel, chromium, steel, aluminum, titanium and their alloys have been under constant studies to determine the best parameters for the required specifications.

The major objective of this paper is to give a comprehensive guide for optimum machining conditions and parameters for various metal that have been studied in the past and provide further suggestions for improving machining performance.

NOMENCLATURE

MRR	Material removal rate
SR	Surface roughness
TW	Tool wear
EDM	Electro discharge machining
WEDM	Wire electro discharge machining
S/N	Signal to noise
Ton	Pulse on time
Toff	Pulse off time

A. Wire EDM

Wire EDM (WEDM) is a kind of EDM in which a thin wire is utilized to machine electrically conductive material. A spark is created because of the dielectric material between the tool and the workpiece. This spark releases a large amount of energy in a very short time period and this leads to material removal **[1].** This process is efficient, time-saving cost-effective, and determines machining parameters precisely **[2]**. In wire electro-discharge machining, a recast layer is formed which is formed when a thin layer of metal is cut up to a depth of a few mm below the surface. We can use a controlled X-ray diffraction pattern to show that this generates an extra residual tensile stress, which is parallel to surface **[3]**. A complete understanding of machining attributes and parameters is necessary to comprehend and improve the process parameters.

II. MATERIAL REMOVAL RATE

Machining parameters and their influence on maraging steel 350 were examined.

It was found that, maximum material removal of 2.835 mm3/min. was obtained at Ton = 104 µs, at a maximum current of 12A and spark voltage of 80 V. The least material removal rate was 0.405 mm3/min and was obtained at Ton = 108 µs, at a maximum current of 10A and spark voltage of 80V.

The maximum current and voltage of the created spark are the major factors that affect the material removal rate (Fig. 1) **[4].**

Inconel is a superalloy known for its strength and toughness. An analysis of response parameters, like, current, wire feed rate, cutting voltage, flushing pressure, etc on cutting of Inconel 718 was done. Lowest machining time was recorded at Ton = 12 µs, the wire feed speed of 12 and cutting voltage of 7 V. It was discovered that when pulse on-time was increased, it brought about a higher wire feed prompting lower machining time, which also causes an increase in the MRR **[5]**. Flushing force and cutting voltage have to be varied appropriately to achieve reasonable MRR. The influence of machining parameters on the MRR of D2, a grade of tool steel, was studied. D2 a type of tool steel that contains high carbon and chromium, extensively utilized in punch and die applications. Higher current and higher duration of pulse brought about higher machining rates. The highest MRR of 0.2225 g/min was obtained at 24 A and a pulse duration of 6.4µs **[6].** For H11 die steel, when copper tungsten is used as an electrode, it was seen that increasing the gap voltage led to an increase in MRR initially also with the further increase, the MRR decreased. A hike in peak current caused the MRR to increase significantly **[7]**.

The behavior of aluminum alloys on being machined using EDM was studied **[8]**. It was found that though MRR is found to be satisfactory, the chances of EDM machined aluminum alloy to corrode is quite high. It is also observed that MRR gets influenced by the table feed and pulse-on time. Thus, optimizing them can control discharging frequency to reduce wire breakage **[2].**

In the case of MMC's, the tension, pulse duration, and wire feed were observed to be noteworthy parameters. MRR values were positively correlated to wire feed tension and pulse time. An Increment in pulse on-time and the wire tension caused a linear increment in MRR **[9].** From AlSiC, it was observed that an increasing the MRR resulted in a change in the machined area of Heat affected zone and also increased the average crater diameter. Along with this, it was found that if B4C particles are added to the composite, a higher number of surface defects are found when compared to the original composite **[10]**.

From the Inconel superalloy series, four different grades were analyzed by experimenting using the EDM process **[11]–[13]**. This was done using various process parameters like duty factor, gap voltage, and peak discharge. The material removal rate was found to be highest for Inconel 601, ranging from 1.82 cubics mm per min to 36.31 cubic mm per min. For Inconel 825, the price was found to be the least, varying from 1.26 cubic mm per min to 25.94 cubics mm per min.

