Frontiers of Multidisciplinary Exploration
Volume 1, Issue 2, September 2025, Page 1-6
ISSN: 3139-4086

Analysis of Material Removal and Surface Integrity in the EDM Process

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Received 1 May 2025, Accepted 19 August 2025, Published online: 12 September 2025

Abstract

Electrical Discharge Machining (EDM) is prevalently applied in the shaping of hard to machine material, but the fundamentals of this process are complicated thermo-electric events that affect material removal as well as the integrity of the surfaces. This research examines how discharge parameters; pulse current, pulse duration, duty factor and dielectric flushing relate to and affect the combination of discharge parameters in determining the rate of material removal (MRR), tool wear, surface roughness as well as metallurgical changes in machined zone. A high-strength alloy was experimented with the help of controlled EDM conditions and then microcracks and surface topography were detailed through characterization of the recast layer, heat-affected zone, and microcracks of the material. Its findings indicate that pulse current and pulse-on time improvements are both effective in raising MRR and worsening surface defects such as recast layers and microcracks. On the other hand, enhanced lower-energy pulses enhance surface quality at reduced material removal speed. Thermal gradients during repetitive discharges can be studied microscopically to observe rapid melting and quenching to form globule debris, crater clusters, and modified microstructures. The paper establishes a window of operation that reduces the amount of damage caused on surfaces and also attains acceptable machining performance. The results add to the better insight of EDM mechanisms and give a practical advice on how to choose the process parameters when the surface integrity is the important factor of a component performance.

Keywords

Electrical Discharge Machining; Material removal rate; Surface integrity; Recast layer; Pulse parameters

1. Introduction

Electrical Discharge Machining (EDM) is now an essential method of machining electrically conducting materials that are hard to cut using traditional methods [1-5]. Its capability to materialize hard alloys, superalloys, carbides and complex geometries demanded in aerospace, automotive, mold-making, and biomedical applications makes it especially effective due to its capability to erode material by means of controlled electrical discharges. Even with these benefits, the EDM process comes with

unique thermal effects which affect the material removal efficiency and quality and integrity of machined surface.

Previous studies have already known that performance of EDM is dictated by discharge energy, which is mainly dictated by pulse current, pulseon period, pulseoff period, and duty cycle [6-9]. An increase in discharge energy increases the rate of melting and vaporization, which increases the rate of material removal (MRR), although it also tends to decrease the surface integrity due to deeper craters, thicker recast layers, and microcracks due to rapid heating and quenching. On the other hand, low-energy pulses could be used to get smoother surfaces but at very low productivity. The dielectric fluid is also very crucial as it flushes debris, stabilizes plasma channels and affects the cooling rates. A combination of these interacting factors establishes a complicated trade-off between machining efficiency and surface quality.

Surface integrity during EDM involves several attributes which include roughness of surfaces, microstructural transformation, residual stresses, microcrack development, and the size of heat-affected zone (HAZ) [10-12]. The way process parameters change these surface properties is vital in a case where the components have to be able to respond to rigid fatigue, wear, or mechanical performance requirements. Nevertheless, since there are concurrent thermal, electrical, and hydrodynamic processes that take place during EDM, predictive control of both MRR and surface integrity does not come easily.

This research will focus on analyzing systematically the effects of the important EDM parameters on the material removal and surface integrity of a high strength engineering alloy. The study measures MRR, tool wear ratio, and surface roughness and examines microstructural features including recast layer thickness and the arrangement of microcracks with the help of microscopes and surface characterization. This paper seeks to determine an optimum parameter range that offers efficiency and quality in machining, which will be of practical information in the engagement of EDMs in industries.

2. Methodology

The die-sinking EDM machine with a programmable pulse generator was used in experiments. The workpiece material was a highly strong alloy that is typical in the field of precision engineering, and the copper electrode was selected because it is a material that has great electrical and thermal conductivity. The electrode and the workpiece were machined to conventional size to facilitate replication of test conditions. Continuous flushing of kerosene based dielectric fluid was applied in stabilizing the discharge gap and also in removing molten debris.

The parametric design methodology was used to investigate the effect of parameters of discharges such as pulse current, pulse-on period, pulse-off period, and duty cycle. The variation of each parameter was under three variations and the rest were constant, allowing the isolation of the effects. Machining was done under regulated spark-gap conditions in order to have constant discharge conditions. Workpiece and electrode were cleaned, dried, and weighed after each of the trials to show the material removal rate (MRR) and tool wear rate (TWR) in terms of mass change.

The surface integrity was assessed with the help of several characterization methods. Contact profilometer was used to measure surface roughness (Ra), average deviation of surface across several paths. Metallographic samples were sectioned and mounted, polished followed by

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etched to view recast layer and heat-affected zone using optical microscope as well as scanning electron microscope (SEM). SEM images were used to determine the crater morphology, micro cracks, the deposition of globules, and patterns of thermal damages. The thickness of recast layer was measured in various regions to obtain local variation due to discharge instability.

Trend plots and comparative analysis were used to analyze experimental data in order to determine the relationship between parameters and responses. The synthesized interpretation of MRR, TWR, surface roughness and microstructural characteristics allowed to find the trade-offs and optimization prospects in the EDM parameter space. Table 1 demonstrates the EDM Process Parameters Used in the Study.

3. Results and Discussion

The results of the experiment showed that there were clear correlations between EDM process parameters and the material removal and surface integrity outcomes. The rate of material removal (MRR) increased with an increase in pulse current and pulse-on period because of higher energy of discharge which increases the melting and vaporisation of the workpiece. At the maximum current of the pulse current, MRR improved over three times as compared to the minimum current level. Nevertheless, this enhancement was at the cost of the additional dislocation of tools because the violent discharges also eliminated the copper electrode faster. The tool wear rate (TWR) trend was also similar with a noticeable change in the uniform wear of the electrode at the low energy level, to cratered uneven wear at the high energy settings. Figure 1 demonstrates the variation of MRR concerning pulse current and pulse on time.

