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Investigating the effect of process parameters on EDM performance of Inconel 725 alloy

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ABSTRACT

In aerospace and automotive sectors, electrical discharge machining is essential for shaping hard-to-machine materials like Inconel 725. Using Taguchi's L16 orthogonal array, this study examines how electrode shape (round and square), peak current (8 and 12 A), pulse-on time (100 and 200 μs), and pulse-off time (1.2 and 1.6 μs) affect material removal rate and surface roughness. The study found that raising peak current from 8 to 12 A considerably improved material removal rate from 0.0593 to 0.1417 mm^3/min. The maximum material removal rate was reached with a round electrode, 12 A current, 200 μs pulse-on, and 1.2 μs pulse-off duration. However, this setting resulted in the roughest surface finish (9.407 μm). However, the square electrode had better surface quality, with the lowest SR value of 5.965 μm at 8 A, 100 μs pulse-on, and 1.6 μs pulse-off. enhanced pulse-on time (200 μs), enhanced material removal rate by 47.77 %, but shorter pulse-off time (1.2 μs) led to more efficient erosion owing to higher discharge frequency. The findings help precision machine advanced alloys like Inconel 725 by emphasizing the need for electrical discharge machining parameter selection to balance high material removal rate and surface integrity.

KEYWORDS

Inconel 725 alloy • electrical discharge machining • DOE • material removal rate • surface roughness

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Introduction

Machining plays a very important role in manufacturing and production sector especially in the automobile sector whereby accuracy, reliability and efficiency are very vital in maintaining competitiveness [1]. The automobile industry is a technology-driven industry in which parts are required to maintain high levels of performance and tight tolerances. The current trend of lightweight, electric mobility and engine economy of vehicles has sharply increased the demand of machining of complex geometries of the hard and heat-resistant materials [2]. Modern engines, gearboxes, turbochargers, brakes, and so on require sophisticated and accurate machining solutions. Traditional machining methods, stable as they are in various applications, are facing limitations to suit these emerging demands, especially with materials that have outstanding hardness, toughness or heat resistance [3]. As the modern manufacturing industry moves towards the more advanced materials, the typical methods of machining, including turning, milling, and drilling, often become unsuitable, particularly in dealing with superalloys or composites [4]. This shortcoming has led to the development and implementation of non-conventional machining (NCM). The methods, including electrical discharge machining (EDM), laser beam machining (LBM) and ultrasonic machining (USM), have certain advantages over the common methods [5]. Non-conventional machining eliminates direct contact between the tool and the workpiece and hence prevents issues related to mechanical forces such as tool wear and workpiece deformation. These methods are especially suited to machining complex shapes, finer cavities or very hard and brittle materials [6]. The wide use in the industrial segment has made EDM unique in dealing with electrically conductive materials which are hard to produce. Figure 1 illustrates the principle of working of the EDM process.

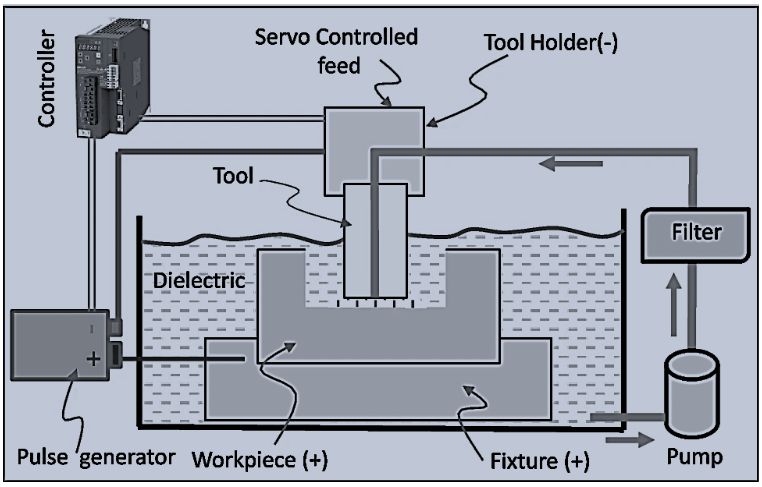

Fig. 1. EDM working principle. Based on [6]

