Parametric Optimization of EN-31 Steel Using Electric Discharge Machining

Optimización paramétrica del acero EN-31 mediante mecanizado por descarga eléctrica

Otimização paramétrica do aço EN-31 utilizando usinagem por eletroerosão

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Summary. - This investigative study was conducted for the parametric optimization of EN-31 material by using a non-conventional machining known as Electric discharge machining (EDM). EN-31 is a steel alloy that is generally used in aerospace industry, automotive parts manufacturing, die making etc. because it possesses high degree of rigidity with extremely good compressive strength and resistance to abrasion. The primary objective of this study was to analyze the impact of four input factors i.e. pulse on time (Ton), pulse off time (Toff), current (LV), voltage (HV) on the five output responses i.e. machining time (Tm), MRR, EWR, Ra and base radius (R). In this study design of experiment (DOE) approach with full factorial design was systematically conducted. Basic experimental runs were prepared and performed and after that data was analyzed using ANOVA to identify significant input factors that has most impact on each output response that are mentioned above. After identification of significant factors optimized input factors and output responses were calculated using ANOVA. The results showed that for machining time (Tm), LV and Ton were significant factors with optimized values of 50 A and 6.5 µs, respectively, resulting in a Tm of 654.29 seconds. For material removal rate (MRR), Ton was the significant factor with an optimized value of 6.5 µs, achieving a maximum MRR of 0.0157 g/min. For electrode wear rate (EWR), LV and Ton were significant with optimized values of 30 A and 4 µs, respectively, resulting in a minimum EWR of 0.07 g/min. Ra optimization revealed that the combination of HV, LV, Ton and Toff were significant, with optimized settings of 50 A, 0.7 V, 4.0 µs and 6.5 µs, respectively, yielding a minimum Ra of 0.018 mm. For base radius (R), the significant factors were HV, LV, Ton and Toff, with optimized values of 0.6152 V, 50 A, 6.5 µs and 6.5 µs, respectively, resulting in a base radius of 1.5 mm. This parametric optimization is extremely significant because EN-31 is a material used in critical applications requiring high strength, hardness and abrasion resistance such as automobile engine components, aerospace rocket parts and dies subjected to extreme temperatures and pressures throughout their lifecycle. Optimizing EDM parameters facilitates the use of this non-conventional machining process for manufacturing EN-31 parts thus enabling researchers, manufacturers, designers and industry practitioners to achieve higher productivity, excellent surface finishes and lower manufacturing costs as compared to traditional manufacturing techniques. This optimization allows for more efficient and effective production of high-performance parts thus making it an invaluable advancement in various industrial sectors.

Keywords: *EDM; Parameters; Machining; Processing; Roughness, EN-31; Optimization; DOE.*

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Resumen. - *Este estudio de investigación se realizó para la optimización paramétrica del material EN-31 utilizando un mecanizado no convencional conocido como mecanizado por descarga eléctrica (EDM). El EN-31 es una aleación de acero que se utiliza generalmente en la industria aeroespacial, la fabricación de piezas de automóviles, la fabricación de matrices, etc., debido a que posee un alto grado de rigidez con una resistencia a la compresión y a la abrasión extremadamente buenas. El objetivo principal de este estudio fue analizar el impacto de cuatro factores de entrada, a saber, tiempo de pulso encendido (Ton), tiempo de pulso apagado (Toff), corriente (LV) y voltaje (HV) en las cinco respuestas de salida, a saber, tiempo de mecanizado (Tm), MRR, EWR, Ra y radio base (R). En este estudio se llevó a cabo sistemáticamente un enfoque de diseño de experimentos (DOE) con un diseño factorial completo. Se prepararon y realizaron ensayos experimentales básicos y luego se analizaron los datos utilizando ANOVA para identificar los factores de entrada significativos que tienen el mayor impacto en cada respuesta de salida mencionada anteriormente. Después de la identificación de los factores significativos, los factores de entrada optimizados y las respuestas de salida se calcularon utilizando ANOVA. Los resultados mostraron que para el tiempo de mecanizado (Tm), LV y Ton fueron factores significativos con valores optimizados de 50 A y 6,5 µs, respectivamente, lo que resultó en un Tm de 654,29 segundos. Para la tasa de remoción de material (MRR), Ton fue el factor significativo con un valor optimizado de 6,5 µs, logrando un MRR máximo de 0,0157 g/min. Para la tasa de desgaste del electrodo (EWR), LV y Ton fueron significativos con valores optimizados de 30 A y 4 µs, respectivamente, lo que resultó en un EWR mínimo de 0,07 g/min. La optimización de Ra reveló que la combinación de HV, LV, Ton y Toff fueron significativas, con configuraciones optimizadas de 50 A, 0,7 V, 4,0 µs y 6,5 µs, respectivamente, lo que produjo un Ra mínimo de 0,018 mm. Para el radio base (R), los factores significativos fueron HV, LV, Ton y Toff, con valores optimizados de 0,6152 V, 50 A, 6,5 µs y 6,5 µs, respectivamente, lo que resultó en un radio base de 1,5 mm.*

Palabras clave: *EDM; Parámetros; Mecanizado; Procesamiento; Rugosidad; EN-31; Optimización; DOE.*