Wire EDM procedure was done to analyze the impact of machining attributes, like, table feed, pulse time, flushing, and so on **[2]**. Investigation on a feed of the table and pulse on-time showed that they give higher results on MRR. Highest MRR was obtained at pulse on-time of 0.8µs and a table feed of 2 mm/min. The influence of common machining parameters and other attributes like tension and wire feed on a wire in the EDM of a titanium alloy, which is known for its quality to retain shape, was examined. On critical examination, the highest material removal was 4.0065 mm3/min and was obtained at a high pulse on time of 115 µm **[14]**.

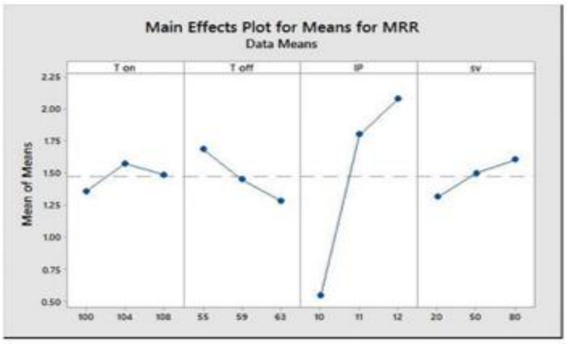

Fig 1. Impact of attributes on MRR [4]

Surface Roughness

The influence of different parameters on maraging steel 350 shows that the lowest surface unpleasantness of 1.276 µm was obtained at Ton = 100, peak current = 12A, and at voltage = 8V. Highest SR of 3.895 µm was obtained at Ton = 100, peak current = 10A and voltage of spark = 20V. The SR of a workpiece relies upon the spark voltage and pulse time. (Fig 2) **[4]**. It is important to strike a balance between spark voltage and pulse time to obtain signs of improvement in the surface finish while maintaining the required MRR. With increasing pulse time and pulsed current, SR increases. However, this will give rise to an increment machining cost and MRR **[15]**.

For Inconel 718, the highest surface roughness was obtained at Ton = 12 µs, wire feed speed = 10, and cutting voltage of 7 V. Results show that, when there is an increment in pulse on-time, it leads to poor surface finish and higher SR **[5]**. Meanwhile, the results of similar experiments on Inconel 625 show that by varying peak current, pulse off time and pulse on-time there is a significant effect on surface roughness and S/N ratios. Higher pulse on-time and lower peak current resulted in lower S/N ratios. However, for better surface finish, the lower pulse duration is required **[16]**. The impact of varying current, pulse on-time and electrode diameter on stainless steel, AISI 304 was analyzed. It was discovered that pulse on-time and peak current affected the SR substantially. S/N ratio is found to be related in an inverse manner to surface roughness. The utilization of electrode with higher diameters led to better and lower SR values. Lower current and higher pulse duration resulted in better surface finish **[1].**

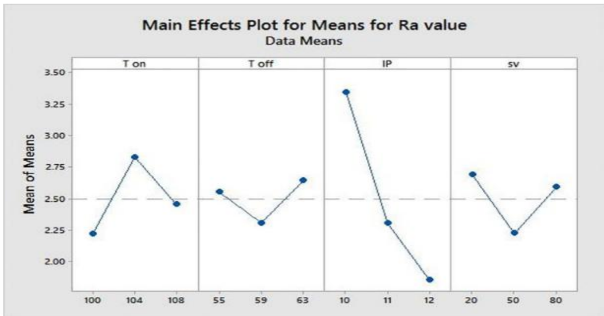

Fig 2. Influence of parameters on SR[4]

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For aluminum, it was researched that an increment in the pulse on-time had essentially incremented the longitudinal SR while increment in pulse off-time prompted an increase in transverse SR. For mild steel, the current was observed to be is the most essential factor for both longitudinal and transverse roughness values. Increasing the peak current values caused a considerable increase in SR of workpiece [**17**].