Electrical discharge machining (EDM) is a thermoelectric process in which the material is removed by means of high-frequency electrical discharges between a profiled electrode and an electrically conductive workpiece by being placed in a dielectric fluid [7]. This is mostly suitable for materials that are difficult to cut with conventional tools due to their hardness or heat-resistant nature. The application of EDM in die and mold fabrication, aerospace components, medical implants and military apparatus has mainly been attributed to its ability to produce high precision components with complex geometries and excellent surface finishing [8]. Mechanical force is not necessary in machining, so EDM is ideal in complicated parts and thin-walled parts, which reduces the possibility of distortion. Inconel 725 is a nickel-based superalloy that is difficult to machine conventionally but extremely important in high-performance engineering [9]. Inconel 725 has been known to have high corrosion resistance, high strength, and pitting, stress corrosion cracking, and crevice corrosion resistance [10]. It has excellent mechanical properties in high temperatures, making it a best option in demanding conditions such as deep-sea oil and gas exploration, aircraft engines, sea gears and chemical processing [11]. Nickel, chromium, and molybdenum are high in concentration, and they provide resistance to oxidation and heat deterioration in addition to strength. However, these individual characteristics make machining on traditional procedures very difficult. Its ability to work-harden together with the lack of heat conductivity and extreme abrasiveness of the material leads to expedited wear on the tool as well as poor surface quality in a conventional machining operation. The electrical conductivity of Inconel 725 and the fact that EDM can machine thermally resistant materials has made the process of machining the alloy using electrical discharge machining (EDM) an effective process [12]. Even though EDM is an appropriate choice, the achievement of the best results in terms of material removal rate (*MRR*) and surface roughness (*SR*) remains a challenge. The performance and the quality of product of EDM process highly depend on some factors such as discharge current, pulse-on time, pulse-off time and flushing pressure [13]. These directly influence the energy per spark, the stability of the spark production, and the ablation of debris of the inter-electrode gap. The improper choice of these parameters could lead to the negative consequences of unstable machining, excessively worn tool, recast layer formation, or even damage of the workpiece. These issues have led to the optimization of EDM parameters becoming an important area of research in order to overcome these difficulties and enhance the productivity and surface quality of components machined using EDM. The process can be refined to meet desired performance goals either by increasing the rate at which material is removed to enhance productivity, or reducing the surface roughness to enhance functionality by optimization of the EDM input variables [14]. However, the complexity and non-linearity of the interaction between the parameters of EDM make the conventional methods of selecting parameters through trial-and-error not efficient in time and cost. This has seen the adoption of statistical and multi-objective optimization techniques that ease the process of making decision-making accurate and reliable. This helps the researchers to determine which factors are paramount and they should be given priority in the optimization process [15]. The study is structured to investigate how the EDM parameters (discharge current, pulse-on time, pulse-off time, Flushing pressure) influence the machining rate of material (*MRR*) and surface roughness (*SR*) when machining Inconel 725 [16].

The results of this study aim at testing the effects of EDM parameters on MRR and surface roughness experimentally, and ANOVA is employed solely in designing the experiments (DOE). The better parameters that will be achieved through this research will be used to curb down manufacturing cost, increase the tool life and ensure reliability of components in the crucial sectors of the aerospace, automotive, marine and oil and gas industries. The predictive model developed in this study will be beneficial in real-time parameter selection in an industrial setup to promote smart manufacture systems and intelligent machining systems.

Materials and Methods

Workpiece Material

The material used in this study is Inconel 725 which is a nickel-based superalloy with high mechanical strength, corrosion resistant and temperature resistant characteristics. Inconel 725 is mainly employed in the aerospace, marine, and petroleum industries because it is resistant to pitting, stress-corrosion cracking and crevice corrosion. The chemical structure of Inconel 725 majorly contains Nickel (Ni), Chromium (Cr), Molybdenum (Mo), Niobium (Nb), and Iron (Fe) that make it have the best properties. The machining workpiece was a rectangular block with a size of 25 × 20 × 10 mm^3. It was good in electrical conductivity therefore the alloy could be machined using the EDM technique.

Tool electrode

The tool electrode is very important in the EDM process, because it is the direct determinant of the shape accurateness and the quality of the surface of the machined component. Copper was used as the tool electrode material in this study because it is highly conductive to electricity, moderately melts, and has excellent wear resistance. Two electrode shapes were taken into consideration: round-shaped electrode (R1) and square-shaped electrode (S1). The two electrodes were made in a similar fashion so that the cross-sectional area would be the same and mounted on the EDM machine so that they were aligned well. Fresh copper electrodes were applied in the experiments to each test to reduce the influence of electrode wear on machining performance and keep trials consistent [17]. The procedure assists in ensuring that the conditions of electrical discharge are uniform during the tests.

