Optimization of Wire Electric Discharge Machining (WEDM) process parameters for AISI 1045 Medium Carbon Steel using Taguchi Design of Experiment

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Research Article

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Abstract

The demand for alloy materials with high hardness, toughness, and impact strength has increased with the growth of the manufacturing industry. These materials are extremely difficult to manufacture using standard techniques, hence, non-conventional machining is used to solve this problem. Wire cut electric discharge machine is one of them. Thus, to attain the required outcome or productivity, it is necessary to control the input parameters that affect the response factors. This research aims to optimize the wire cut electric discharge machining process parameters using the Taguchi design of experiment (DOE) for AISI 1045 medium carbon steel. In this work, experiments are performed in an automotive sector to analyze the influence of WEDM process parameters such as current, voltage, and pulse on time on material removal rate (MRR) for AISI 1045 medium carbon steel. The signal-to-noise (S/N) ratio and analysis of variance are used to analyze the impact of error in this experiment, establishing the best set of process parameters for optimizing the material removal rate. According to the present investigation, the current has a significant effect on the material removal rate. The observed optimal process parameter settings for higher material removal rate based on the Taguchi DOE were found to be, I=16amp,V=60volt, pulse on time =100µs. The conclusion of the paper includes the disclosure of findings, analysis, and judgments.

1 Introduction

Economic globalization is constantly pushing the manufacturing sector to its advanced and innovative transformation through groundbreaking and state-of-the-art technologies. Hence, to remain competitive in today's marketplace, mechanical components must not only be manufactured with high accuracy and reliability but also in the shortest amount of time possible. Material sciences have led to the development of advanced engineering materials such as super alloys, composites, and ceramics. These materials are hard and difficult to machine, and often pose impediments to smooth machining with traditional machining processes such as turning, milling, drilling, and grinding. Electrochemical machining, ultrasonic machining, wire cutting, electrical discharging machines (WEDM), and other non-traditional ways of machining are used on such complicated machine materials.

Wire-cut electric discharge machining (WEDM) is a fast-growing, non-conventional advanced manufacturing process used for high-strength materials. Every hard material can slice through WEDM, which is difficult to cut with other conventional methods [1]. To meet the rapidly increasing desire for materials with unique properties in such sophisticated professional programs as aeronautical and medical devices, WEDM is the best option [2]. The WEDM process is used to extract particles from the surface thermal erosion [3]. In order to use WEDM, the workpiece and tool, must be electrically conductive [4], [5]. The wire used acts as a cathode, and the work material acts as an anode. There is no physical contact between the workpiece and wire, so we can make sensitive, breakable objects without risking damage [6], [7]. Stress is reduced since the tool and workpiece do not interact during machining [8], [9]. A shock is created in terms of discharge energy, and spikes of electricity at limited intervals are supplied. When the electric field is improved, a release is started [10], [11]. When the spark comes in contact with the dielectric fluid (present between the workpiece and tool), it gets ionized,
allowing current to flow between the tool and workpiece, forming an ionization gradient [12]. This results in a rapid increase in the temperature of the metal, i.e., from 8000 °C to 12000 °C (occasionally much higher), causing the surface particles of the workpiece to melt rapidly. The gap between the tool and the workpiece is precisely acclimatized to ensure that ionization occurs. If the gap between the workpiece and the tool is not correctly maintained, there will be no spark, due to which no cutting will be done, so a constant gap of 0.5 mm is maintained between the workpiece and the tool to produce a spark [13], [14]. A dielectric fluid is mostly used in wire-cut EDM having sufficiently high dielectric resistance so it does not break down electrically too quickly but at the same time ionize when electrons collide with its molecules. Moreover, during sparking, it should be thermally resistant as well. Deionized water is used as a dielectric fluid for most of the WEDM process [15], [16]. In order to measure WEDM’s performance, the literature review shows key output factors, which are, i.e., Material Removal Rate (MRR) and Surface Roughness [17], [18]. Similarly, the input factors from the literature review for WEDM are, i.e., current, voltage, pulse on time, pulse off time, wire tension, and wire speed [19]. There is a lot of interest in improving the material removal rate as it depends on how fast an item is manufactured. There are several variables that affect MRR, including current, voltage, and pulse on time. The current is determined during the on-time of each pulse. The pulse on time is determined as the time that the current is permitted to flow each cycle [20], [21]. Voltage influences MRR, which can be calculated from the spark zone average power during machining. Voltage influences the amount of overcutting and the gap in the spark [22]–[24], [25], [26]. In the process of fabricating carbon-carbon alloys, the best EDM machine setup for input parameters is current, voltage, and pulse on time. These parameters have an impact on the electrode wear rate. The Taguchi design of experiments was utilized to find the best EDM variable settings [27], [28].