Resumo. **-** *Este estudo investigativo foi conduzido para a otimização paramétrica do material EN-31 utilizando uma usinagem não convencional conhecida como eletroerosão (EDM). O EN-31 é uma liga de aço geralmente utilizada nas indústrias aeroespacial, de autopeças, de matrizes, etc., devido à sua alta rigidez, excelente resistência à compressão e à abrasão. O objetivo principal deste estudo foi analisar o impacto de quatro fatores de entrada, ou seja, tempo de pulso ligado (Ton), tempo de pulso desligado (Toff), corrente (LV) e tensão (HV), sobre as cinco respostas de saída, ou seja, tempo de usinagem (Tm), taxa de remoção de material (MRR), taxa de desgaste da ferramenta (EWR), rugosidade superficial (Ra) e raio da base (R). Neste estudo, foi aplicada uma abordagem de planejamento de experimentos (DOE) com planejamento fatorial completo. Ensaios experimentais básicos foram preparados e realizados, e os dados foram analisados por meio de ANOVA para identificar os fatores de entrada significativos que mais impactam cada resposta de saída mencionada. Após a identificação dos fatores significativos, os fatores de entrada otimizados e as respostas de saída foram calculados utilizando ANOVA. Os resultados mostraram que, para o tempo de usinagem (Tm), a tensão de limiar (LV) e a taxa de variação da corrente (Ton) foram fatores significativos, com valores otimizados de 50 A e 6,5 µs, respectivamente, resultando em um Tm de 654,29 segundos. Para a taxa de remoção de material (MRR), a Ton foi o fator significativo, com um valor otimizado de 6,5 µs, atingindo uma MRR máxima de 0,0157 g/min. Para a taxa de desgaste do eletrodo (EWR), a LV e a Ton foram significativas, com valores otimizados de 30 A e 4 µs, respectivamente, resultando em uma EWR mínima de 0,07 g/min. A otimização da rugosidade média (Ra) revelou que a combinação de alta tensão (HV), LV, Ton e Toff foi significativa, com configurações otimizadas de 50 A, 0,7 V, 4,0 µs e 6,5 µs, respectivamente, resultando em uma Ra mínima de 0,018 mm. Para o raio da base (R), os fatores significativos foram HV, LV, Ton e Toff, com valores otimizados de 0,6152 V, 50 A, 6,5 µs e 6,5 µs, respectivamente, resultando em um raio da base de 1,5 mm.*

Palavras-chave: *EDM; Parâmetros; Usinagem; Processamento; Rugosidade; EN-31; Otimização; CORÇA.*

1. Introduction. - Machining processes have progressed significantly over time [1]. The reason of this progression is actually driven by the growing demand of industry to use parts and components that have excellent precision and accuracy as per the designed component, must be produced by using efficiency manufacturing techniques because of mass manufacturing demands of industry and cost reduction and manufacturing techniques' capacity to work with a wide range of materials while maintaining the excellent surface finish [2] [3]. Traditional machining techniques such as turning, milling and drilling have been used in manufacturing industry from many centuries [4] [5]. These conventional manufacturing techniques are the foundation of manufacturing sectors. These techniques have limitations especially when dealing with exceptionally hard or brittle materials, during manufacturing of complicated geometries and where tight tolerances are required especially in manufacturing of automotive parts or during die making [6] [7]. In order to address these issues researchers started working on non-traditional machining technologies and amongst those techniques Electric Discharge Machining (EDM) [8] became the most popular one.

In a list of non-traditional techniques, EDM [9] achieves great accuracy while producing the materials that are difficult to shape [10]. It works by removing material from a part by producing electrical discharges in repetitive pattern. These pulses are generated at short intervals between two electrodes i.e., electrode and a workpiece [11]. A dielectric fluid separates the electrodes, allowing eroded particles to be flushed out of the gap between them. These successive electric sparks raise the temperature of workpiece and the tool's surface above their melting or boiling temperatures [12]. Thus, material is scraped off in the form liquid and vapor phases and the surface that are formed consist of debris melted or vaporized during machining [13] [14]. During this whole process tool does not physically contact the workpiece and because of these mechanical properties of material are unaffected during this whole non-conventional machining operation. Thermal and electrical properties have a significant impact on the EDM [15] process performance [16] [17] [18].

EN-31 is a steel alloy that is made up of high concentration of carbon and is composed up of carbon (between 1.0% and 1.2%), (0.30% to 0.75%), chromium (1.0% to 1.6%) and silicon (0.10% to 0.35%) and all of these contribute to its excellent performance qualities in high wear environment [19]. EN-31 is extremely hard material with excellent strength and addition of chromium increases the corrosion resistance making it a preferred material to be used in harsh conditions specially in the components which are subjected to severe abrasion, wear and high surface loading on periodic basis. These properties like its ability to retain high tensile strength and durability following heat treatment makes it a preferred material to be used in the parts made for automotive, aerospace and manufacturing industries because component reliability and longevity are of extreme importance in these industries and single components failure can cause unbearable amount of damage [20]. Understanding the qualities and applications of EN-31 can provide substantial insights into its role in enhancing engineering processes and boosting performance and longevity [21].

