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OPTIMIZATION OF WIRE ELECTRICAL DISCHARGE MACHINING OF INCONEL- 625

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ABSTRACT

Inconel-625 is a nickel-alloy based material with superior properties such as high fatigue strength, high hardness, and oxidation resistance. These properties make it suitable for applications in marine, aerospace, and power generation industries. Due to its high hardness, the material is difficult to machine by conventional machining methods such as turning, milling or grinding. For this reason, an alternative method known as Wire Electrical Discharge Machining (WEDM) can be adopted for such materials. In this paper, WEDM is optimized through Taguchi optimization technique. Inconel-625 plates of 10 mm thickness were used as specimen in experimental work. For maximum material removal rate (MRR) and minimum surface roughness (SR), it was observed that the optimum pulse- on time (TON), wire feed rate (WF), and gap voltage (SV) could be set to 0.4 µs, 10 mm/min and 68 V respectively.

Keywords: Material removal rate, Pulse-on time, Surface roughness, Gap voltage, Wire electrical discharge machining, Wire feed rate.

1. INTRODUCTION

Wire electrical discharge machining is an electro-thermal process that utilizes a wire electrode that is continuously travelling to erode material from the workpiece submerged in a dielectric fluid as shown in Figure 1.

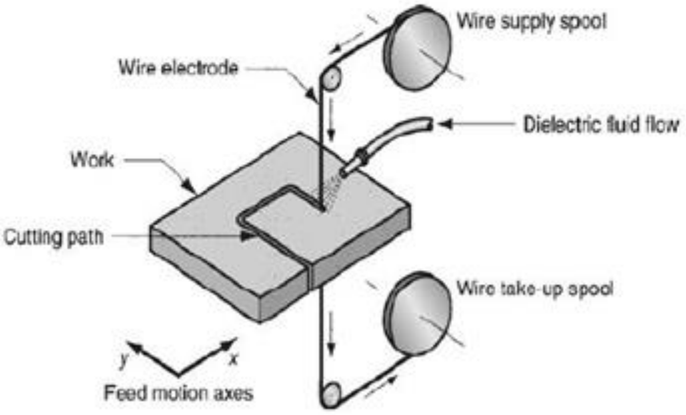


Fig. 1: Schematic diagram of WEDM process [1]

In WEDM, the optimum machining process parameters are governed mainly by the properties of the workpiece material [2]. Improper selected machining parameters may result in undesirable effects such as low MRR, wire breakage, short-circuiting of wire, and poor surface finish [3]. WEDM processes have been reported in literature. [4] studied the influence of duty cycle and peak current in the WEDM of Inconel-625 by applying Taguchi orthogonal array to optimize these parameters for minimization of SR. In their study, the SR was found to increase as the TON increases and decrease as the pulse-off time (TOFF) decreases.

[5] Conducted a study on the WEDM of Inconel-625, in which the influence of peak current, wire tension, TOFF, wire diameter, and TON on MRR, corner accuracy, and SR was investigated. It was reported that for optimum MRR, good surface finish and improved corner accuracy, the peak current, wire tension (WT), wire diameter, TON and TOFF should be set to 7A, 1400N/mm2, 0.25mm, 8 µs and 17µs, respectively. [6] Studied the influence of cutting process parameters on MRR and SR in WEDM of Inconel-625. The input parameters were TON, TOFF, WT, and peak current. The study used Taguchi technique and analysis of variance to analyze the impact of these parameters on output parameters. As results, it was concluded that WT had no much effect on both SR and MRR. The TON was found to have an influence on the two output parameters, whereas TOFF influences less on SR than on MRR. It was also found that the peak current has the largest influence on the SR.

[7] Conducted a study on surface characteristics and MRR in WEDM of Inconel-625. In the study, the input parameters were peak current, TON, and TOFF. It was reported that both MRR and SR increase as the peak current and TON increase. [2] Researched on the machining performance of WEDM of Inconel-625. In the research, application of fuzzy inference systems coupled with Taguchi's technique was found to be an efficient method for optimization of input

parameters on SR and MRR. It was reported that the optimum values of TON, flushing pressure, peak current, and SV should be 200 µs, 0.6 bars, 5 A and 90 V respectively.

