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ANALYSIS AND OPTIMIZATION OF SURFACE INTEGRITY IN WIRE ELECTRICAL DISCHARGE MACHINING PROCES

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ABSTRACT

Wire Electrical Discharge Machining (WEDM) process is one of the most important and effective technologies in modern manufacturing due to its versatility in producing complex-shaped components with high precision. It can be used to machine various hard materials and non-ferrous metals regardless of their hardness. In general, surface integrity includes several tests such as surface roughness tests, recast layer measurement, microhardness testing, residual stress measurement, microstructural analysis, chemical and metallurgical tests and fatigue and wear testing. The present study focused on evaluating surface roughness and recast layer of stainless steel 1610 which has many applications like tubes industry and tools, also it has been noticed that a little studies focused on it in the survey. The study was conducted by selecting three variable parameters: servo feed (400, 500,600 m/min), pulse-on time (24,28,32 µs) and pulse-off time (36,40,44 µs) which have the greatest role on the process, while keeping the other machine parameters constant. The obtained data were analyzed using (ANOVA) which was satisfied for predicting and explain the relation between the input parameters and the process characteristics, and it was found that a smoother product surface can be achieved by reducing the values of servo feed (SF) and pulse on time (T_{ON}) while increasing the pulse off time (T_{OFF}). As for the recast layer, it increased proportionally with SF and T_{ON} and began to stabilize at higher levels of T_{OFF}.

KEYWORDS

Wire electrical discharge machining, Surface integrity, Surface roughness, Recast layer, Stainless steel 1610.

1. INTRODUCTION

The nontraditional machining process is more commonly used to manufacture geometrically complicated and accurate parts for the electronics, aerospace, and automotive industries (Ibrahim, Abdulwahhab and Shabeeb, 2021). The Wire-Electric Discharge Machining (WEDM) process is an advanced form of electrical discharge machining (EDM) that uses a thin metal wire in the form of an electrode to cut the electrolysis through thermal erosion (Khudhir, Ahmed and Shukur, 2024). In this process, the workpiece is completely or partially in a dielectric fluid, with the wire that is kept between upper and lower diamond guides and continuously fed with a coil (Kumar, Mitra and Dhanabalan, 2018). The advantages of the WEDM process include the capacity of the strict material of the machine that is difficult for the machine using traditional methods, high precision products, the size of the machine complex, low mechanical stress, good surface finish, versatility with leading materials and flexibility in design. These benefits create an essential technology in various industries, such as tools and dye, aerospace, and the production of complex and accurate components (Ehsan Asgar and Singh Singholi, 2018).