EN-31 is the carbon steel alloy that is known for its hardness, strength and its wear resistance properties and this makes it a nightmare for researchers and manufacturers to use traditional machining techniques as the high hardness causes rapid tool wear and cutting forces are extremely high leading to poor surface finish and low material removal rates [22] [23]. Researchers and manufacturers are developing EDM at brisk pace but still considerable research gap is there in machining EN-31 [24]. Most of the researchers optimize one or two output responses at one time during the experiment but in EDM it is a trade off in which optimizing one parameter impacts the other parameter negatively [25]. For example, increasing the current leads to high rate of material removal from workpiece usually but it results in a rougher surface finish (Ra) and higher electrode wear rate (EWR) and this results in reduced dimensional accuracy and base radius of the part that is being machined. Similarly, in order to increase surface quality by varying Ton time and Toff time frequently result in longer machining times and lower MRR leading to loss in productivity. There is a no data related to EDM optimization of EN-31 material is available in which all output responses mentioned previously were optimized at the same time. Addressing this gap is of extreme importance in order to use EDM for mass manufacturing of parts and for industries like automotive, aerospace, die making etc. in which parts quality and properties are of extreme importance.

This study has important practical implications in wider range of industries including automotive and aerospace industries where EN-31 steel is widely utilized for its high strength, wear resistance and exceptional mechanical qualities [26] . Precision machining of EN-31 is critical in aerospace applications for making highly stressed components like landing gears and turbine shafts. In the automobile industry, EN-31 is utilized for transmission gear, engine parts and in bearings where dimensional accuracy is of extreme importance along with excellent surface finish as these are critical for performance and longevity. By developing an optimized EDM processing strategy, this study enables manufacturers to achieve higher productivity, lower electrode wear, improved surface quality and lower manufacturing costs, making EDM a more viable and efficient method for machining EN-31 steel than traditional techniques.

The main target of this research study is to improve the process parameters of electric discharge machining (EDM) for EN-31 high-carbon steel in such a way the optimized input parameter produces the best output response resulting in excellent quality of final product. This research attempts to optimize Tm, EWR, MRR (Material removal rate), Ra & R by varying the input parameters like Ton time, Toff time, Current & Voltage all at once. All of the iterative experiments were done by using DOE and then factorial screening for optimizing Tm, MRR, EWR (Electrode wear rate), Ra and R.

Significance of this research work lies in optimizing all the output responses at once without any trade off on any of the outputs. This research study will help industry practitioners in optimizing efficiency and productivity of their manufacturing setup by increasing the product quality, reducing production time and increasing the productivity of the machinery reducing the manufacturing cost of the product and increasing the profit margins. This research and experimental work were performed in a very controlled environment where settings of all input parameters were comparatively on low scale and still encouraging results were observed.

2. Methodology and Materials. - EN-31 high-carbon steel was chosen for parametric optimization was because of its industrial usage on such a large scale and the challenges manufacturers face during the production of the parts made up of EN-31. It is well-known that EN-31 exhibit excellent properties specifically harness and has very high degree of wear resistance and tensile strength. It is also widely being used in the production of key components such as bearings, gears, automotive engine parts, bio medical equipment manufacturing and die making where durability and precision are of extreme importance. These qualities make EN-31 extremely beneficial but on the other hand make it extremely difficult for manufacturers to process it using conventional machining methods thus resulting in swift tool wear, poor surface finishes, high machining times and low material removal rates. Optimizing parameters of electric discharge machining (EDM) for EN-31 can increase efficiency of machining, tool life and surface quality (by reducing surface roughness) thus resolving the constraints of EN-31 machining via conventional machining processes. Composition EN-31 [27] is mentioned in Table 1.

Element	Percentage (%)
C - Carbon	0.96 – 1.11
Mn - Manganese	0.39 – 0.69
Cr - Chromium	1.21 – 1.61
Si - Silicon	0.10 – 0.35
S - Sulphur	0.05 max.
P - Phosphorous	0.04 max.
Fe - Iron	Balance

Table 1. - Chemical composition - EN-31 steel.

For this parametric optimization study of EN-31, copper (Cu) was chosen as the electrode material. Cu was chosen as electrode material because of excellent electrical and thermal conductive properties and these are basic requirement for efficient working of electric discharge machining (EDM) process. It is evident from research that copper has a higher electrical conductivity and this leads to stable spark generation [28]. This results in higher MRR and superior surface finish quality as compared to other electrodes like zinc, brass, graphite etc. Furthermore, when graphite electrode was used higher tool wear was observed along with poor surface finishing of the part being produced [29]. Copper has better wear resistance and electrode wear rate is comparatively less as compared to other materials such as graphite. As a result of this frequency of electrode replacements during manufacturing of part produced via EDM reduces. There are other materials available as well like tungsten, copper alloys etc. with properties that are suitable for EDM manufacturing process but they are quite expensive and economically not viable. Because of these reasons copper was chosen for this optimization study of EN-31.

In this study, two EN-31 blocks, each measuring 100 × 10 × 20 mm, were used and secured together. The electrodes were produced with a step-turned geometry, combining a flat circular tip of 3 mm diameter.

For the EDM process, a Gen Spark EDM (Model - E5B1041) machine was employed to drill 5.5 mm deep holes into the EN-31 workpiece. The machine automatically logged the Tm for each test run after the program was uploaded to the system through the control panel. A CONTOURMATIC T2 surface roughness tester was used to measure surface roughness. The components were weighed using a precision balance (Scitex BAE3123HTP) in order to compute MRR and EWR. A stereo microscope with 23× magnification was used to inspect the workpiece, while the electrode wear and material removal patterns were analyzed under 18× magnification. The base radius (R) was measured using a stereo microscope/image analysis system. The radius was defined as the curvature at the machined cavity base and geometric fitting determined from captured images. Multiple measurements were taken to ensure repeatability, and the average value was reported to minimize measurement uncertainty.