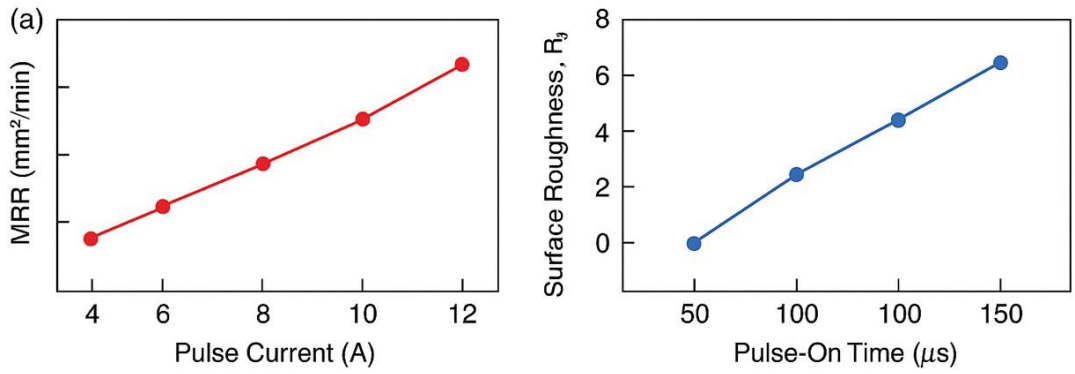


Figure 1. Material removal rate (MRR) as a function of pulse current and Pulse on Time.

There was a high dependence of the roughness of the surface on discharge energy. The larger pulse-on times caused deeper and wider craters and the surface roughness was rougher by up to 200 percent compared to the low-energy situation. On the contrary, the shorter pulse-on times produced less coarse crater formations and even surfaces. This portrays the classic trade-off between EDM, better productivity with poor surface. The pulse-off period was also a factor because of inadequate off-time limiting the plasma collapse and removal of debris, resulting in uncontrolled discharges and isolated micro-damage. An increase in pulse-off periods increased stability but decreased MRR marginally. The change in roughness of the surface with change in pulse on time is depicted in Figure 2.

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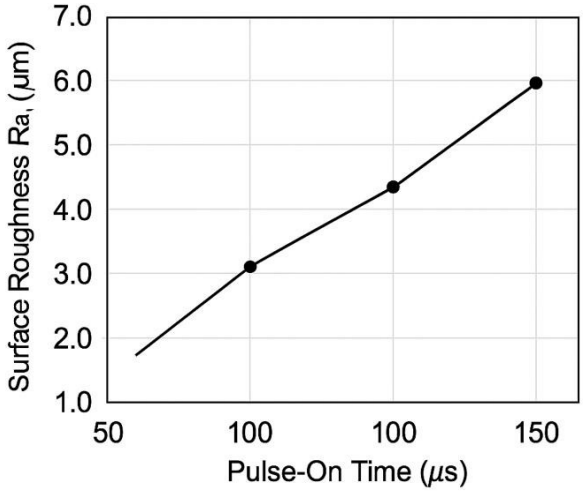


Figure 2. Surface roughness (Ra) variation with pulse-on time.

Surface integrity was important, and can be analyzed microscopically. The recast layer became very thick at the higher discharge energies, usually in the range of 10-25 um, and pronounced microcracks were formed as a result of the large rate of thermal shock during quenching. The surface after recast revealed traces of globule deposition, refreezed droplets and clusters of craters. Conversely, the recast layer was thinner (3-8 um) and the cracking minimum and the microtopography of the sample were smoother in samples subjected to lower-energy conditions. High-energy conditions were also characterized by a more pronounced HAFZ with a manifestation of grain refinement and localized structural adjustments as a result of severe thermal cycling.

The integrated analysis shows that the process parameters have to be chosen very attentively to achieve a balance between machining efficiency and surface integrity. Higher current levels are preferable where quickness in the removal of materials is desired at the expense of the quality of surfaces and fatigue life in critical components. Reduced discharge energy settings have better surfaces and little metallurgical damage but at a slower machining rate. These findings suggest that there are two optimal intermediate ranges used where moderate pulse current and controlled pulse-on time can be used to obtain acceptable MRR without damaging the surface in functional limits. Table 1 is about Surface Integrity Parameters of Various Discharge Energies.

Table 1. Surface Integrity Parameters for Different Discharge Energies

Discharge Condition	Surface Roughness (Ra, µm)	Recast Layer Thickness (µm)	Microcrack Presence	Surface Features
Low energy	2.1	5–8	None	Fine craters, smooth texture
Medium energy	3.8	10–15	Minor	Uniform craters, small globules
High energy	6.4	20–30	Frequent	Large craters, globules, microcracks

4. Conclusion

This paper has discussed how the major parameters in EDM processes affect the process of removing the material and material surface integrity of a high strength alloy. The findings prove that both MRR and surface characteristics are very sensitive to discharge energy, and higher pulse current and pulse-on duration lead to the significant increase of material removal and aggravation of thermal damage, surface roughness, and recast layer formation. Microscopic observation of the environment showed that high-energy environments favor deep craters, deposition of globules and formation of microcracks whereas low-energy environments produce smooth surfaces and less modification due to metallurgy. A middle range of parameters was found with the machining efficiency and surface integrity being in a reasonable balance. It is particularly applicable in components whose dimensional accuracy and surface quality is of high importance. The results lead to useful conclusions regarding optimization of the EDM conditions in the industrial work and add to the further comprehension of the thermal-material interactions during the EDM process.

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