Optimization of Wire EDM Process Parameters in the Fabrication of Spur Gear Using Taguchi Technique

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Abstract

Wire EDM is a specialized thermal machining method that uses a thin wire electrode to cut conductive materials with high precision, including complicated shapes and sharp edges. The investigation uses a CNC Wire EDM machine with a molybdenum wire electrode and an AISI 4140 steel workpiece. The aim was to achieve superior surface finish and dimensional accuracy for spur gears. Control parameters like current, Pulse on (T-on) time, and pulse off (T-off) time were chosen to experiment with the performance measure in terms of surface roughness. 9 experimental runs (L9 OA) were conducted in total, using an orthogonal array, and for the Surface Roughness, the appropriate combination of control factor levels was identified. The Minitab-18 program is used to apply the Taguchi method to determine the level of importance and optimum machining parameters. The findings offer valuable insights for manufacturers to enhance product quality and optimize manufacturing processes.

Keywords
Wire EDM, Taguchi technique, Spur gear, Surface Roughness, AISI 4140 steel

1. Introduction
The practical application of Wire Electrical Discharge Machining (WEDM) relies on the established phenomenon of conventional EDM sparking, which employs a non-contact method of material removal. Since its inception, WEDM has progressed from a simple technique for creating tools and dies to the preferred form for producing highly accurate micro-scale parts with exceptional surface finish quality. Patel and Vaghmare assert the extensive utilization of WEDM across industries, including aerospace, medical, automotive, and electronics (Patel & Vaghmare 2013). Spur gears are widely employed in mechanical systems due to their unique capabilities and advantages. The manufacturing process of spur gears ensures the desired dimensional accuracy and surface finish. Since wire EDM can cut spur gears to high-quality standards, it is frequently used as one of the possible manufacturing techniques. A study conducted by Chaubey and Jain demonstrated the use of wire EDM to create meso and micro gears using a tiny wire formed of an electrically conducting substance. Wire EDM gives remarkably high precision and accuracy while being a relatively slow technique (Chaubey & Jain 2018). Additionally, wire EDM can cut intricate forms and rigid materials, making it appropriate for manufacturing spur gears. Spur gear must, therefore, be manufactured carefully to guarantee their usability and dependability in mechanical systems.

In recent years, an increased focus on WEDM process parameter optimization to improve performance metrics has emerged. El-taweel and Hewidy examined and assessed the parameters for wire-cut EDM machining of CK45 steel to measure process performance indicators such as the material removal rate, tool wear, and surface roughness (El-taweel & Hewidy 2013). Similar studies have been conducted by Alias et al. on the impact of parameter changes on the machining of titanium Ti-Al-4V using wire EDM and the Taguchi method (Alias et al. 2012). These studies show how significantly better WEDM process parameter performance may be achieved through optimization approaches.

The process parameters, such as pulse on-time, pulse off-time, peak current, and wire feed rate, significantly influence the final components' machining performance and quality. The required precision, surface roughness, and material removal rate can only be attained by optimizing these parameters. Ehsan Asgar and Singh Singholi have used various optimization techniques, including the Taguchi method, grey relational analysis, and response surface methodology, to achieve this. The Taguchi approach stands out among these methods for its ease of use and potency in determining the ideal arrangement of process parameters (Ehsan Asgar & Singh Singholi 2018).

The Taguchi approach has been effectively used in WEDM to improve machining performance metrics like surface roughness by optimizing parameters like pulse on-time, pulse off-time, and current. For example, Alias et al. used the Taguchi approach to determine the best machining conditions for Titanium Ti-Al-4V using WEDM. They found that reducing the machine feed rate resulted in the narrowest kerf width (Alias et al. 2012). The Taguchi approach was used in a different study by Fakkir Mohamed and Lenin to optimize the Wire EDM process parameters for AA6082-T6. The study conducted nine experiments on an L9 orthogonal array to identify the optimal combination of control factor levels for producing minimal surface roughness. According to the study, the Taguchi method offers a rational and systematic strategy for improving Wire EDM's operating parameters (Fakkir Mohamed & Lenin 2020). The Taguchi method is valuable for optimizing WEDM process parameters to get high-quality machining outputs.