A precise digital balance with defined resolution (e.g., ±0.001 g) was used to determine MRR and EWR. Before weighing, the workpiece and electrode surfaces were washed with a suitable solvent to eliminate dielectric residue, debris, and impurities, and then properly dried under regulated conditions. To avoid measurement mistakes caused by moisture or surface deposits, proper handling procedures were followed.

Surface roughness was determined using a calibrated surface roughness tester with a predetermined cutoff length (e.g., 0.8 mm) and evaluation length (e.g., 4 mm). Multiple traces (at least three) were collected at various sites, with the average value presented. Measurements were taken perpendicular to the machining direction to capture the actual surface imperfections. Prior to testing, the instrument was calibrated using a standard reference specimen.

EWR was calculated using the equation [30] stated below in Equation 1:

$$EWR = \frac{Eb - Ea}{Tm}\ (g/\mathrm{min})$$

MRR was calculated using the equation [31] and is stated below in Equation 2:

$$MRR = \frac{Wb - Wa}{Tm}\ (g/\mathrm{min})$$

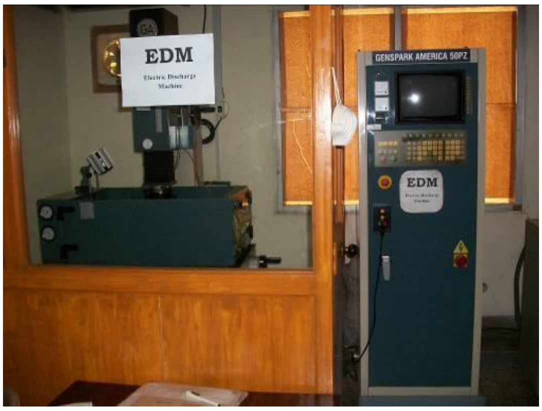

Figure I. GENSPARK EDM Machine used for EN-31 steel.

To confirm the effect of input factors on output responses, the experiments were designed using a DOE technique. This method involves investigating combinations of the input parameters at various levels (low and high). In this study four input parameters i.e., Ton, Toff, LV and HV were evaluated at two distinct levels. This binary factor level arrangement provides for a thorough examination of the key effects and interactions between the input and output parameters.

The total number of experimental runs needed is 24 = 16 runs with four input parameters, each of which has two levels. Table 2 lists the level of input parameters, and Table 3 Table lists the fundamental experimental runs.

Factor	Unit	Levels	No. of Levels
Workpiece	-	EN-31	1
T_{on}	µs	4, 6.5	2
T_{off}	µs	5.5, 6.5	2
HV	V	30, 50	2
LV	A	0.3, 0.7	2

Table II. Input parameters level and units.

Factor	Unit	Levels	No. of Levels
Workpiece	-	EN-31	1
T_{on}	µs	4, 6.5	2
T_{off}	µs	5.5, 6.5	2
HV	V	30, 50	2
LV	A	0.3, 0.7	2

Table III. Table of basic experimental runs values.

In order to develop prediction models that explain the links between the input parameters, Ton, Toff, LV, and HV, and the output responses, Tm, MRR, EWR, Ra, and "R," regression analysis was carried out using Minitab following the completion of basic experimental runs. These regression models show how changes in input parameters affect output responses, resulting in a quantitative foundation for predicting outcomes across varied situations. The models helped to detect trends and patterns in the data, allowing for a better understanding of the major elements impacting the EDM process and helping the development of strategies to improve machining performance.

Analysis of variance (ANOVA) was then used to determine the important input parameters for each output answer. An ANOVA was performed using Minitab software to ascertain the input parameters' statistical significance. The purpose of this study was to determine which parameters significantly affected the EDM process and to measure the magnitude of their influence on output responses. ANOVA separated the total variation in the data into components assigned to various sources, revealing the relative significance of each input parameter and their interactions.

Following are the objectives of this experimental study.

- To reduce the Tm of EN-31 steel by using EDM
- To increase the MRR of EN-31 steel by using EDM
- To reduce the EWR of EN-31 steel by using EDM
- To improve the Ra of EN-31 steel by using EDM
- To minimize the variation in R of EN-31 steel by using EDM

3. ANOVA Analysis. - An ANOVA was performed using Minitab software to ascertain the input parameters' statistical significance. The purpose of this study was to determine which parameters significantly affected the EDM process and to measure the magnitude of their influence on output responses. ANOVA separated the total variation in the data into components assigned to various sources, revealing the relative significance of each input parameter and their interactions.

The model is then adjusted by eliminating the insignificant factors and a revised ANOVA table is created to highlight the most significant ones. The standardized effects normal plot and residual plots for the variable's response are generated again. Additionally, Main effect and interaction plots are generated and analyzed. Significant interactions are shown by non-parallel lines between levels in the interaction plot, whereas a steep slope in the main effect plot indicates the significance of the effect.

The Response Optimizer program generates practical solutions. A specified aim (Minimize, Equate, or Maximize) is selected and lower, target and upper values are entered to examine the desirability function. A 'd' value close to one indicates that the response is close to the target value supplied. The results of this exercise comprise the optimum value of the considered factor, the optimized response value and the desirability factor.