From the foregoing, it can be seen that much work has been done on the influence of discharge current, duty cycle, wire diameter, WT, and TOFF using fuzzy inference systems and Taguchi orthogonal arrays. The main focus has been on how these parameters affect MRR, SR, and corner accuracy. However, the influence of combined set of TON, WF, and SV has not been investigated. In this study, authors aim at optimizing WEDM process of Inconel-625, considering a combination of the above mentioned parameters. This research, therefore, contributes through investigating the effect of combined set of TON, WF, and SV on MRR and SR in machining of Inconel-625 by using AWT6S WEDM machine.

2. MATERIALS AND METHODS

2.1 Description of Used Materials and Procedures

Experiments were conducted on the AWT6S wire EDM machine. The SR and the kerf width were measured using MITUTOYO SJ-30 surface roughness tester and MITUTOYO PJ311 profile projector respectively. The MRR was obtained from the volume of the metal removed for a given machining time. Photographs of the equipment used are shown in Figures 2-4.

Fig. 2: AWT6S wire EDM machine

Fig. 3: Setup for measument of surface roughness using Mitutoyo surface rougness tester

Fig. 4: Setup for measurement of kerf width using profile projector

The specifications of the AWT6S wire EDM machine, MITUTOYO SJ-30 surface roughness tester, and PJ311 profile projector are shown in Table 1.

Table 1: Specifications of equipment used

Wire EDM	Model	AWT6S
	Dielectric fluid	Deionized water
	TON range (µs)	0.005-1.2
	TOFF range (µs)	1-50
	WF range (mm/min)	1-15
	SV range (V)	20-150
SR tester	Model	PJ-301
Profile projector	Model	PJ-311
	Screen diameter (mm)	300
	Rotation (degrees)	360

Experiments were designed using full factorial design of experiments (DOE) technique. 10 mm thick specimen of Inconel-625 were used. Experimental study was carried out within permissible working range for AWT6S wire EDM Machine which is from 0.005 µs to 1.2 µs; 1mm/min to 15 mm/min; and 20 V to 150 V for TON, WF and SV respectively. MRR was obtained as:

$$MRR=V/t \qquad (1)$$

Where *V* is the volume of *MRR* for duration of time *t*. The volume is determined from the material thickness and the kerf width. The SR was measured by applying *JSB0601-2001 and ISO* standard. Sample of printout of SR results is shown in Figure 5.

Fig. 5: Sample of printout of surface roughness results

In order to determine the standard parameter-levels to use in the study, preliminary studies on machining performance of various input parameters were carried out.

2.2 Preliminary Experiments

2.2.1 Influence of Pulse-on time on Machining Process

The effect of TON on the machining process was investigated varying the levels of this parameter and keeping constant the levels of WF and SV. From the operational manual, the designer of the AWT6S machine recommends that, for better machining performance, the WF can be set between 7 mm/min and 10 mm/min. In this study, straight cuts were performed and the surface was found lower at a WF of 9 mm/min. In addition, optimization was done for the WEDM of Inconel-X750 by applying the analysis of variance for raw data as well as for signal to noise ratio using Taguchi technique and results revealed that the SR is minimum for a SV of 65V [8]. Since this material is similar to Inconel625 in terms of properties that affect machining process such as hardness, electrical resistivity, and thermal conductivity, then the effect of SV on both materials can be assumed to be the same and consequently, this parameter was kept constant at 65V. The effect of TON on performance measures namely SR and MRR was investigated by varying the levels of TON from 0.005 µs to 1.2 µs and keeping WF and SV constant at 9 mm/min and 65 V, respectively. However, the small pulses could not be good enough to create energy for eroding the material and therefore significant machining process was observed starting from a TON of 0.4µs. Average SR, Ra (µm) was used to measure the roughness of the material. The Main Effects Plot (MEP) was used to plot the data mean for the levels of TON to examine how this factor influences the SR and MRR as shown in Figure 6.