Wire Electrical Discharge Machining (WEDM) parameters have been the subject of extensive research. Some noteworthy studies include the application of grey relational analysis (GRA) for optimizing WEDM of Titanium (grade 2) while taking into account multiple output parameters (Sahoo et al. 2019), the use of vegetable oil as a dielectric fluid with Taguchi-based hybrid optimization (Singaravel et al. 2020), and the investigation of the effects of various process parameters on material removal rate, surface roughness, kerf width, and dimensional deviation in WEDM of Ti49.5Ni50.6 SMA (Takale & Chougule 2019). The use of distilled water as a dielectric fluid, a brass wire with a 0.25mm diameter tool, and molybdenum high-speed tool steel as a workpiece has also been investigated in research (Deshpande 2019). Creating an Artificial Neural Network (ANN) model to forecast metal removal rate (MRR) and surface roughness (Ra) values for milling AISI 1045 steel was the topic of one more study (Alduroobi et al., 2020). It also examined the importance of pulse on-time, pulse off-time, and servo feed for MRR and Ra optimization. Innovative ideas have also been shown, including Wire-EDM turning on hard-to-cut materials (Owhal et al. 2020). It has also been researched how process factors affect the pace at which material is removed when cutting aluminum alloy (5086) with WEDM (Kumar & Sharma 2020). To reduce wire lifetime (WLT) and increase material removal rate, it has also been investigated to optimize the Wire EDM process parameters using the Taguchi technique and the creation of Jaya algorithms (Fakkir Mohamed & Lenin 2020; Sahoo et al. 2019). A metal matrix composite (MMC) composed of aluminum 7075, boron carbide, and graphite (Al/B4C/Gr) has also been noted for its effect on output responsiveness due to process variables (Rizwee & Rao 2021).

By analyzing the pulse on-time, pulse off-time, peak current, and wire feed rate of the Wire EDM process, this study seeks to identify the ideal configuration of parameters for producing spur gears. Signal-to-noise (S/N) analysis is done to determine the effects of each parameter on machining performance. The experimental design makes use of the L09 orthogonal array. While reducing process variability, the goal is to improve the gears' surface finish.

2. Methodology

2.1 Experimental Setup

A CNC Wire EDM machine (Model: DK7735) was used to complete the Wire EDM procedure of AISI 4140 steel. Specification of the EDM machine is given in Table 1, and a schematic diagram of the EDM machine and EDM process is shown in Figure 1. 10 mm thick AISI 4140 steel was used as the workpiece, and chemical composition and mechanical properties are shown in Table 2 and Table 3 respectively. Molybdenum wire of 0.25 mm diameter is used to cut the workpiece.

Table 1. Specification of Wire EDM Machine (Model: DK7735)

Item	Unit	Value
Travel of X, Y, Z	mm	350*450*500
Table size	mm	490*730
Cut taper/thickness	°/mm	3/80
Cut accuracy	mm	0.015
Max cut speed	mm²/min	180
Roughness accuracy	um	1.2-2.5
Wire diameter	mm	0.13-0.2 (usually 0.18)
Max electrical current	A	10
Power	Kw	1.6
Voltage	V/Hz	220/380/415V, 50/60Hz
Max load of table	Kg	400

Weight of machine	Kg	1250
Machine Dimensions (L*W*H)	mm	1550*1150*1750

The experimental design included three process parameters, namely pulse on-time, pulse off-time, and peak current, each with three levels. The levels of each parameter are shown in Table 4.