4. Results and discussion. - ANOVA is a statistical method used to identify the important input variables that significantly affect each of the five output answers listed in the preceding section. It doesn’t only identify the significant parameters but also the combined effect of different input parameters on output responses. By using ANOVA, this investigative study ensures that study is accurate.

4.1 Machining time (Tm) ANOVA results. - Minitab software was used to construct the ANOVA table for Tm in Table 7. As input factors, ton, toff, LV, and HV were taken into consideration. Significant factors were those with a p-value of less than 0.05. The goal is to shorten the EN-31 material's machining time in order to produce more units per hour (UPH). LV and Ton are important parameters when taking Tm into account for EN-31, according to the ANOVA table in Table 7 and the Normal Probability Plot in Figure 4. After that, the model was rebuilt using only LV and Ton as input variables and excluding non-significant input parameters.

Main effect plots (Figure 5) and interaction plots (Figure 6) were created following the identification of relevant factors. The main effect plot's steep mean slopes support the idea that LV and Ton have a major influence on Tm optimization in EN-31. Calculating the optimal values of the important input factors was the following stage. The upper number was set to 427 seconds, which indicated the quickest machining time, and the target value was set to 0 seconds in order to optimize machining time. After evaluating the desirability functions (Figure 7), a desirability value (d) of 0 indicates that the answer is far from the target, indicating that the target value is less significant. A desirability value of 1 might have been attained if the goal had been set closer to 600 with a value greater than 2000.

The optimal values of input parameters were LV = 50 A & Ton = 6.5 µs as specified in Appendix 1. For these adjusted input parameters, the minimum Tm was calculated to be 654.29 seconds.

The results in Appendix 1 (Table 6) shows that higher the values of LV and Ton, shorter will be machining times (Tm) and vice versa. This means that inverse relationship exists between LV & Ton with machining time. The experimental runs as mentioned in table 4 in Appendix 1 also shows an inverse relationship between LV and Ton in with Tm. As we know that greater the LV and Ton time values result in large depressions/craters on the workpiece and these large craters results in poor surface finish (Ra) and poor surface finish leads to the final product which is not fit for use especially in the fields of bio implant manufacturing, automotive parts manufacturing etc. where good surface finish is of extreme importance. That why parametric optimization of all the output responses of EN-31 in EDM is necessary to have a product that meets the customer and manufacturer demands.

4.2 MRR ANOVA results. - The ANOVA (Table 11) for MRR was created in Minitab. All four input variables were taken in to account while performing the analysis. Ton is a significant factor in MRR in EN-31, according to the ANOVA table (Table 11) and the Normal Probability Plot (Figure 9). Following that, non-significant components were eliminated from the model (Table 10), leaving only Ton as an input factor.

Main effect Plot (Figure 13) and Interaction Plot (Figure 14) were prepared for MRR after the determination of significant factors. The Main effect Plot shows that Ton is a significant factor whereas the Interaction Plot shows that Ton and LV are significant factors as LV p-value is 0.055 which makes it quite close to be a significant factor. Now the optimized value of significant factors is calculated. MRR was optimized with a goal value of 1 g/min and a lower value of 0.0267 g/min, indicating the highest observed value of MRR. The desirability functions (Figure 15) were then assessed. A desirability value (d) of 0 shows that the response is distant from the target, meaning that the target value is not as important. If the objective had been set closer to 0.015 with a lower value less than 0.014, a desirability value near to 1 may have been obtained.

The optimized value for Ton was found to be 6.5 µs, as detailed in Appendix 1. For this optimized setting, the maximum MRR was calculated to be 0.0157 g/min.

The results in Appendix 2 show that greater values of Ton result in higher material removal rates (MRR). This means that direct relationship exists between Ton vs MRR in EN-31 material. The experimental runs also show a direct relationship between Ton and MRR. However, Ton optimization must be matched with other input factors in order to achieve an good surface quality (Ra) and overall machining performance. Therefore, in order to provide the best possible final product, the parametric optimization of the EDM process aimed to balance all output reactions.

4.3 EWR ANOVA results. - Minitab was used to create the EWR ANOVA table (Table 12). Ton, Toff, LV, and HV are all considered as input elements. LV and Ton are important factors affecting EWR in EN-31, according to the ANOVA table (Table 12) and the Normal Probability Plot (Figure 16). Consequently, non-significant factors were eliminated from the model (Table 13), leaving only LV and Ton as input variables. The importance of these factors and the model itself was confirmed by the p-values from the modified model's ANOVA table (Table 13).

Following the identification of important components, EWR's main effect plot (Figure 19) and interaction plot (Figure 20) were created. Steep mean slopes in the Main Effect Plot show how LV and Ton have a major influence on EWR in EN-31. Strong interaction effects between different parameters are displayed in the interaction plot. Finding the ideal values for the pertinent input factors was the following stage. EWR was optimized by setting the upper value to 0.00523 g/min, the lowest measured EWR, and the target value to 0 g/min. The desirability functions (Figure 20) were then assessed. A desirability value (d) of 0 shows that the response is far from the target, meaning that the target value is not as important. If the objective had been set closer to 0.015 with a lower value less than 0.014, a desirability value near to 1 may have been obtained. The optimized values were found to be 30 A for LV and 4 µs for Ton, as detailed in Appendix 1. For these optimized settings, the minimum EWR was calculated to be 0.07 g/min.