(Raju, SVSS Srinivasa and Sandeep, 2019) tested the elements affecting material removal rate (MRR) and surface roughness (SR) in stainless steel AISI 316 and the usage of each spark and wire-reduce EDM strategy. A 0.25 mm brass twine turned into applied because the device and distilled water because the dielectric fluid in cord-cut EDM. The input variables covered pulse ON time (25 µs, 30 µs, 35 µs), current (2 A, 3 A, 4 A), and twine feed charge (40 mm/s, 60 mm/s, 80 mm/s). In Spark EDM, a copper electrode with a duration of sixty-five mm and a diameter of 12 mm is used, with parameters inclusive of voltage (30 V, 35 V, 40 V), modern (6 A, 12 A, 16 A), and pulse ON time (50 µs, 100 µs, 200 µs). We used ANOVA evaluation and the L-9 Orthogonal Array (OA) to optimize MRR and SR. (Das, Partha Protim and Diyaley, Sunny and Chakraborty, Shankar and Ghadai, 2019) investigated Using grey-fuzzy common sense, the high-quality set of parameters for the WEDM procedure for milling EN31steel is discovered. ANOVA became used to study the results of every technique parameter: workpiece thickness (WT) at 5, 6, and 7 kg; servo voltage (SV) at 20, 30, and 40 V; pulse-off time (TOFF) at 30, 35, and 40 µs; and pulse-on time (TON) at 110, 115, and 120 µs. Surface roughness (SR) and cloth removal price (MRR) were examples of multiple responses that were taken under consideration. The outcomes confirmed that TON at 115 µs, TOFF at 35 µs, SV at 40 V, and WT at 5 kg-f got the fine grade for gray-fuzzy reasoning. These settings maximized MRR and progressed SR the most. (Bisaria and Shandilya, 2019) A (NI55.95, TI44.05) analyzed the integrity of the surfaces, which are mechanized by using the memory laid on optimal parameters. Important properties, including surface morphology, topography, relapse layer, phase analysis, and subtle hardness, were investigated. A mathematical model for surface roughness (SR) and material removal rate (MRR) was developed using a reaction surface function, with regard to the servo voltage, the pulse-on time (TON), pulse-off time (Toffee), wire voltage (WT), and wire feed (WF). Gray relationship analysis adapted to the parameters and ANOVA valid model. The optimal settings achieved an MRR of 8,223 mm/min, 1.93 µm SR and 1.98 times the surface microhardness. (Chaudhari et al., 2020) studied the effect of WEDM process parameters on the surface morphology of nitinol SMA using 3D surface analysis, scanning electron microscopy (SEM), and energy-dispersive X-ray (EDX) analysis. 3D surface analysis results indicated a higher value of surface roughness (SR) on the top of the work surface and a lower SR on the bottom portion of the work surface. The surface morphology of the machined sample obtained at optimized parameters showed a reduction in microcracks, micropores, and globules in comparison with the machined surface obtained at a high discharge energy level. EDX analysis indicated a machined surface free of molybdenum (tool electrode).. The three-dimensional surface examination indicated an increase in surface roughness (SR) at the top of the mechanized surface and reduced SR at the bottom, due to the low risk of the dielectric fluid. Compared to mechanized surfaces with high discharge energy, people who were treated under custom conditions showed fewer micropores, microcracks, and balls. The EDX analysis confirmed a molybdenum-free mechanical surface, indicating any tool electrodes. For nitinol (toff = 12 µs, tonnes = 40 µs, and current = 1 A), the use of optimal welding parameters and a molybdenum electrode was recommended to reduce surface defects, preserve the size, and ensure a clean, MO-free surface. (Gholipoor, Shabgard and Arghavanian, 2020) Effects of the WEDM input variables were investigated, such as the duration of the pulse and the work flow, the depth of the heat-affected area (HAZ), and 617 the thickness (RLT) to the Relapse Tail (RLT). Conclusions showed that increasing the workflow increases the maximum RLT, while the depth of the shark has decreased. The depth of both has and RLT thickness increased with long heart rate. In addition, the results demonstrated that WEDM increased the corrosion resistance of mechanized workpieces. (Vora et al., 2023) An experiment investigated the WEDM process on Ti6Al4V, using material removal rate (MRR) and surface roughness (SR) as the output measures. The input factors included current (I) at 1, 3, and 5 A, pulse-off time (TOFF) at 6, 16, and 26 µs, and pulse-on time (TON) at 20, 60, and 100 µs. The link between the input and output components was examined using a three-level Taguchi L9 design. Analysis of variance (ANOVA) was used to assess the model terms' acceptability. With a 74.95% influence on MRR, TOFF was the most influential, followed by TON at 16.39% and

I at 6.56%. With an influence of 50.24%, TON was the most important component for SR. I came in second with an impact of 43.99%, while TOFF had a negligible impact of 1.47%. (Hammami et al., 2023) We used a three-factor, three-level WEDM process, set on 1, 24 and 64 s on heart rate (tonnes), heart rate-of time (toffee) 1, 2 and 4 s, and at 4 s, and power (i) 1, 2 and 3. We employed an L9 Taguchi orthogonal array to construct the trials and assess the influence of different process factors. Surface roughness (SR) measurements, the signal-to-noise ratio (S/N) which is the ratio between the desired information or the power of a signal and the undesired signal or the power of the background noise and it will be negative when it is better for minimizing the output, and the results of ANOVA showed that TON and TOFF had a big effect on SR. The surface topography of both aluminum alloys exhibited no fractures post-treatment.

$$S/N = -10 * \log(\Sigma(Y2)/n))$$

2. METHODOLOGY AND MATERIAL USED

The workpiece material used in the present experimental work is stainless steel 1610 with dimensions (250 × 250 × 16) mm, as shown in Fig. 1, Table 1 lists the chemical composition of the metal used. which were then machined using wire-EDM.

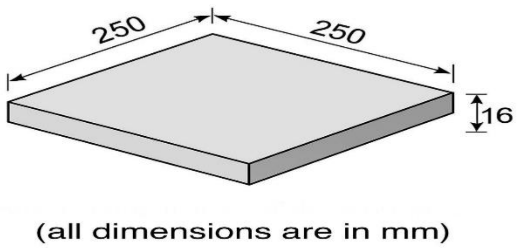

Fig. 1 Dimensions of the workpiece before machining

Table 1 chemical composition of stainless steel 1610

Test report chemical composition of workpiece material									
Element	C	Cr	Ni	Mo	Mn	Si	N	P	S
Exp.	0.65	16.8	10.4	1.12	1.2	0.80	0.155	0.339	0.005
ASTM	0.8	16-18	10-14	2-3	2	0.75	0.1	0.045	0.030

The stainless steel grade 1610 was selected due to its relatively high hardness and corrosion resistance, which makes it representative of difficult-to-machine materials often encountered in industrial applications.