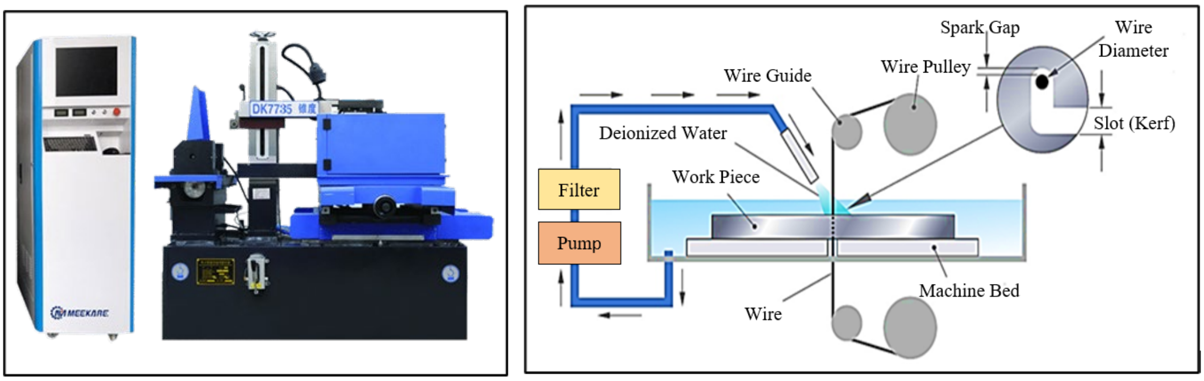


Figure 1. Wire EDM Machine and Machining Process

Table 2. Chemical Composition of AISI 4140

Element	C	Cr	Mo	Mn	Si	S	P	Cu	Ni	Fe
Composition (%)	0.40	1.12	0.18	0.93	0.33	0.031	0.025	0.02	0.17	Balance

Table 3. Mechanical Properties of AISI 4140

Density (kg/m^3)	Young's Modulus (GPa)	Yield Stress (MPa)	Poisson's Ratio	Hardness, Vickers	Melting Temperature (°C)
7850	205	415	0.3	319	1520

2.2 Gear Design

Gears are significant components for electronic appliances, motors, and pumps. Spur gear is a gear with a cylindrical shape with teeth that run parallel to the axis. It is the most widely used and is simple to produce. The same spur gear model, cut using WEDM, is designed using spur gear generator software "Engineers Edge," shown in Figure 2(a)..

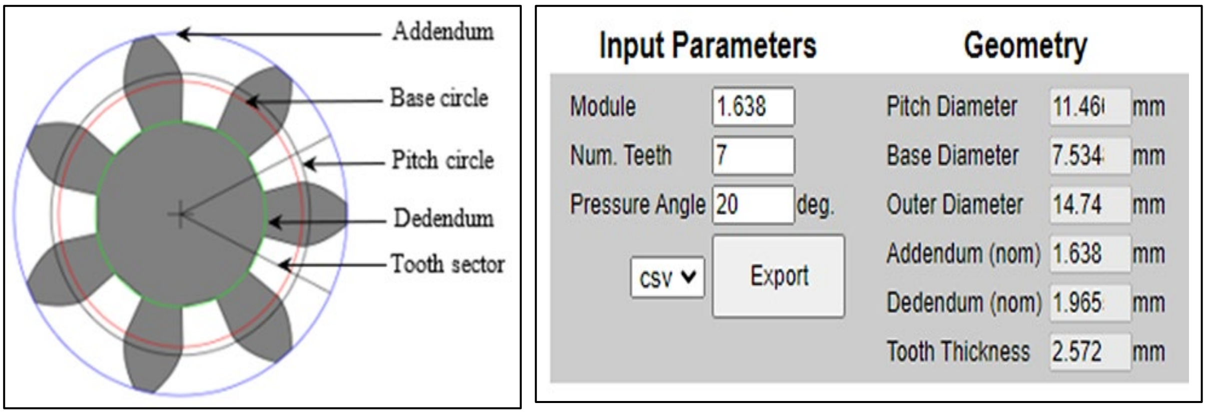


Figure 2. (a) 7 teeth gear design, (b) Design parameters

2.3 Surface Roughness Measurement

The input parameters, such as the module, which is the unit of size that indicates the gear size, number of teeth, and pressure angle, are shown in Figure 2(b). Moreover, the measurement of overall geometry is presented in the exact figure

A typical surface measuring instrument will include a stylus with a small tip (fingernail), a gauge or transducer, a traverse datum, and a processor. The surface is measured by moving the stylus across the surface. As the stylus moves up and down across the surface, the gauge or transducer measures the variation in the surface texture. Surface processing conditions are referred to as surface roughness. The texture and look of the surface, which are essential factors in the features of that surface, are determined by the irregularities found on the object's surface. Only the stylus tip must follow the surface being tested for proper data collection; the gauge must pass over the surface in a straight line. Using a straightness datum, this is accomplished. This can take the shape of a datum bar that has been precision ground or lapped with a high straightness tolerance. This is usually a better choice for small portable instruments and can raise the cost of the device. It is feasible to utilize a different type of data in certain circumstances. The roughness measurement is done by the machine model Surfcome Touch 50, shown in Figure 3, along with the evaluation profile. It is a high-level compact-type model in the Surfcome Touch series with high resolution and straightness.