2 Literature Review

It is critical to choose machining parameters in WEDM to achieve optimum machining accomplishment. The appropriate machining parameters are usually established based on experience. This, however, does not guarantee that the chosen machining settings provide optimum or near-optimal machining performance for that specific electrical discharge machine and environment. Different ideas have been put forward in the literature about improving the different machining response parameters.

Nitin et al. studied the effects of wire-EDM machining input parameters on surface roughness and cutting speed of titanium (Ti-6Al-4V) alloy. Input parameters included servo voltage, wire feed speed, and wire tension. Response surface methodology (RSM) and analysis of variance (ANOVA) are used in this study [29]. The effects of WEDM machining input parameters on material removal rate, surface roughness, gap voltage, gap current, and cutting rate for AISI D2 steel were analyzed by Vikram. et al. Input parameters are pulse on time, pulse off time, peak current, servo voltage, and wire feed rate. The Taguchi L27 orthogonal array was used along with surface response methodology and analysis of variance [30]. The effects of WEDM input parameters on material removal rate for hot die steel AISI H-11 are explained by H.singh et al. Input parameters are pulse on time, pulse off time, gap voltage, peak current, wire feed, and wire tension. This paper uses a one variable at a time approach, and the result
shows that the pulse on time is directly proportional to the MRR in this study [31]. G. selvakumar et al. studied the effects of WEDM input parameters on cutting speed, surface roughness, and the taper error for AISI D3 tool steel, which are pulse on time, peak current, wire tension, and taper angles. Taguchi-based grey relational analysis has been used along with the Taguchi L9 orthogonal array [32]. In another work, the effects of pulse on-time, pulse off-time, wire feed, and wire tension on the material removal rate and surface roughness for tungsten carbide were analyzed by PHaja Syeddu Masooth et al. through the Taguchi L9 orthogonal array along with analysis of variance (ANOVA) [33].

The effects of WEDM input parameters on the surface roughness and material removal rate for high-strength armor steel are explained by Ravindrannadh Bobbili et al. Input parameters are pulse-on time, pulse-off time, wire feed, flashing pressure, spark voltage, and wire tension. The Taguchi’s DOE with an L27 orthogonal array was used along with ANOVA [34]. M. Fakkir Mohamed et al. studied the effects of WEDM input parameters on the machining time for aluminium 6082 T6 alloy. Input parameters are pulse on-time, pulse off time, and current. Taguchi’s DOE with an L9 orthogonal array was used [35]. K. Satyanarayana et al. examined the effects of WEDM input parameters on the surface roughness and material removal rate for Inconel 600. Input parameters are current, pulse on, and pulse off time. Taguchi’s DOE with L9 orthogonal array was used along with ANOVA [36]. Swarup S. Deshmukh et al. explained the effects of WEDM input parameters on the surface roughness and kerf width of AISI 4140. Input parameters are pulse on time, pulse off time, servo voltage, and wire feed. Taguchi’s DOE with L9 orthogonal array was used along with grey relation analysis, ANOVA, and regression analysis [37]. Yasir Nawaz et al. examined the effects of WEDM input parameters on material removal rate, kerf width, and surface roughness of DC53 Die Steel. Input parameters are pulse on time, current, pulse off time, and wire speed. Taguchi’s DOE with L27 orthogonal array was used along with ANOVA [38]. V.K. SAINI et al. studied the effects of WEDM input parameters on the surface roughness of composite material (AL6061/SICP). Input parameters are pulse on-time, pulse off time, and current. Taguchi’s DOE with L9 orthogonal array was used along with ANOVA [39]. The effects of WEDM input parameters on the surface roughness of VANADIS 4e (powder metallurgical cold worked tool steel) were analyzed by D.Sudhakara et al. Input parameters are pulse on time, pulse off time, servo voltage, peak current, wire tension, and water pressure. Taguchi’s DOE with L27 orthogonal array was used along with ANOVA [40]. Zahid A. Khan et al. examined the effects of WEDM input parameters on surface roughness and kerf width of the stainless steel (SS 304). Input parameters are pulse on time, pulse off time, and current. Taguchi’s DOE with L9 orthogonal array was used, along with grey relational analysis and analysis of variance (ANOVA) [41]. G. Rajyalakshmi et al. explained the effects of WEDM input parameters on material removal rate, surface roughness, and spark gap of Inconel 825. Input parameters are pulse on time, pulse off time, voltage, flushing pressure, wire feed rate, wire tension, spark gap, and servo feed. Taguchi’s DOE with L36 orthogonal array was used, along with grey relational analysis and analysis of variance (ANOVA) [42]. K. Lingadurai et al. examined the effects of WEDM input parameters on metal removal rate, kerf width, and surface roughness of stainless steel AISI grade-304. Input parameters are voltage, pulse on time, pulse off time, and wire feed rate. Taguchi’s DOE with L18 orthogonal array was used along with analysis of variance (ANOVA) [43].
In light of the literature review, it is clear that optimizing the process parameters of WEDM is one of the most important design objectives for achieving a greater rate of material removal. Taguchi DOE has been shown to be the most effective technique for determining the optimal amounts of process variables and their corresponding interaction effects for a given target. In comparison to other DOE approaches, it is not only straightforward, efficient, and trustworthy for decreasing costs and enhancing quality, but it also dramatically decreases the number of trials. Then analysis of variance. The goal of this study is to find the best input machine settings for AISI 1045 medium carbon steel in order to get a higher rate of material removal.