3. EXPERIMENTAL WORK

Wire Electrical Discharge Machining (WEDM) process was used to cut the samples for the processing of thickness up to 16 mm. The parameters and their levels applied in this experimental work were based on a previous research experiment conducted on 20 samples. Also, the Taguchi technique was utilized to select and manage the optimal input values for achieving high precision in the WEDM process. Copper wire electrodes are the most commonly used in this machining process, with a diameter of 0.25 mm. The process input parameters were pulse-on-time (Ton) (in µs), pulse-off-time (Toff) (in µs), and servo feed (SF) (in m/min), which were considered to be the variable parameters as shown in Table 2. These parameters were selected due to their direct impact on product quality. The wire speed (S) affects the wire's ability to remove chips and prevent adhesion or breakage, improving surface quality during machining. The feed rate (F) influences the machining time and dimensional accuracy, helping to study the balance between production speed and final surface quality. The pulse on time (TON) affects both surface quality and roughness. While the parameters kept constant are shown in Table 3, Fig. 2 illustrates the WEDM machine settings used in the machining process.

Table 2 Cutting parameters.

Parameter	Level 1	Level 2	Level 3
Servo feed (m/min)	400	500	600
Pulse on time (µs)	24	28	32
Pulse off time (µs)	36	40	44

Table 3 Constant input parameters during machining

Constant parameters	Value
Spark gap voltage	15 V
Current	12 A
Water pressure	11 pascal
Wire feed	9 mm/min
Wire tension	7 Kg

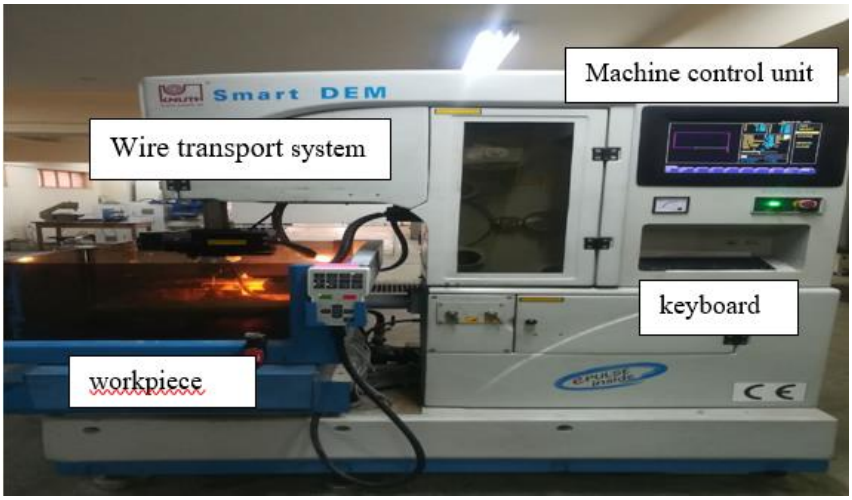

Fig. 2 Experimental setup of wire electrical discharge machining

4. RESULTS AND DISCUSSION

Table 4 presents the experimental outputs of machining stainless steel 1610 as per the L9 orthogonal mixed array. The machining responses, including RLT in µm and surface roughness, have been calculated and enhanced, as detailed in the subsequent section.

Table 4 experimental outputs of machining stainless steel 1610

EXP. NO.	Coded values			Real Values								
	A	B	C	Srvofeed	Pulse ON	Pulse Off	Ra	RLT	SNRA1	MEAN1	SNRA2	MEAN2
1	1	1	1	400	24	36	3.482	14.39	-10.8366	3.482	-23.1612	14.39
2	1	2	2	400	28	40	3.733	14.62	-11.4412	3.733	-23.2989	14.62
3	1	3	3	400	32	44	3.271	14.86	-10.2936	3.271	-23.4404	14.86
4	2	1	2	500	24	40	3.189	15.59	-10.0731	3.189	-23.8569	15.59
5	2	2	3	500	28	44	3.880	15.96	-11.7766	3.880	-24.0607	15.96
6	2	3	1	500	32	36	4.274	16.81	-12.6167	4.274	-24.5114	16.81
7	3	1	3	600	24	44	3.983	18.69	-12.0042	3.983	-25.4322	18.69
8	3	2	1	600	28	36	4.936	19.69	-13.8675	4.936	-25.8849	19.69
9	3	3	2	600	32	40	4.972	20.09	-13.9306	4.972	-26.0596	20.09