Pulse duration, current, and frequency of pulse were distinguished as major parameters for the SR analysis of tool steels. It was observed that lower current and reduced time of pulse reduced the roughness of the workpiece. The most superior surface roughness of 3.53 µm was obtained at 16A and at a pulse duration of 3.2 µs **[6].** It was seen that higher MRR leads to poorer surface finish and vice versa. The impact of predominant machining parameters, on alloy steels was investigated. It was found that, at first, an increment in pulse-on time diminishes the surface roughness values, however further increment leads to increased SR. Upon increment in current and voltage promotes increase of surface roughness **[7].**

Quality of manufacturing of WEDM-ed gear was observed to be DIN 5. EDM machining has resulted in better machining quality than other common gear generation processes such as hobbing or some other ordinary procedure **[18], [19].**

A complete examination of surface roughness and surface quality as a function of different parameters for different Inconel grades was done, the roughness of workpiece surfaces was found to be, highest in the case of Inconel 718, ranging from 6µm to 12.3µm. In the case of Inconel 825, it was the least, varying from 3.73µm to 13.2µm. **[11]–[13].**

The effect of pulse-on time on surface roughness is considerably high. Increment in pulse on-time results in increased SR **[2].** The influence of EDM process attributes on a titanium-based composite was studied. Results show that an increased pulse time results in an increment in SR. The rate of feed wire supply also leads to similar outcomes **[14].**

Tool Wear Rate

In the experiments performed of H13 die steel using EDM, it was found that tool wear rate was substantially influenced by the most important and dominant parameters like peak current, feed and pulse time. On further analysis, it was found that increasing current results in increased tool wear rate, but feed has very little significance **[7].**

The electrode surface will always wear in EDM. SR of the machined workpiece increases if the electrode surface quality reduces due to the pulsing in the current density **[15].**

Die EDM

This process is a type of EDM in which a die shaped like the negative image of the required part is used as an electrode in the process. The electrode material can be made by any material that can conduct electricity.

Material Removal Rate

Investigation of changes in output parameters such as MRR by utilizing metals like copper, brass, and graphite as electrode materials were done. H13 was used as the workpiece material. For graphite and copper electrode, initially, MRR increased with increasing current and time of pulse and then reduced with further increment in current and pulse time. Meanwhile, for brass electrode, an increment in current and time of pulse prompted a significant increment in MRR. It was also found that the copper electrode with a maximum current of 14A and 150µs pulse on-time gave the highest MRR **[20].**

On studying the effect of dielectric material on MRR, it was observed that, when distilled water is used as a medium, it brings about higher removal rates and results in reduced wear ratio than hydrocarbon oil. EDM can likewise be done by using gases like oxygen and air as a dielectric medium. It is also observed that, when compared to hydrocarbon oils,gas-based dielectric mediums can give higher MRR **[21]**. Tap water was found to give the best performance. Including chemicals like glycol and sucrose improves the performance of deionized water.

The effect of common EDM attributes like the voltage, current and pulse duration for Monel has analyzed grey relational and regression analysis **[22]**. Results show that MRR values increased with an increment in the current. Very low correlation is obtained between the gap voltage and removal rates. Highest MRR was achieved when the current was 15A and duration of pulse was 409µs.

Prediction of MRR in die EDM was done for various types of steel, brass, and aluminum. It was discovered that MRR relies upon the overall cyclic electrical charges. To increase the removal rates, an increment in current and reduced pulse duration is required **[23]**. To establish a correlation between current and MRR, EDM was done on AISI 1045 tool steel. Results show that increased MRR was obtained as a result of higher current values **[24]**.

Using electrical discharge machine EN8 and D3 materials were synthesized. Another reason for choosing those materials is their high industrial applications. Cast Copper and PM copper were used as electrodes. ANOVA and the surface material process were used to check the correctness of the above parameters **[25].**

The copper electrode was later compressed in a die with 22 tonnes load to attain a 15mm diameter cylinder. Green compacts were sintered after coating with ceramic to avoid oxidation of the material and then allowed to dry for 12 hours. They were then sintered at 900 °C for 60 minutes following which they were cooled in the furnace. Later these green compacts were cleaned with acetone and used for manufacturing D3 and EN8 workpieces. Significant parameters identified for MRR are tool diameter, pulse-on time and max current.

Surface Roughness

The effect of input factors, like peak current and pulse on time on H13 steel was analyzed. It was found that an increase in SR values was prompted by the large pulse on time. The brass electrode produced the best results for SR values **[20]**. For Monel superalloys, roughness values experienced a gradual increment with increment in the pulse on time. The impact of current is found to be less important than the effect of time of the pulse. Least surface roughness was seen at a peak current of 9 amperes and the time of pulse was 204µs **[22]**. For EN8 and D3 materials, significant parameters for surface roughness are pulse-on time and current **[25]**.