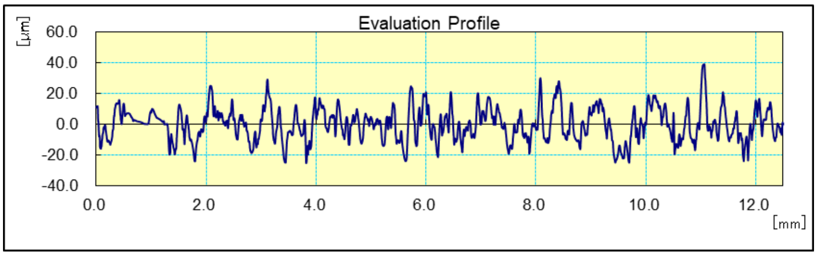


Figure 3. Surface Roughness Measurement

2.4 Taguchi and S/N Analysis

When a product is shipped to the consumer, Taguchi determines the quality of the product in terms of the harm the product causes to society. Some of these Losses result from functional variation because the product's helpful characteristic deviates from the desired target value. Noise factors are the uncontrollable elements that lead to available features of a product deviating from the target values. Quality engineering aims to create products that are resilient to all noise influences. To meet this need, Taguchi develops a typical orthogonal array. He chose the signal-to-noise (S/N) ratio as the preferred quality criterion. Analysis of the signal-to-noise (S/N) ratio was performed to determine the impact of each process parameter on the machining efficiency. The output response quality is gauged by the S/N ratio, which is computed as follows: S/N ratio = -10log (1/n Σ(yi^2)), 'n' is the number of repeats, and 'y_1' Is the machining parameters. Since the standard deviation reduces as the mean increases and vice versa, the S/N ratio is employed as a measurable statistic instead of the standard deviation. According to empirical evidence, Taguchi's two-stage optimization method with S/N ratios does produce the parameter level combination whereby the standard deviation is kept to a minimum. At the same time, the mean remains within acceptable bounds. This suggests that engineering systems react so that the three kinds of altered production elements can be identified: nominal is best, more minor is better, and more significant is better.

Table 4. Machining Parameters Used in the Experiment Factors

Parameters	Level 1	Level 2	Level 3
Current (amps)	5	7	9
T-on (µs)	50	70	90
T-off (µs)	7	8	9

In this study, the surface finish, dimensional correctness, and material removal rate of the gear were assessed using the S/N ratio. Surface roughness is desired to be at a minimum; the Lower, the Better characteristic is used for S/N ratio calculation. The optimal setting would be the one that could achieve the lowest S/N ratio. For each combination of process parameters, the S/N ratios were computed, and the impacts of each parameter were examined using the analysis of variance (ANOVA) method. Each parameter's main and interaction effects were determined using the ANOVA results, and the ideal set of process parameters that would produce the best machining performance was identified.

3. Result and discussion

Minitab 18 software is used to transform the results of the L9 Orthogonal Array into Response Tables and Graphs for Mean and Signal to Noise Ratio. SR versus pulse on, pulse off, current S/N ratios, and mean are displayed in Figure 4 as part of the Taguchi Analysis. Figure 4 depicts the most critical consequence plots for S/N ratios regarding the Surface roughness. It is crystal clear that the surface roughness first decreases, and after some point, it starts to increase with a rise in Ton, and the opposite goes for T-off. Since the T-off signifies the pause between the two consecutive sparks, the period time increases between the two sparks. This pause helps to flush away the debris and material to cool down, thus improving the surface finish. Current also influences the SR. From the range of 5 to 9, the SR decreases.