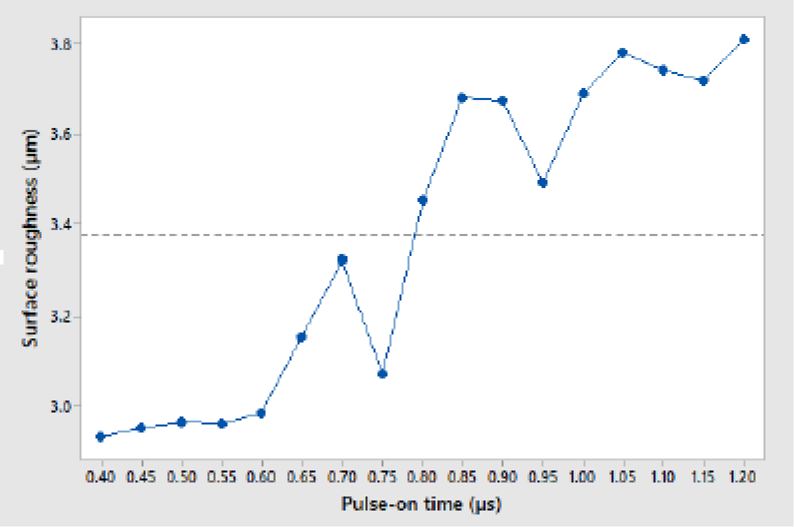


Fig. 6: Effect of pulse-on time on surface roughness

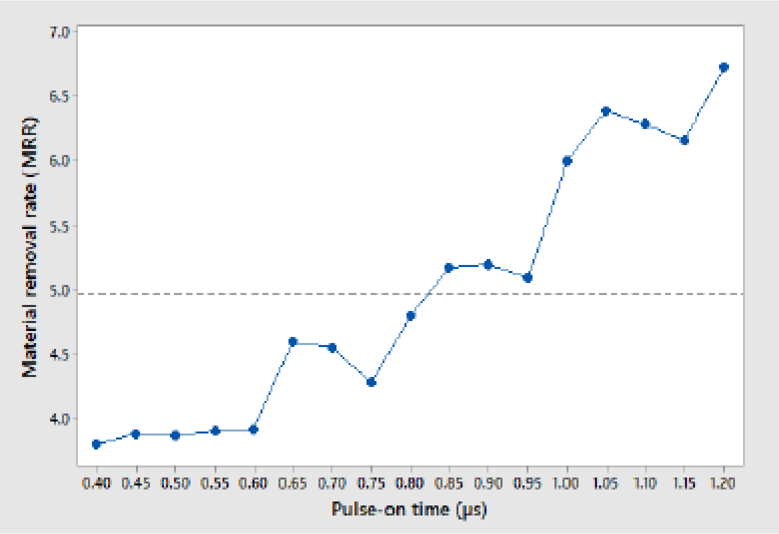


Fig. 7: Effect of pulse-on time on material removal rate

The results presented in Figures 6-7 show that both SR and MRR increase with the increase in TON. As the latter increases, the higher peak discharge current and pulse width occur, hence the cutting speed increases. The increase in cutting speed causes instability in the process and therefore the SR increases. However, wire will easily break during coarse discharge and the SR will increase. In order to minimize and avoid the possibility of wire breakage, the TON was set within 0.4 µs and 0.6 µs and the SR was found minimum at 0.5 µs.

2.3 Influence of Gap Voltage on Machining Process

The effect of SV on the machining process was investigated by varying this parameter from 20 V to 150 V and keeping WF and TON constant at 9 mm/min and 0.5 µs respectively. To minimize the number of experiments, an increment of 2V to 3V was kept between two successive levels of SV. The MEP was used to plot the data mean for the levels of SV to investigate the effect of this parameter on both the SR and MRR as shown in Figures 8-9.