EDM machine setup

The tests were carried out using a die-sinking EDM machine that had servo control and parameter setting features (digital). The experiment structure of the EDM process is shown in Fig. 2. The machine table was then strictly clamped, and the electrode was inserted in the tool holder. The dielectric fluid was kerosene that was required to assist in the erosion process of the spark as well as to clean up the particles of debris that were generated in the inter-electrode gap [18]. The temperature of the dielectric fluid under our experimental conditions was passively kept at ambient laboratory temperatures. Data To maintain machining conditions and to avoid temperature increase caused by machining heat, the kerosene was constantly circulated and filtered during machining.

Fig. 2. EDM experimental setup

Characterization detail

Experimental design - DOE

The experiment trials were designed using Taguchi robust design method. Four process parameters were analyzed using orthogonal array of L16 (24) at two levels using the least amount of experiments [19]. This design method is beneficial to determine the main effects and interactions as well as the optimization of the EDM process. The EDM process is inputted to examine four parameters of the process based on literature review and initial trial:

1. Electrode shape (R1, S1).
2. Discharge current (I): 8 and 12 A.
3. Pulse-on time (T_{on}): 100 and 200 μs.
4. Pulse-off time (T_{off}): 1.2 and 1.6 μs.

At these two levels, these parameters were varied and the experimental matrix was created based on Taguchi L16 orthogonal array that is efficient in investigating more than a number of parameters at a lower cost [20]. Every combination of parameters was tried once and the results of MRR and surface roughness were measured. All trials of EDM were held at the constant duration of 10 min under constant conditions of dielectric flushing. This time was chosen because it was necessary to be able to compare machining with a stable condition and measure the material removal to compare it with *MRR* and surface roughness evaluation.

Response parameter

Two primary performance indicators were chosen as output responses to evaluate machining performance. Material removal rate (*MRR*) indicates the volume of material removed per unit time and was calculated using the equation [21]:

$$MRR = \frac{W_i - W_f}{\rho \, x \, t}, \tag{1}$$

where W_i is the initial weight of the workpiece, W_f is the final weight after machining, ρ is the density of Inconel 725 (8.4 g/cm^3), and t is the machining time in minutes.

Surface roughness (*SR*): surface finish was obtained through Taylor Hobson surface profilometer. The roughness was established at the surface at three points depending on the trial, and the mean was taken so that there is consistency and loss of error in the experiment is minimal [22].

Results and Discussion

Test results for workpiece

A progression of electrical discharge machining (EDM) tests was carried out in order to test the machining characteristics of Inconel 725 once the composition of the workpiece was established along with the powder used. The Taguchi method was used to develop the experimental design, and an L16 Orthogonal Array (OA) was chosen to combine the parameters [23–25]. The major EDM parameters that were taken into consideration in this study were peak current, pulse-on time, pulse-off time and powder concentration which were all to be varied in two levels. In particular, the levels were the following: peak current (8 and 12 A), pulse-on time (100 and 200 μs), pulse-off time (1.2 and 1.6 μs), and electrode shape (round and square). Prior to the commencement of the experiment the work-piece was put to test, and the report of the testing is in Table 1.

The electrode material was made of copper, and the workpiece material was Inconel 725. After defining parameters and level values, machining tests were conducted according to the combinations that are defined in L16 OA matrix. After the completion of

Table 1. Test results for composition of work-piece

Elements	Max. limit of impurities, %
Silicon (Si)	0.048
Manganese (Mn)	0.107
Phosphorus (P)	0.009
Sulfur (S)	0.006
Chromium (Cr)	20.76
Molybdenum (Mo)	7.294
Nickel (Ni)	57.860
Aluminum (Al)	0.176
Niobium (Nb)	2.985
Titanium (Ti)	1.562

Table 2. Values of various responses

Tool shape	*I, A*	T_{on}, μs	T_{off}, μs	*MRR*, mm^3/min	*SR*, μm
R1	8	100	1.2	0.0648	6.323
R1	8	100	1.6	0.0722	5.977
R1	8	200	1.2	0.066	6.84
R1	8	200	1.6	0.095	6.771
R1	12	100	1.2	0.0959	8.478
R1	12	100	1.6	0.0988	8.98
R1	12	200	1.2	0.1417	9.407
R1	12	200	1.6	0.115	8.06
S1	8	100	1.2	0.0593	7.389
S1	8	100	1.6	0.0658	5.965
S1	8	200	1.2	0.0691	7.079
S1	8	200	1.6	0.0883	7.454
S1	12	100	1.2	0.0924	7.668
S1	12	100	1.6	0.0863	7.708
S1	12	200	1.2	0.0956	8.119
S1	12	200	1.6	0.0987	7.801

Fig. 3. Specimen after machining at EDM

experiments, the weighing of the work piece and electrode was done using a precision weighing machine to ascertain material removal rate (*MRR*) [26]. Table 2 gives the values of the surface roughness (*SR*) [27] measured by a surface roughness tester. Figure 3 displays the pictures of the specimen at the end of doing the experiments.