The findings in Appendix 2 demonstrate a direct proportionality between the LV and Ton levels with EWR. EWR values increase with increased LV and Ton, and vice versa. Additionally, the experimental runs showed a direct proportionality between EWR and LV and Ton. Optimizing these input parameters is crucial to achieving a proper surface finish (Ra), improved productivity, and overall machining performance because lower LV and Ton values will result in lower MRR and higher Tm. Therefore, in order to provide the best possible final product, the parametric optimization of the EDM process aimed to balance all output reactions.

4.4 Surface finish (Ra) ANOVA results. - The ANOVA table (Table 13) for Ra was created in Minitab. All input factors (Ton, Toff, LV, HV) were considered. The ANOVA table (Table 13) and the Normal Probability Plot (Figure 23showed that there are no significant factors influencing Ra in EN-31. As a result, there was no need to retrofit the model. However, the Main effect Plot (Figure 25) and Interaction Plot (Figure 26were still generated for Ra. The Interaction Plot shows non-parallel lines, showing that the parameters interact significantly.

The optimal values for the significant factors were then calculated. Ra was optimized with a goal value of 0 mm and an upper value of 0.006 mm, which represented the minimum observed surface roughness. The desirability functions (Figure 27) were then assessed. A desirability value (d) of 0 shows that the response is distant from the target, meaning

that the target value is not as important. Had the target been set closer to 0.009 with an upper value greater than 0.015, a desirability value close to 1 could have been achieved.
The optimized values of Ra for EN-31 were found to be LV = 50 A & HV = 0.7 V, Ton = 4.0 µs and Toff = 6.5 µs as shown in Appendix 1. For these optimized settings, the minimum Ra was calculated to be 0.018 mm.

4.5 Base radius (R) ANOVA results. - The ANOVA table (Table 14) for 'R' was created in Minitab, considering all input variables. The ANOVA table (Table 14) and the Normal Probability Plot (Figure 28) showed that the interactions HV*LV*Ton and HV*LV*Ton*Toff are significant factors for R in EN-31. As a result, the model was refined (Table 15) by eliminating non-significant in, leaving only HV*LV*Ton and HV*LV*Ton*Toff as input variables. The p-values from the updated model's ANOVA table (Table 15) supported the significance of these interactions and the model as a whole.

After identifying significant factors, the Main effect Plot (Figure 32) and the Interaction Plot (Figure 33) were created for R. The Main effect Plot displays steep slopes of means, indicating the significance of the interactions, while the Interaction Plot displays non-parallel lines, indicating significant interaction effects between these variables. After that optimum value of input factors were calculated that were considered significant. To optimize R, the target value was set to 1.5 mm, with maximum and lower boundaries of 1.55 mm and 1.45 mm, respectively. The desirability functions (Figure 34) were then assessed. A desirability value (d) near to one shows a strong preference for the target value, implying that the response closely matches the desired target. The optimized values were found to be HV = 0.6152 V, LV = 50 A, Ton = 6.5 µs and Toff = 6.5 µs as shown in detail in Appendix 1. For these optimized settings, the base radius R was calculated to be 1.5 mm.

The results in Appendix 1 demonstrate that optimizing these parameters must be balanced with other factors to ensure a desirable overall machining performance. Therefore, the parametric optimization of the EDM process aimed to balance all output responses to achieve an optimal final product.

5. Conclusion. - This study focused on optimizing processing parameters in Electric Discharge Machining (EDM) for EN-31 steel by systematically analyzing their impact on key machining responses. The investigation aimed to minimize Tm, maximize MRR, reduce EWR, enhance Ra and control 'R'. A full factorial experimental approach, combined with regression analysis and ANOVA, was used to identify and optimize the most significant parameters, namely Ton, Toff, LV and HV.

The observed results are governed by electro-thermal interactions occurring in EDM. The primary mechanism involves localized melting and vaporization of the workpiece material due to high-energy electrical discharges between the electrode and the workpiece. The MRR is directly proportional to the Ton since longer discharge durations allow greater heat input, leading to higher melting and vaporization rates. Similarly, a higher discharge LV increases spark energy, which enhances material removal but also contributes to greater electrode wear (EWR).

The optimization results show that higher LV (50 A) and Ton (6.5 µs) significantly reduced Tm to 654.29 seconds by accelerating material removal. However, increasing these parameters beyond optimal levels resulted in excessive energy input, leading to large craters, poor surface finish (Ra) and undesired tool wear. This highlights the need for a balanced parameter selection, as excessively high current can degrade dimensional accuracy due to excessive thermal damage.

For EWR, a lower LV (30 A) and shorter Ton (4 µs) minimized electrode erosion (0.07 g/min), which is crucial for extending tool life. This occurs because lower discharge energy reduces thermal stress on the electrode, thereby slowing down the material erosion rate.

Ra is influenced by a complex interplay of spark intensity and pulse durations. The study found that an optimal combination of LV (50 A), HV (0.7 V), Ton (4.0 µs) and Toff (6.5 µs) minimized Ra to 0.018 mm. Mechanistically, this is because shorter pulse durations prevent excessive heat accumulation, reducing crater depth and ensuring a smoother surface. Additionally, higher HV improves ionization, stabilizing the plasma channel and leading to more uniform material removal.