3 Problem Statement

In previous approaches, the majority of optimization has been done on different alloys and super alloys by using different optimization techniques like optimization through mathematical modeling, optimization with full factorial design, optimization through response surface methodology, and optimization through the Finite element method. The problem discussed here is how to achieve the best values of input parameters with the minimum number of experiments to attain a higher material removal rate for a mechanical part called a timing chain sprocket. Instead of performing different experiments to attain the best input values, suggest a basic technique from which we can get those optimized values and directly apply them to the machine to get higher cutting rates to speed up the production. As a result, both production costs and time can be reduced.

4 Proposed Solution

In this work, the problem mentioned above is resolved through parametric optimization of the machining process with the help of Taguchi DOE along with an analysis of variance considering AISI 1045 medium carbon steel. Taguchi DOE gives an optimal set of input values in very few experiments, which saves a lot of experimental costs as well as time. After applying this Taguchi DOE parametric optimization technique, the best set of input parameter values will come out. These input values are then applied to wire-cut EDM for AISI 1045 medium carbon steel for higher material removal rates.

4.1 Methodology:

In this paper, parametric optimization of process parameters with the help of Taguchi Design of experiment is used, which is an effective way to handle responses provoked by the use of numerous factors. In order to pick the ideal process conditions, there is robust testing equipment that provides a simple, effective, and thorough way. When it comes to correctly modelling response factors, a large number of experiments are no longer necessary with the Taguchi DOE. The foremost objective of the Taguchi method is to optimize the various design criteria. It also has the ability to change the process parameters and settings if the results don't meet the functional requirements. The graphical representation of the proposed methodology is shown in Fig.1.
Actions to be concerned about are:

1. Find out what reactions and system parameters need to be analyzed.
2. Calculate possible relations between key parameters as well as their degrees of freedom.
3. Decide which orthogonal array is correct, then assign it the appropriate parameters.
4. Choose the best system parameters based on the results of the experiments.
5. Perform a confirmation test to confirm that the optimal configuration values have been determined [46].

4.2 Materials and Method

In this research work, 1045 medium carbon steel was used because it is a high-solidity steel with excellent weld ability, formability, and max hardness. AISI 1045 has sway properties in both standardized and molten forms.

In a standardized or heat-treated state, AISI 1045 metallic offers the best formability. A variety of operations can be performed on AISI 1045 steel with the appropriate feeds and tool types and speeds depending on manufacturer recommendations [44]. The chemical properties of AISI 1045 medium carbon steel are illustrated in Table 1, and Table 2 shows the mechanical properties of AISI 1045 medium carbon steel.

4.3 Determination of process parameters and relevant settings

In this presented work, only those parameters are included which influence the material removal rate of AISI 1045 medium carbon steel. With the help of literature review, best input control factors are selected for work materials, which are listed below in Table 3.

4.4 Selection of OA
A Taguchi orthogonal array is created in accordance with the process parameters. The design of an orthogonal array depends upon the number of elements, each factor's magnitude, and the interconnections between them. The control variables are believed to be independent of each other[47]. Table 5 displays the Taguchi L9 Orthogonal array used in this experiment.