4.1. RESULTS FOR (Ra)

Table 4 shows the experimental outputs of machining stainless steel 1610 according to L9 orthogonal mixed array. The machining response, Ra in µm has been measured and optimized as shown in Fig. 3. It can be noticed from Fig. 3 and 4 that minimizing pulse on-time (Ton) the pulse energy of the electric spark is decreased. Therefor the minimum the pulse duration time, the less the melted material, and there for the formation amplitude of the surface roughness is minimized. Also for pulse off time it can be seen that maximizing the pulse off-time, energy of the electric discharge is decreased, therefor the higher the pulse off-time, the less the molten material, and consequently the distribution of the surface irregularities is reduced. It can be noticed from Table 6 that at low level of the servo feed the S/N ratio is maximized. Therefore, the formation of the recast layer at this level is minimized which Leeds to good surface finish as mentioned in Table 5.

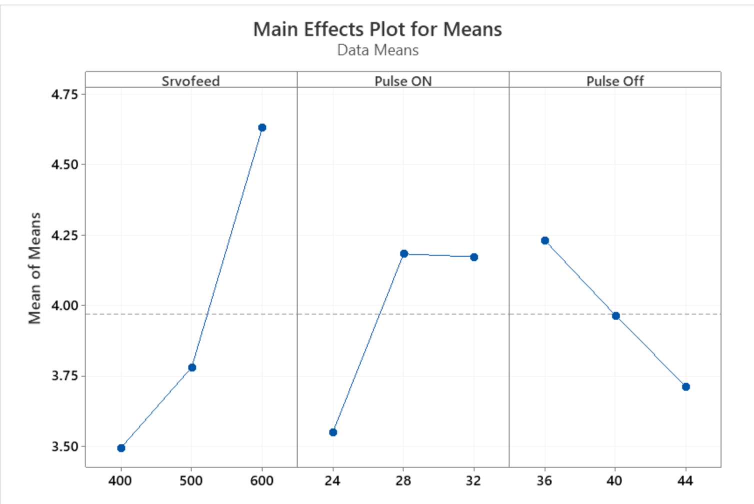

Fig. 3. Main effect plot for means of Ra

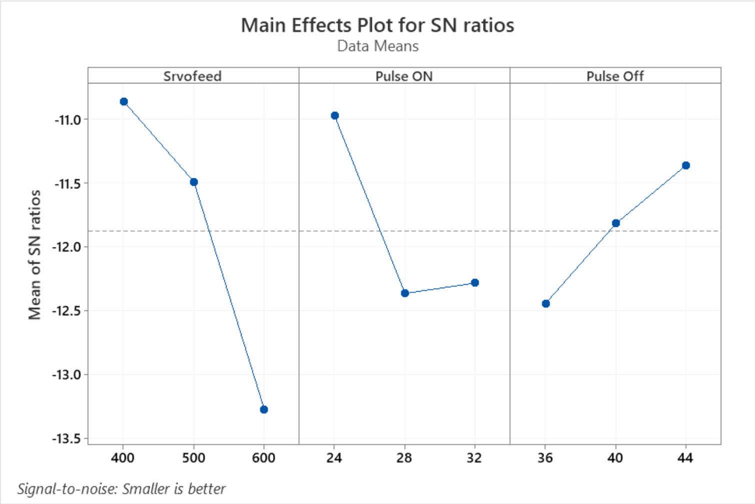

Fig. 4. Main effect plot for signal-to-noise ratio of Ra

Table 5 Response Table for Means

Level	Srvofeed	Pulse ON	Pulse Off
1	3.495	3.551	4.231
2	3.781	4.183	3.965
3	4.630	4.172	3.711
Delta	1.135	0.632	0.519
Rank	1	2	3

Table 6 Response Table for Signal to Noise Ratios

Level	Srvofeed	Pulse ON	Pulse Off
1	-10.86	-10.97	-12.44
2	-11.49	-12.36	-11.81
3	-13.27	-12.28	-11.36
Delta	2.41	1.39	1.08
Rank	1	2	3