Table 5. Taguchi L9 (3X3) Orthogonal Array and control parameters

Sample No	Power Amplifier	Pulse Width	Pulse Interval	SR	S/N Ratio
1	5	50	7	7.113	-17.0411
2	5	70	8	8.081	-18.1493
3	5	90	9	7.972	-18.0313
4	7	50	8	7.766	-17.8039
5	7	70	9	9.478	-19.5343
6	7	90	7	9.255	-19.3275
7	9	50	9	8.596	-18.6859
8	9	70	7	10.667	-20.5608
9	9	90	8	7.778	-17.8174

It was observed by Bobbili et al. that SR identified T-on as the most critical factor, followed by peak current as the second most essential element. The surface finish of the workpiece suffers as the discharge current and energy increase, causing the formation of more and deeper craters on the surface. The discharge craters on the machined surface grew larger when the peak current and pulse length were increased.

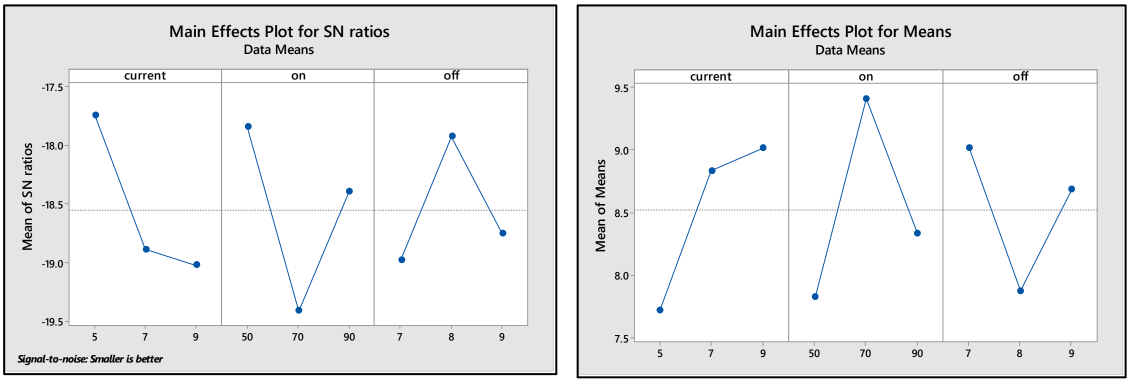


Figure 4. Main Effect Plot for S/N Ratio Main Effect Plot for Means

A larger peak current causes a more significant amount of energy to be discharged, which leads to the formation of large craters that are accountable for a poor surface finish (Bobbili et al. 2013). Kumar and Sharma found that reduced spark rate can be achieved by decreasing the pulse on time, which transfers less energy to the electrode. The time it takes for the energy released by the plasma channel to reach the electrodes grows in proportion to the time the pulse is on. Craters on the surface of the workpiece are caused by molten material. As T-on increased, so did the size of the surface craters and the distance between them. The surface quality of the machined surface tends to deteriorate because of the longer pulse-on times, which allow the electrical sparks to create larger craters on the surface of the workpiece (Kumar & Sharma 2020).

Table 6. Response table for S/N ratio- Smaller-the-better

Level	Current	T-on	T-off
1	-17.74	-17.84	-18.98
2	-18.89	-19.41	-17.92
3	-19.02	-18.39	-18.75
Delta	1.28	1.57	1.05
Rank	2	1	3

According to the findings of Chiang and Chang, the arc on time of discharging has a greater impact on SR than the arc off time of discharging, the on time of discharge, and the servo voltage. On the surface, a protective coating will form, preventing any additional oxidation or corrosion.

Table 7. Response table for means- Smaller-the-better

Level	Current	T-on	T-off
1	7.722	7.825	9.012
2	8.833	9.409	7.875
3	9.014	8.335	8.682
Delta	1.292	1.584	1.137
Rank	2	1	3

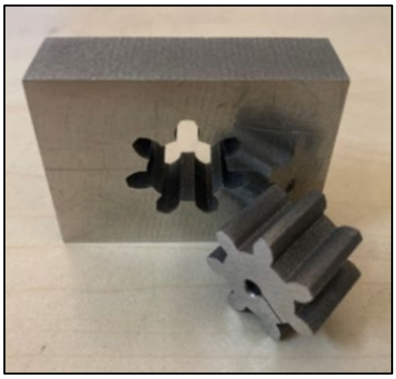
Through passivation, surface irregularities can be made more uniform, which leads to a reduction in surface roughness (Chiang & Chang, 2006). The ideal set of process parameters that would produce the highest machining performance was found using the Taguchi optimization approach. The target S/N ratio and the process parameter levels necessary to attain it were determined during the optimization process. This investigation used the minimum S/N ratio determined by the S/N analysis as the target S/N ratio. The S/N ratios for each parameter level were examined to find the best combination of process parameters, and the combination with the highest S/N ratio was chosen. Table 8 shows the optimum Parameters Combination for Surface Roughness.