'R' was found to be highly dependent on interaction effects among HV, LV, Ton and Toff. A precise combination of HV (0.6152 V), LV (50 A), Ton (6.5 µs) and Toff (6.5 µs) ensured controlled energy distribution, leading to accurate base radius formation (1.5 mm). This confirms that high-energy discharges must be regulated to maintain dimensional accuracy while achieving efficient material removal.

The findings of this study offer industrial significance by providing an optimized EDM processing strategy for EN-31 steel, which is widely used in automotive, aerospace and die-making applications. The optimized settings enable faster production, improved surface quality, reduced tool wear and cost savings, making EDM a more viable manufacturing technique for high-hardness materials.

In conclusion, this study not only advances knowledge on EDM process optimization for EN-31 steel, but also provides a scientific basis for balancing machining efficiency and quality through electro-thermal parameter control. Future research may further refine these findings by exploring adaptive control strategies and hybrid EDM processes for enhanced precision and sustainability in machining operations.

Conflict of interest

The authors confirm that there are no conflicts of interest related to this research. They have disclosed all relevant affiliations and financial relationships.

References

[1] Tajdeen, A.; Khan, M. W.; Basha, K. K.; Sakthivelmurugan, E.; Koppula, N. Experimental Investigation and Optimization of EDM Process Parameters on EN31 Steel Using Genetic Algorithm. Mater. Today Proc. 2022, 64 (1), 821–827. https://doi.org/10.1016/j.matpr.2022.05.326.

[2] Sahu, A. K.; Sivarajan, S.; Padmanabhan, R. Optimization of Machining Parameters in Turning of EN31 Steel with TiAlN Coated Cutting Tool. Mater. Today Proc. 2021, 46 (17), 7497–7501. https://doi.org/10.1016/j.matpr.2021.01.180.

[3] Kamenskikh, A. A.; Muratov, K. R.; Shlykov, E. S.; Sidhu, S. S.; Mahajan, A.; Kuznetsova, Y. S.; Ablyaz, T. R. Recent Trends and Developments in the Electrical Discharge Machining Industry: A Review. J. Manuf. Mater. Process. 2023, 7 (6). https://doi.org/10.3390/jmmp7060204.

[4] Behera, A.; Sahoo, A. K.; Mahapatra, S. S. Experimental Investigation of Plain and Nano-Graphene Oxide Mixed Dielectric for Sustainable EDM of Nimonic Alloy Using Cu and Brass Electrode: A Comparative Study. Measurement 2025, 241. https://doi.org/10.1016/j.measurement.2024.115659.

[5] Harish, B.; Kumar, D. S. A Novel Statistical Investigation on Tensile Property of High Alloy Steel (EN31) and Carbon Steel (EN09). Mater. Today Proc. 2023, 79 (1), 49–52. https://doi.org/10.1016/j.matpr.2022.08.286.

[6] Langenberg, B.; Janczyk, M.; Koob, V.; Kliegl, R.; Mayer, A. A Tutorial on Using the Paired t Test for Power Calculations in Repeated Measures ANOVA with Interactions. Behav. Res. Methods 2023, 55, 2467–2484. https://doi.org/10.3758/s13428-022-01902-8.

[7] Samantra, C.; Barua, A.; Pradhan, S.; Kumari, K.; Pallavi, P. Parametric Investigation of Die-Sinking EDM of Ti6Al4V Using the Hybrid Taguchi-RAMS-RATMI Method. Appl. Sci. 2024, 14 (16). https://doi.org/10.3390/app14167139.

[8] Garba, E.; Abdul-Rani, A. M.; Yunus, N. A.; Aliyu, A. A. A.; Gul, I. A.; Al-Amin, M.; Aliyu, R. A Review of Electrode Manufacturing Methods for Electrical Discharge Machining: Current Status and Future Perspectives for Surface Alloying. Machines 2023, 11. https://doi.org/10.3390/machines11090906.

[9] Singh, G.; Kumar, A.; Aggarwal, V.; Singh, S. Experimental Investigations and Optimization of Machining Performance During Turning of EN-31 Steel Using TOPSIS Approach. Mater. Today Proc. 2022, 48 (5), 1089–1094. https://doi.org/10.1016/j.matpr.2021.07.381.

[10] Varpe, N. J.; Hamilton, N.; Anurag. Investigation into Burnishing Process to Examine Effect on Surface Integrity, Wear and Corrosion Resistance of Carbon Alloy (EN31) Steel. J. Mater. Eng. Perform. 2024, 33, 3691–3705. https://doi.org/10.1007/s11665-023-08524-x.

[11] Okokpujie, I. P.; Bolu, C. A.; Ohunakin, O. S.; Akinlabi, E. T.; Adelekan, D. S. A Review of Recent Application of Machining Techniques, Based on the Phenomena of CNC Machining Operations. Procedia Manuf. 2019, 35, 1054–1060. https://doi.org/10.1016/j.promfg.2019.06.056.

[12] Ram, J. S.; Jeavudeen, S.; Mouda, P. A.; Ahamed, N. The Role of Various Dielectrics Used in EDM Process and Their Environmental, Health, and Safety Issues. Mater. Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.05.137.