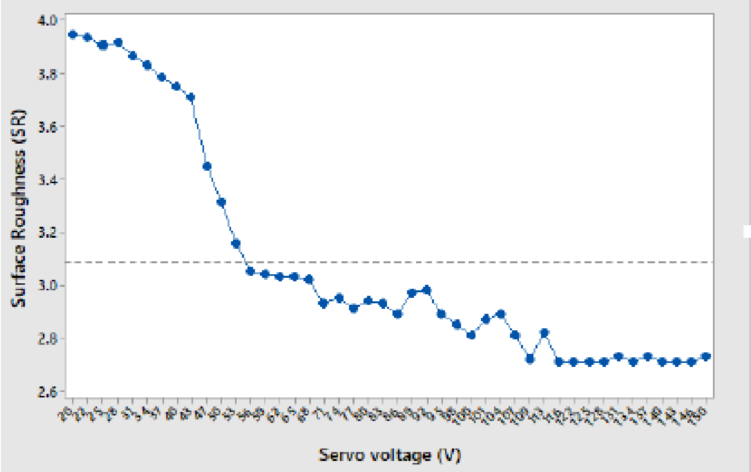


Fig. 8: Effect of gap voltage on surface roughness

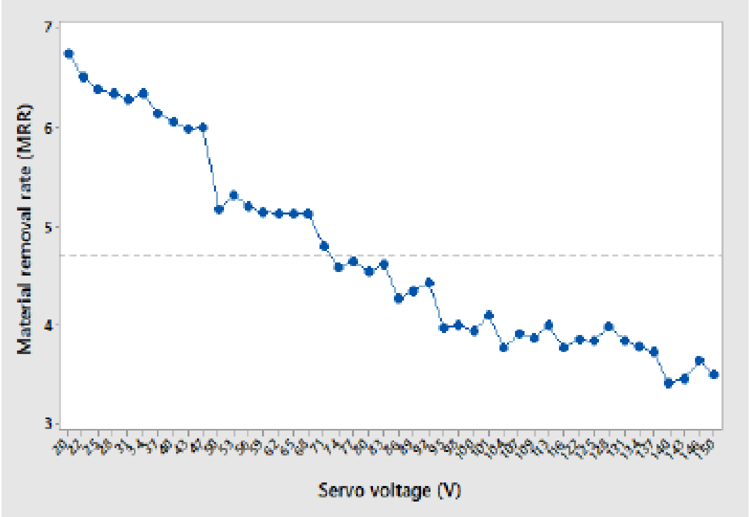


Fig. 9: Effect of gap voltage on material removal rate

The results show that both SR and MRR decrease with the increase in SV as shown in Figures 8-9. This can be interpreted in a way that the SV initiates the discharge speed, and as the latter becomes larger and larger, the stability increases and the SR decreases. The smaller value of SV causes faster discharge speed and the smaller gap groove during cutting process. Therefore, if the value is set too small, discharge will be instable and wire will easily break during the process. In addition, results show that both SR and MRR decrease gradually from 20V to 53V thereafter, staying almost constant until the value of SV reaches 68V. Afterwards, it can be seen that responses reduced unsteadily which could cause wire breakages. For this reason, the SV was held within 56 V and 68V. Experiments were conducted to investigate how this parameter responds to SR within this range and it was found that the minimum SR occurs at 62V. Therefore, the effect of WF was studied keeping the TON and SV constant at 0.5 μs and 62V respectively, and varying the WF from1mm/min to 15mm/min.