Table 8. Optimum conditions using the Taguchi Method

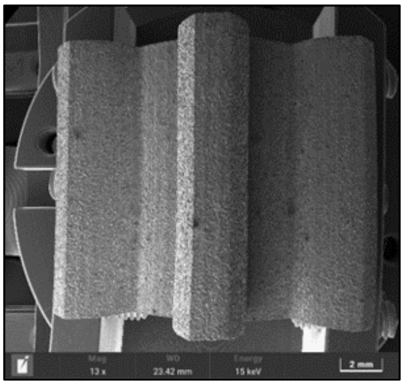
S. No	Control Factors	Surface Roughness	
		Best Level	Value
1	Current	2	9
2	T-on	1	70
3	T-off	3	7

3.1 Morphological Analysis

A Scanning Electron Microscope (Tescan: Vega 4) is used to analyze the surface pattern of the machined surface of Gear teeth. SEM yielded helpful insights into the microstructural qualities of the manufactured spur gears. The results of adjusting the settings were shown in the SEM pictures as a reduction in surface imperfections, a finer grain structure, and an improvement in surface integrity. It is clear from the images of the surface roughness that the high S/N ratio brings up lower surface roughness. Sample 1, which shows the lowest S/N ratio, gives the lowest surface roughness, supported by the picture we got from SEM, shown in Figure 5 (c). On the other hand, the highest S/N ratio provides the highest surface roughness, which is, in this case, sample number 8. Figure 5 (d) also supports the statement, showcasing the most elevated surface roughness.



(a)



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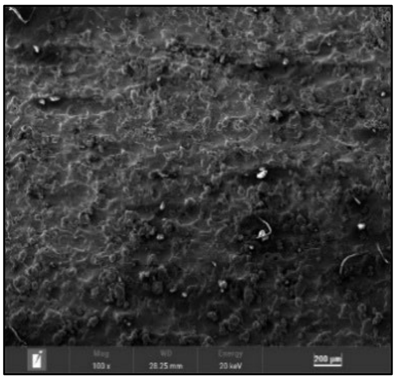
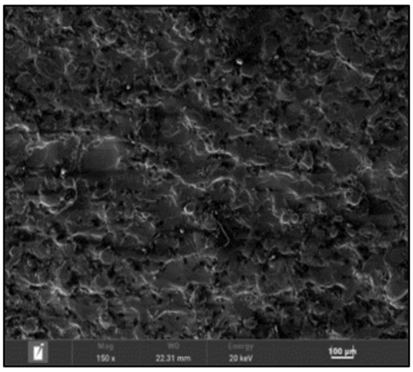


(c)



(d)

Figure 5. (a) The spur gear after cutting by wire EDM, (b) Microscopic image by SEM, (c) indicates very low surface roughness, whereas (d) shows the highest surface roughness

4. Conclusion

The operation of a better gear needs to have a surface roughness that is lower than average since this reduces friction and wear. The following findings were reached from this work based on the Results and Discussion, and a trial was set up to figure out the various machining parameters on Wire Electrical Discharge. For performance measurements supported by Taguchi's optimization process, machining used molybdenum wire 0.25 mm in diameter. The optimized input parameter combinations to encourage minimal Surface Roughness are Pulse on 70 µs, Pulse off 7 µs, and Current 9 amps. Increased mechanical performance is a direct result of the decreased surface roughness and improved microstructural properties. In fabricating spur gears, combining the Taguchi method with SEM analysis has proven to be an effective strategy for optimizing the Wire EDM process parameters. This was achieved through the integration of both approaches. Additional studies could investigate the effect of various materials and intricate geometries on the Wire EDM manufacturing process and the resulting microstructure.

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