The objective of the experimental study was lower EDM parameters of Inconel 725 based on the L16 Orthogonal Array (OA) system of Taguchi by using an electrode shape, maximum current, pulse-on time, and pulse-off time as input variables. Material removal rate (*MRR*) and surface roughness (*SR*) were measured to identify what effect each parameter had on machining performance. The findings revealed that increased peak current (12 A) resulted in significant rise in *MRR* with values of 0.1417 mm^3/min when using the round electrode (R1) at pulse-on time of 200 μs and pulse-off time of 1.2 μs. This was because the more the current, the greater the amount of discharge energy and thus the higher the erosion of the workpiece material. Nevertheless, the increase in current led to the increase in the roughness of the surface to its maximum depth of 9.407 μm since the excessive heat would lead to deeper craters and the deposition of molten material. Pulse-on time was also a significant aspect of *MRR* enhancement with 200 μs pulse-on time considered better in enhancing *MRR* than 100 μs because of higher energy transfer per spark. A reduced pulse-off time (1.2 μs) also increased *MRR*, and enabled more frequent discharges per unit time, and also reduced the period between discharges between sparks. The findings further indicated that round electrodes (R1) had higher *MRR* than square electrodes (S1) as a result of the better distribution of the spark and smooth wear properties. On the other hand, square electrodes gave a better surface finish and less surface roughness values were registered in a number of trials. An example is that when the square electrode was used, pulse-on = 8 A, pulse-off = 100 μs and *SR* = 5.965 μm was recorded, but when the round electrode was used, *SR* = 5.977 μm was observed (Fig. 4). In general, the experiment showed that increased current and the length of pulse-on affect MRR positively and adversely affect surface roughness, whereas shorter pulse-off time positively affects machine performance. Electrode shape is also a major factor that influences machining performance with round electrodes showing better MRR and square electrodes showing better surface quality. The results indicate

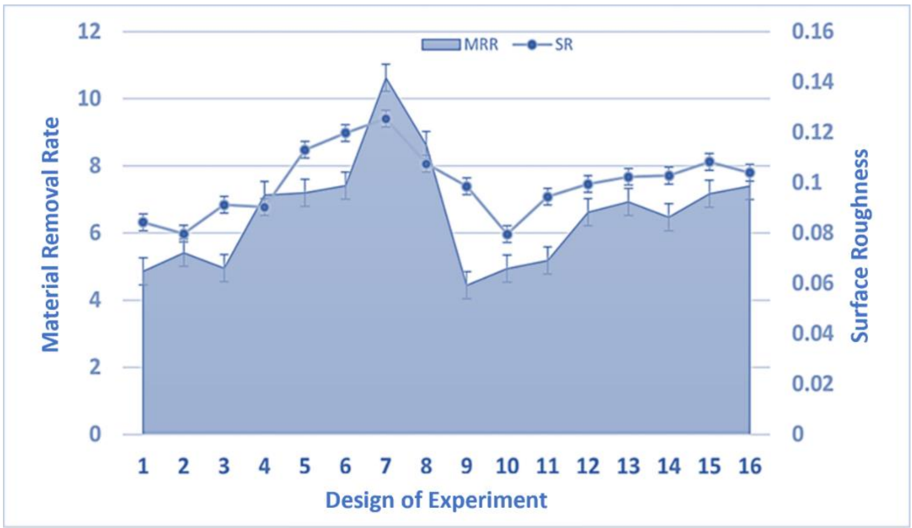

Fig.4 Specimen after machining at EDM

that parameter optimization is needed to realize an optimal combination of machining efficiency and surface integrity during machining Inconel 725 by using EDM [28–30].

Experimental analysis of EDM parameters for Inconel 725

The experimental research aimed at optimization of EDM parameters of Inconel 725 with the help of Taguchi L16 Orthogonal Array (OA). The performance of machining was compared in terms of material removal rate (*MRR*) and surface roughness (*SR*) with the main input variables being electrode shape, peak current, pulse-on time and pulse-off time. The results obtained (Table 2) were processed to establish the effect of each parameter.