4.2. RESULTS FOR (RL)

The primary effects plot on the RLT may be inferred from Fig. 5 and 6, which indicate that SF, Ton, and Toff significantly impact RLT, as corroborated by Tables 7 and 8. The RLT of machined samples is exactly proportional to the SF, as seen in the Fig. 5 and 6. The SF demonstrates a significant increase of (16.12) µm and (19.49) µm in the mean of WLT as the SF escalates from (400 mm/min to 500 mm/min) and (500 mm/min to 600 mm/min), respectively. This phenomenon is attributed to the enhancement of SV, which amplifies the heat transferred to the machined surface, thereby increasing the volume of molten metal. The fixed quantity of liquid metal that the dielectric can remove results in the dielectric's inability to eliminate the molten material, hence forming a white or recast layer on the machined surface. The augmentation in pulse length leads to an increase in the thermal energy lost to the workpiece, resulting in greater molten material and thus higher surface roughness. Ultimately, extending the pulse off time allows for a greater volume of molten metal to be removed by the dielectric, resulting in an improved surface quality.

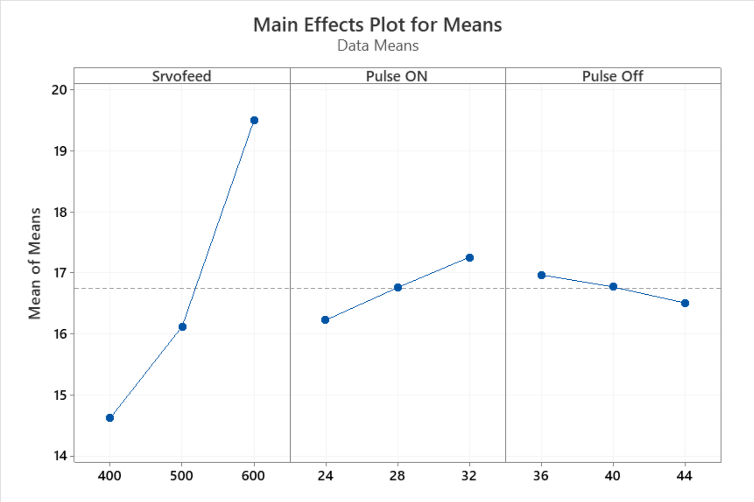

Fig. 5. Main effect plot for means of RLT

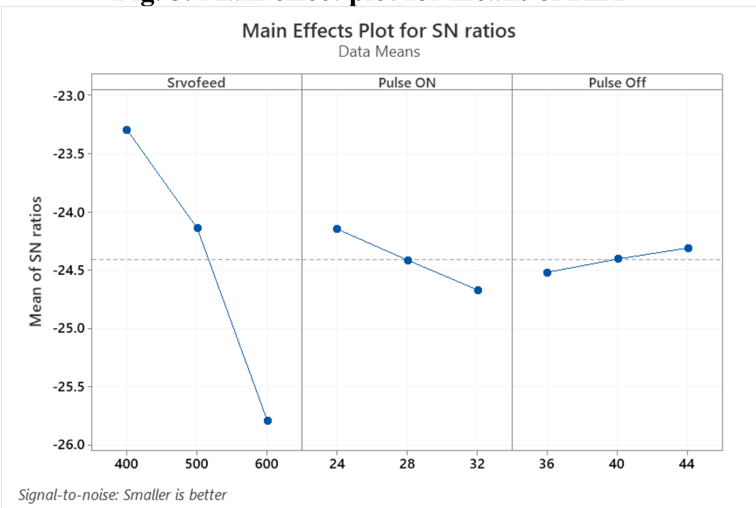

Fig. 6. Main effect plot for signal-to-noise ratio of RLT

Table 7 Response Table for Means

Level	Srvofeed	Pulse ON	Pulse Off
1	14.62	16.22	16.96
2	16.12	16.76	16.77
3	19.49	17.25	16.50
Delta	4.87	1.03	0.46
Rank	1	2	3

Table 8 Response Table for Signal-to-Noise Ratios

Level	Srvofeed	Pulse ON	Pulse Off
1	-23.30	-24.15	-24.52
2	-24.14	-24.41	-24.41
3	-25.79	-24.67	-24.31
Delta	2.49	0.52	0.21
Rank	1	2	3

5. CONCLUSIONS

This experimental study identifies the WEDM process factors that influence the quality of end goods fabricated from stainless steel 1610. The outcomes of modifying parameters within the chosen process variables during the WEDM cutting of stainless steel 1610 are provided. The subsequent conclusions are derived from the experimental results and analysis:

Increasing pulse on time and servo feed results an increase in surface roughness.

Increasing pulse off time leads to minimizing the surface roughness.

From the results, it can be noticed that maximizing pulse duration will increase thickness of recast layer.

The results revealed that increasing pulse off time minimizing thickness of recast layer.

Finally increasing servo feed increasing recast layer thickness.

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