{Insert Table 5 here}

5 Case Study

The methodology presented in this paper has been used to evaluate the material removal rate for AISI 1045 medium carbon steel. Selection of appropriate material is an important criteria in the WEDM process. AISI 1045 medium carbon steel was chosen as the base material for the timing chain sprocket, since it's a good gear material with very high material strength. The second step was the selection of the right machining method. From a literature review, wire cut EDM was chosen. The third step was the selection of the best parameters. From the past literature and experimentation on WEDM, these parameters were selected (current, voltage, and pulse on time). Each factor has 3 levels of input values. The most important step was the selection of an optimization technique. Many different techniques were used in the literature reviews, but in this paper, we use parametric optimization of the machining process along with Taguchi DOE to achieve a higher material removal rate.

5.1 Experiment

Tests were carried out on the "DK7725" wire cut electric discharge machine. The electrode wire used in the DK7725 is molybdenum. This sort of wire cut EDM can be utilized in place of brass wire cut EDM, which is significantly more expensive. Medium carbon steel is used as an anode and molybdenum wire is used as a cathode. A gap is maintained between the tool and the work piece so a spark can occur. Deionized water is used as a dielectric fluid for this experimental setup. The Molybdenum wire used in this experiment is shown in Fig. 2, and the specifications of molybdenum wire are listed in Table 6.

{Insert Table 6 here}

{Insert Fig. 2 here}

AISI 1045 medium carbon is used to manufacture a mechanical part known as a timing chain sprocket. To find the MRR equation, 1 is used. An L9 orthogonal array was chosen. Nine experiments were performed under different levels of controllable factors. The specifications of the WEDM machine are shown in Table 7, and the experimental setup for these tests is shown in fig.3. Timing chain sprocket dimensions are listed in Table 8.

{Insert Table 7 here}

{Insert Fig. 3 here}
First of all, the design is made with the help of CAD and then imported into the WEDM machine. Fig.4 (a) shows the design of the timing chain sprocket gear’s teeth profile made through CAD software. The different measurements for the timing chain gear teeth profile are highlighted. Fig.4(b) shows the system operating on a gear profile while giving commands to the WEDM machine through machine software. The software used in this DK7725 wire-cut EDM is the HF WEDM programme and control system. This powerful software allows users to customize skim passes, independent lead-ins and lead-outs, glue stops, cutting conditions, and 4 axis synchronization. A complete wire EDM programming solution. Initially, the base part is made, and after that, a gear cutting operation is performed on the base part. It is shown in Fig.6. Fig.7 shows the final part called the timing chain sprocket. A very fine quality of work is done with the help of WEDM.

5.2 Evaluation of MRR:

For (MRR), the material’s density and machining time are taken into consideration \[48\] using the Eq 1 \[49\].

\[
\text{MRR (mm}^3/\text{min.}) = \frac{\text{Initial Weight of workpiece (gm.)} - \text{Final Weight of Workpiece (gm.)}}{\text{Density (gm./mm}^3\text{)} \times \text{Machining Time (min.)}} \tag{1}
\]

MRR for 9 different experiments that were performed on WEDM are listed below in Table9.

5.3 Calculation of Signal to Noise ratio (S/N) and Analysis of variance (ANOVA)

Uncontrollable factors are reduced in a product or procedure through the use of Taguchi designs, which leverage resilience to their advantage (noise elements). Control elements are parameters that may be changed in the layout and methodology of a system. Experimentation is the only way to control noise in the manufacturing of a product, yet it is possible to do so. It is important to control noise variables in a Taguchi-DOE in order to generate variability to identify appropriate control element settings that are able to withstand the effects of disturbance. More sensitive control elements become aware of noise-reducing settings as their signal-to-noise ratios improve (s/n). The resilience of a design may be measured using
the signal-to-noise (S/N) ratio, where "signal" denotes the intended value and the unwanted value is represented by "noise." Eq. 2 [47] is used to calculate the S/N ratio [50]. Table 10 shows the S/N ratios.

\[
\eta = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \tag{2}
\]

As the goal of this study is to maximize the material removal rate, the "larger the better" characteristic is used. ANOVA is a test for differences in means it is a statistical method that has been in use since in a nutshell. ANOVA informs you if the means of three or more independent groups vary statistically. One-way ANOVA is the simplest type of statistical analysis. Multiple dependent variables are compared using a one-way ANOVA to examine the impact of one independent variable. In ANOVA, p-value is very important because it determines the effect of responses as well as the percentage contribution of the error [47].