The impact of process attributes on the SR in the machining of die steel was investigated. SR increases for increasing the values of pulse current.

No change in the values of root means square for pulse current 1.5A for both voltages. For current of (3A), there are minimum differences, while they are greater for 12A and 24A. The largest increase in SR is between the 1.4 ampere and 2.9-ampere pulse currents. Growth in the maximum height of peaks was seen with increasing pulse current (Fig. 3) **[15], [26]**. For pulse voltage, lower roughness was generated at voltage of 200V than for 80V.

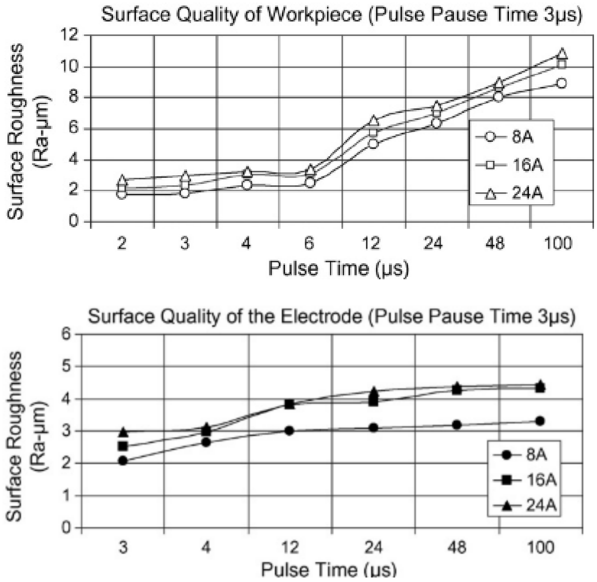

Fig 3. Impact of pulse time on SR [15].

Tool Wear Rate

The impact of current and the diameter of the electrode or tool on tool wear was analyzed by performing EDM on AISI1045. It was found that an increase in tool diameter led to a decrease in tool material loss. Increasing the current resulted in higher tool wear **[24]**

Dry EDM

Dry electro-discharge machining is a new type of machining. In this, instead of the usual liquid dielectric materials, gas-based dielectric materials are used. Oxygen, nitrogen, helium, etc. are used in dry EDM. It has been seen that gas-based dielectrics can replace liquid-based dielectric materials effectively when the gas is supplied at high velocity **[27]**

The advantages of dry EDM include lower tool wear, higher precision, no fire hazard, no toxic fume generation, narrower discharge gap length, the possibility of arbitrary machining directions. Disadvantages, however, include low material removal rates and poor process stability.

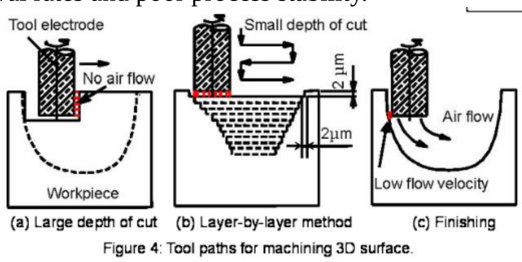

Fig 4. 3D dry EDM [28]

Material Removal Rate

Trials were run to observe conclusive parameters in determining removal rate, wear and surface abnormalities. The possibility and effects of using oxygen gas with dielectric gas in the dry EDM process have been explored. It was found that the removal rate is directly and positively related to the value of the current. Straight polarity aids the process to a greater extent than reverse polarity as is evident from a negative slope of the graph. An increase in gas flow pressure increments the value of removal rate until it reaches a maximum. Thereafter, MRR decreases significantly. The mean of S/N Ratio monotonically increases with both R.P.M. and pulse duration. With an increment in gap voltage, the mean of S/N Ratio reaches maxima thereafter it becomes constant **[29].**

A run of 18 experiments was performed on workpiece material Si3N4-TiN by varying the attributes of voltage, pulse-time, and current. The range of MRR obtained from the experiment was from 0.0021 to 0.0168 g/min. It showed that MRR was high at a higher voltage and current and pulse on-time did not seem to have much effect on it. The optimum MRR is taken to be in a range of 0.6270 g/min to 1.0899 g/min which can be achieved at a voltage of 50 volts, 5 amps current and pulse duration of 500µs **[30].**