Influence of peak current on MRR and surface roughness

The rate of removal of material per current (*MRR*) was higher with higher current (12 as compared to 8 A). An example is that at 8 A, *MRR* was between 0.0593 and 0.095 mm^3/min whereas at 12 A, the rate was maximum (0.1417 mm^3/min). This can be attributed to the fact that the discharge energy increases with increase in current thereby increasing material erosion. Nonetheless, as current was increased, surface roughness (*SR*) also increased with more deeply cratered and more deposition of molten material. *SR* was 5.965 to 7.454 μm at 8 A, and 9.407 μm at 12 A. Excessive thermal damage was due to the increased energy input, which resulted in a rough surface finish [31].

Effect of pulse-on and pulse-off time

Pulse-on time was very important in affecting *MRR*. At 200 μs pulse-on time, *MRR* was greater than when pulse-on time was 100 μm. Case: *MRR* at R1 electrode of 12 A was 0.0959 mm^3/min (100 μs) and then 0.1417 mm^3/min (200 μs). The longer the pulse-on the more energy will be transferred and thus the material removed will be more. The reason behind a higher MRR was a shorter pulse-off time (1.2 μs) than a pulse-off time of 1.6 μs since short pulse-off time implies more discharges/second, and thus, continuous erosion of the material occurred. Example: *MRR* at 12 A and 200 μs was 0.0956 mm^3/min (1.2 μs pulse-off) vs. 0.0987 mm^3/min (1.6 μs pulse-off) with S1 electrode [32].

Influence of electrode shape (round vs. square)

Round (R1) and square (S1) electrodes did not have equal machining efficiencies. Round electrodes recorded higher *MRR* in the majority of applications, perhaps because they have a higher distribution of spark, as well as uniform wear. Available data: using the round electrode (R1) at 12 A, 200 μs, 1.2 μs pulse-off, the electrode attained 0.1417 mm^3/min, whereas the square electrode (S1) had 0.0956 mm^3/min at the same conditions. In the majority of cases, surface roughness was reduced under square electrodes [33–35]. Sample: *SR* = 5.965 μm and *SR* = 5.977 μm were obtained with square and round electrodes, respectively, at 8 A, 100 μs, 1.6 μs pulse-off.

Conclusions

1. Material removal rate with an increase in peak current by 8 to 12 A was significantly enhanced. The highest *MRR* of 0.1417 mm^3/min was achieved with 12 A current, 200 μs pulse-on time and 1.2 μs pulse-off time using the round electrode (R1).
2. The longer pulse-on time augmented spark energy and *MRR*. To illustrate, at 12 A upsurge in pulse-on time, 100 to 200 μs, caused a 47.77 percent augmentation in *MRR* of 0.0959 to 0.1417 mm^3/min. spark duration plays a vital role in the removal of materials.
3. Fewer pulse-off (1.2 μs) reduced spark discharges and enhanced MRR. At pulse-on of S1, 12 A, 200 μs, *MRR* was 0.0956 mm^3/min at 1.2 μs, a little smaller than 0.0987 at 1.6 μs. Smaller pulse-off times resulted in better erosion since the idle time was minimized.
4. Experiments were all conducted with better MRR with the round electrode (R1). Under the same conditions (12 A, 200 μs, 1.2 μs), R1 showed the most highest *MRR* (0.1417 mm^3/min) in comparison with the one of S1 (0.0956 mm^3/min). This may be due to reduced tool wear and homogeneity of spark in round electrodes.
5. Most studies have found that the square electrode (S1) was of better quality in terms of surface. Short pulse-on of 8 A, pulse-off of 100 μs and pulse-on of 1.6 us, S1 was able to achieve a surface roughness of 5.965 μm, a little more improved than the 5.977 μm of R1, which showed that S1 has advantages in surface quality.
6. Optimal conditions of maximal MRR uses are: round electrode (R1), 12 A current, 200 μs pulse-on time, and 1.2 μs pulse-off time. In order to enhance surface polish, apply square electrode (S1), 8 A current, 100 μs pulse-on time, and 1.6 μs pulse-off time, as result will be *SR* = 5.965 μm.

CRediT authorship contribution statement

Himanshu: conceptualization, writing – review & editing, writing – original draft; **Ravish Arora:** supervision**,** review & editing; **Kushdeep**: data curation, writing – review & editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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