{Insert Table 10 here}

{Insert Table 11 here}

6 Results And Discussions

In this research, nice different experiments were performed with different input controllable factors on AISI 1045 medium carbon. Taguchi DOE was used for this experiment to find out the best input factor settings to get the maximum material removal rate using the L9 orthogonal array. MRR is calculated from experiments after S/N ratio and ANOVA are applied. The results from the S/N ratio are shown in Table 10 and their ranking are shown in Table 11. Table 11 clearly shows that current ranks first, indicating that current has the greatest influence on the material removal rate. Results from ANOVA are listed in Table 12, Table 13 and Table 14. In these 3 Tables look at the p-value. It will determine which factor has a great impact on MRR. If the p-value for an input factor is less than .05, it means that the input factor has a greater impact on the response factor. Table 12 MRR vs Current it can be seen that the p-value for current is 0.021, which is less than 0.05, which means current has a great impact on material removal rate.

{Insert Table 12 here}

Model summary of Table 12 shows that current also has a large R sq percentage, which is 72.4%, clearly indicating that current has a greater effect. Table 13 shows the ANOVA for MRR vs Voltage. It shows that voltage has a p-value of 0.933, which is higher than .05, which means that voltage has no significant effect on the material removal rate in this case study. Similarly, the model summary from Table 13 shows that R-sq has a very low percentage, which is 2.30%, so it is clear that voltage has very little effect on MRR.

{Insert Table 13 here}
Table 14 shows the ANOVA for MRR vs. pulse on time. It shows that pulse on time has a p-value of 0.629, which is greater than 0.05, which shows that the pulse on time also has a low impact on material removal rate in this study. From the model summary Table 14, it can be seen that R-sq has a very low percentage, which is 14.34%, so from all these 3 tables of ANOVA, it can be concluded that current has the greatest impact on material removal rate after that pulse on time and least and last voltage.

Fig. 8 shows the main effect plot for means and S/N ratios. It is clear from fig. 8 that as the current increased, the material removal rate also increased for voltage. It shows that as voltage increased, the material removal rate slightly increased but as the pulse on time increased, the material removal rate decreased. So the best input parameter values for this study are found to be I = 16 amp, V = 60 volt, and pulse on time = 100µs. If we choose these input values for AISI 1045 medium carbon steel, we will be able to get the maximum material removal rate to speed up the production of timing chain sprocket.

7 Conclusion

The goal of this research was to evaluate the effect of WEDM process parameters (current, voltage, pulse on time) on the material removal rate of AISI medium carbon steel 1045 for an industrial case (timing chain sprocket) from the automobile sector. Taguchi’s L9 orthogonal array was used for conducting experiments on AISI 1045 medium carbon steel to find the optimum process parameters. The significance of machining factors and their effects on MRR is determined by using analysis of variance. The study resulted in the following conclusions: The input parameters like current have the greatest influence on material removal rate for AISI 1045 medium carbon steel, followed by pulse on time and voltage. As the current increases, the material removal rate also increases. When voltage is increased, the material removal rate decreases. Similarly, as the pulse on time increases, the material removal rate decreases. It can be seen from table 11, which shows the ranking of input parameters after S/N ratio is applied, that current has got the first rank, which means it has the highest effect on MRR. Analysis of variance shows that current has a 72.44% contribution to the material removal rate, while voltage has a 2.30% contribution and pulse on time has a 14.34% contribution. The best set of optimal values to achieve higher material removal rates are concluded from the graph to be I 16-amp, V = 60 volt, and pulse on time = 100µs. The technique that is used in this work has the advantage that if the specified process parameters do not fulfil the functional requirements, we can re-design the parts easily. Future research can be carried out by using multi-objective optimization technique to find the effect of input parameters on various response factors like surface roughness, tool wear rate for AISI 1045 medium carbon steel.

Declarations
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Conflicts of interest
The authors declare that they have no known competing financial interests or personal relationships that could have seemed to affect the work reported in this paper.

Availability of data and material
Data will be provided if required

Code availability
Not applicable

Ethics approval
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Consent to participate
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Tables
Tables 1 to 14 are available in the Supplementary Files section

**Figures**

![Diagram showing the proposed methodology]

**Figure 1**

Proposed Methodology
Figure 2

Molybdenum wire
Figure 3

Wire cut electric discharge digital control machine DK7725
Figure 4

Wire cut electric discharge digital control machine DK7725

Figure 5

Base of the desired part
Figure 6

Gear cutting operation on base part

Figure 7

Final part design of timing chain sprocket
Figure 8

Graph for I & MRR, V & MRR, Pulse-On-Time & MRR

Supplementary Files

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