Between tool and workpiece, several electric sparks are generated, with the help of dielectric material. During machining, when short circuit-ing between the electrodes takes place, some material is removed from both the tool and workpiece surface **[31]**. A new way to improve the efficiency of EDM by using oxygen was discovered. The gas was injected into the working gap. It has been discovered that the rate of removal was increased because of the greater volume of the crater and due to the increased frequency of electro-discharge **[28].**

Dry EDM was performed on AISI 304 and it was discovered that the MRR increased by 7.5% in case of air blowing condition and 28% during the sucking condition compared with the no air condition. Hence, it was concluded that Material Removal was best in case of sucking conditions. The peak material removal rate was obtained with a pulse time of 9µs & a pulse interval of 2µs (Fig. 5) **[32].**

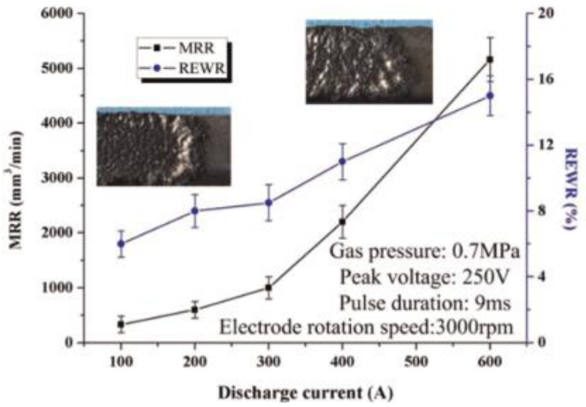

Fig 5. Influence of current upon removal rates [32]

Surface Roughness

Reverse polarity aids Ra more than straight polarity. The gas flow pressure, pulse duration and current are very important attributes. Pulse duration and voltage increase the mean of S/N Ratio initially and after hitting a maxima value starts to fall. Discharge current and gas flow pressure, decrease the Mean of S/N Ratio initially and after hitting a minima value starts to rise **[29]**.

Experiments on AISI 304 was done using dry EDM, the best surface finish for dry EDM was obtained using kerosene mist with air combined with a copper infiltrated graphite electrode. It was observed that the dry EDM at the greater pulse energy level and long pulse duration resulted in better machining stability and hence good surface finish. On furthermore lowering the pulse duration and energy, it will result in even better surface finish **[32].**

Tool Wear Rate

For EDM, TWR is mostly insignificant. TWR is indirectly proportional to R.P.M. and the discharge current. When the gas flow rate increases, TWR decreases till it hits a minimum beyond which it starts to rise again. The most significant factors for determination of TWR are gas flow pressure, speed of rotation, and the pulse on time(Fig.6) **[29], [32]**. As the aim is to minimize EWR, it is seen that the EWR is lower as current and pulse time increases. Voltage has a minor effect on EWR. The optimum EW is found to be in the range of 0.0002 - 0.0009 grams/min. The optimal machining parameters are found to be: Voltage = 30V, at current – 5 A, and a pulse on-time - 600 micro secs **[30].**

The viability of machining 3D surfaces using EDM was researched to ascertain the effect of gas pressure, DOC, duration of the pulse, the tool's speed and pulse interval and the rotational speed of the tool electrode on the final product. The best combination of the duration of pulse, pressure and the cutting depth was investigated. For depth of cut 25 mm, there is the least amount of tool wear and highest MRR. The tool wear is directly proportional to the speed of rotation **[33].**

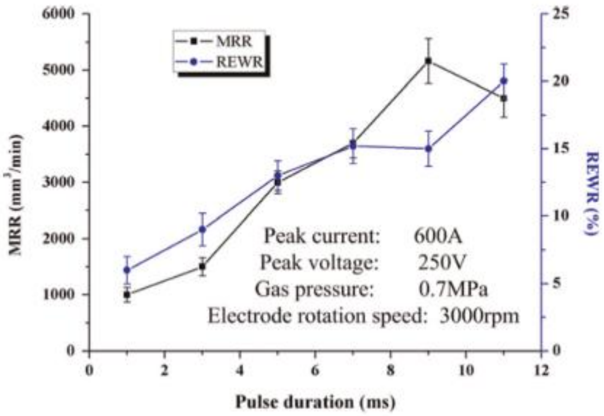

Fig 6. Influence of pulse time on electrode wear-rate [32]