[13] He, J.; Zeng, Z.; Li, H.; Wang, S. The Microstructure and Mechanical Properties of Copper in Electrically Assisted Tension. Mater. Des. 2020, 196. https://doi.org/10.1016/j.matdes.2020.109171.

[14] Kumar, J.; Soota, T.; Rajput, S. K. Modelling and Optimization of EN 31 Work Material on Wire Electric Discharge Machining. Mater. Today Proc. 2019, 18 (7), 2984–2992. https://doi.org/10.1016/j.matpr.2019.07.169.

[15] Kamei, K.; Davis, R.; Pereira, R. B. D. Experimental Investigation of the Effect of Input Control Variables and Thermal Treatments on the Impact Toughness of EN-31 Steel. Mater. Sci. Forum 2024, 1133, 47–54. https://doi.org/10.4028/p-ge4bbx.

[16] Karthik, S.; Karunakaran, P.; Velmurugan, G. Experimental Investigation of WE43(T6) Magnesium Metal Matrix Composites to Enhance Mechanical Properties and EDM Process Parameters. Int. J. Electrochem. Sci. 2024, 19 (5). https://doi.org/10.1016/j.ijoes.2024.100553.

[17] Galati, M.; Antonioni, P.; Calignano, F.; Atzeni, E. Experimental Investigation on the Cutting of Additively Manufactured Ti6Al4V with Wire-EDM and the Analytical Modelling of Cutting Speed and Surface Roughness. J. Manuf. Mater. Process. 2023, 7 (2). https://doi.org/10.3390/jmmp7020069.

[18] Martínez-Olvera, C. The Role of Manufacturing Efficiency in the Achievement of Sustainable Mass Customization 4.0. Manuf. Res. 2022, 10 (1), 132–159. https://doi.org/10.1080/21693277.2022.2064360.

[19] Farooq, M. U.; Anwar, S.; Bhatti, H. A.; Kumar, M. S.; Ali, M. A.; Ammarullah, M. I. Electric Discharge Machining of Ti6Al4V ELI in Biomedical Industry: Parametric Analysis of Surface Functionalization and Tribological Characterization. Materials 2023, 16 (12). https://doi.org/10.3390/ma16124458.

[20] Kumar, P. M.; Sivakumar, K.; Selvarajan, L. EDM Machining Effectiveness for Ti–6Al–4V Alloy Using Cu–TiB2 Ceramic Composite Electrode: A Parametric Evaluation. Ceram. Int. 2024, 50 (11 Part B), 20118–20132. https://doi.org/10.1016/j.ceramint.2024.03.135.

[21] Singh, R. P.; Sharma, V.; Kumar, R. Optimization of Response Parameter of Machining EN31 While Electro-Discharge-Machining Using TLBO. Mater. Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.02.121.

[22] Shastri, R. K.; Mohanty, C. P.; Mishra, U.; Hotta, T. K.; Patil, V. V.; Prashanth, K. G. Optimizing the Electrical Discharge Machining Process Parameters of the Nimonic C263 Superalloy: A Sustainable Approach. J. Manuf. Mater. Process. 2024, 8 (3). https://doi.org/10.3390/jmmp8030126.

[23] Ganapathy, S.; Palanivendhan, M.; Balasubramanian, P.; Susitra, K. Process Parameter of EDM to Optimize Material Removal Rate Using Box Behnken's Design. Mater. Today Proc. 2023, 82, 38–42. https://doi.org/10.1016/j.matpr.2022.11.148.

[24] Sharma, S.; Kumar, U.; Vates, A.; Bansal, A. Parametric Optimization of EN-31 Steel in Wire Cut Electro Discharge Machining by Taguchi Technique. Adv. Sci. Eng. Med. 2020, 10, 881–887. https://doi.org/10.1166/asem.2020.2645.

[25] Pawar, S. S.; Bera, T. C.; Sangwan, K. S. Towards Energy Efficient Milling of Variable Curved Geometries. J. Manuf. Process. 2023, 94, 497–511. https://doi.org/10.1016/j.jmapro.2023.03.078.

[26] Bhowmick, S.; Mondal, R.; Sarkar, S.; Biswas, N.; De, J.; Majumdar, G. Parametric Optimization and Prediction of MRR and Surface Roughness of Titanium Mixed EDM for Inconel 718 Using RSM and Fuzzy Logic. CIRP J. Manuf. Sci. Technol. 2023, 40, 10–28. https://doi.org/10.1016/j.cirpj.2022.11.002.

[27] Sharma, V. K.; Saini, A.; Gupta, M.; Sehgal, S. S. Multi-Response Optimization in Face Milling of EN-31 Steel Using Analytical Hierarchy Process-Based GRA. Int. J. Interact. Des. Manuf. 2024, 18, 6187–6194. https://doi.org/10.1007/s12008-023-01540-0.

[28] Dwivedi, Y. D.; Kumar, T. V.; Dharme, A.; Kumar, K. B.; Gori, Y.; Chandra, P. K.; Abdul-Zahra, D. S.; Kumar, D.; Jain, A. A Critical Review on Different Aspects of Electric Discharge Machining. Mater. Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.03.748.

[29] Qin, Y.; Liu, X.; Yue, C.; Wang, L.; Gu, H. A Tool Wear Monitoring Method Based on Data-Driven and Physical Output. Robotics Comput. Integr. Manuf. 2024, 91. https://doi.org/10.1016/j.rcim.2024.102820.

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2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
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