III. OTHER EDM TYPES

Material Removal Rate

For electrodes of aluminum and copper, a high discharge current, provides the highest MRR, whereas brass gives good surface finish and MRR. As the current increases, MRR increases. For pulse on time the MRR first increased with linearly with increase in pulse off time, MRR decreased insignificantly **[34].** In a strategy, which is UEDM, material removal procedure is done in gas. An increment in MRR was found with the decrement in diameter of pipe, increment of pulse duration, amplitude of ultrasonic vibration and open voltage. It was also observed that oxygen gas gives more MRR than air **[35].**

In the study of dielectric performance for the case of micro EDM, it was observed that the efficiency was better when dielectric oils with lower viscosity were used. It was also found that these oils affect machining time more than the hydrocarbon oils **[21].** The impact of different dielectric materials such as pure kerosene and graphite-based dielectric with mixed kerosene was analyzed experimentally **[36].** The consequence of various electrode materials types on Electric discharge machining of W9Mo3Cr4V, a type of high-speed steel was analyzed. Aluminum, stainless steel, brass, etc. were used for electrodes. Results show that aluminum had the MRR of 219.019 mm^3/min, while graphite had the highest MRR of 7065.08 mm^3/min **[35].**

Surface Roughness

The most substantial factor was once again followed by on and off-time of the pulse. As the current increased in a nonlinear function, SR increases significantly **[37].** For an increment in pulse on time SR increased. SR experiences a reduction with respect to an increment in pulse off time **[34].**

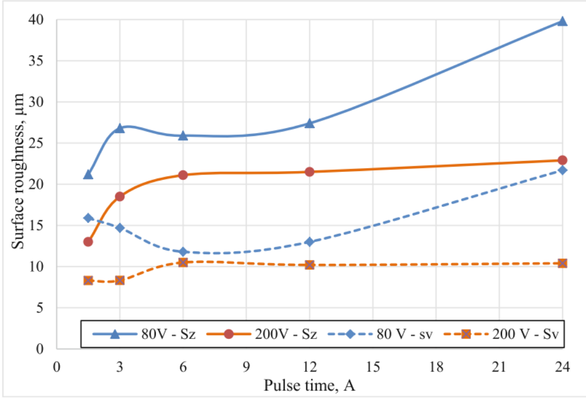

Fig 7. Influence of pulse time on SR for different voltages [26]

Tool Wear Rate

It was observed that due to no uniformity in the distribution of heat, disruptions and cracks occur in Aluminium electrode machined **[37].** Tool wear rate gets affected by peak current, on-time of pulse, after that by pulse T(off) **[34].** As compared to pure kerosene dielectric, this caused a 28% decrease in tool wear **[36].** In the case of W9Mo3Cr4V high-speed steel, different electrode materials were used to test for tool wear. It was found observed graphite had the least tool wear of 1.45 mm^3/min while aluminum had the highest tool wear of 531.79 mm^3/min. Graphite electrode is found to have significant advantages over other electrode materials **[35].**

IV. CONCLUSIONS

The parameter optimization procedure for any machining process is very essential. It helps in performing the machining in an efficient and cost-effective manner. However, due to the lack of availability of proper and accurate parameters, many machining processes end up being inefficient and unfit for commercialization. Especially, in electro-discharge machining, which is a process with high energy demands, optimized parameters are an essential factor in determining the machining efficiency.

After an extensive study of different categories of process parameters and attributes for different types of EDM, it was observed that irrespective of the type of electro-discharge machining, the variation pattern of output attributes like MRR, SR, and TW, is very similar. Peak current and pulse duration emerge as best parameters to determine the efficiency.

The following interpretations were made in our study.

- The material removal rate gets affected by both peak current and pulse duration. An increment in current and pulse duration leads to an increase in MRR.
- Surface roughness highly depends mainly on the current. However, it is inversely related to voltage. Voltage affects surface roughness in combination with the current.
- Surface roughness is inversely related to MRR.
- Tool wear is inversely dependent upon the current, pulse on time and electrode material
- Striking a harmonious balance between MRR, SR and tool wear to give the optimum combination will result in the best machining quality.

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