2.3.1 Influence of Wire Feed Rate on Machining Process

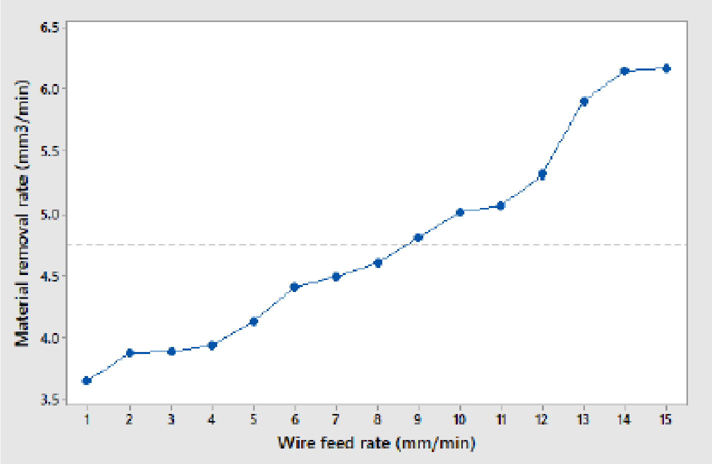


Fig. 10: Effect of wire feed rate on material removal rate

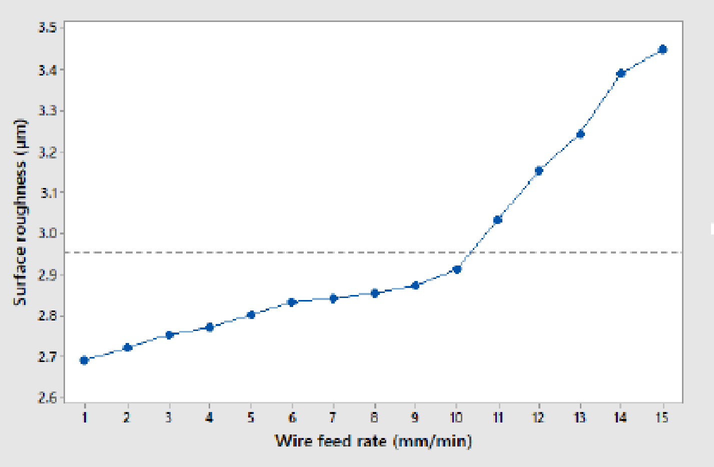


Fig. 11: Effect of wire feed rate on surface roughness

As shown in Figures 10-11, both the SR and MRR increase with the increase in WF which, when set to higher values, causes more discharges to occur and the MRR to increase. However, the discharge will be unstable and therefore causes the SR to increase gradually. It can be seen that the SR and MRR increase with the increase in WF. Setting the WF to a bigger value avoids wire breakage and enhances cutting precision. On the graph shown in Figure 10, it is seen that the gradient reduced at a WF of 6 mm/min and increased at a WF of 10 mm/min. This shows that there was a tendency for reduction of SR within that range. Further experimentation was conducted on this behavior. The parameter-levels resulted from preliminaly investigations are shown in Table 2.

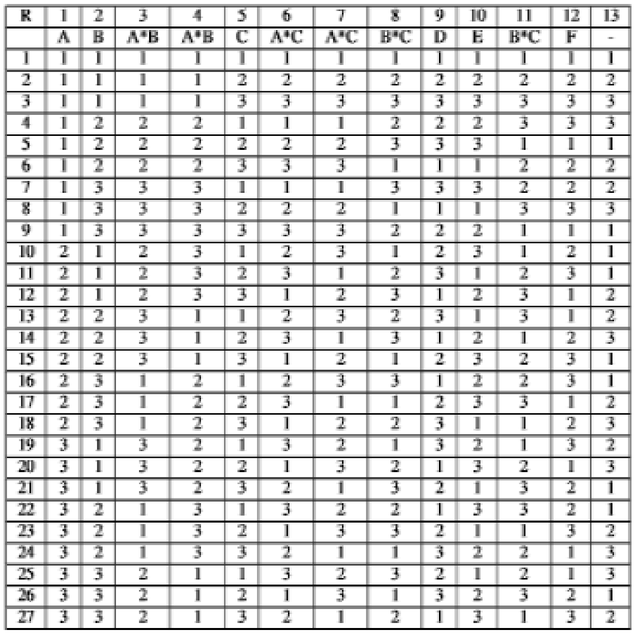
Table 2: Parameter-levels used

Factor	Parameter	Level		
1	TON (µs)	0.4	0.5	0.6
2	WF (mm/min)	6	9	10
3	SV (V)	56	62	68

In order to investigate the effect of combined input parameters on output performance, the parameter-levels obtained after preliminary investigations as shown in Table 2 were considered as inputs to the Taguchi's L27 orthogonal array presented in Table 3.

2.4 Influence of Combined Input Parameters on Machining Process

Table 3: Taguchi's L27 orthogonal array



R	1	2	3	4	5	6	7	8	9	10	11	12	13
	A	B	A*B	A*B	C	A*C	A*C	B*C	D	E	B*C	F	-
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	1
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

The influence of combination of TON, WF and SV on both MRR and SR was investigated by applying Taguchi's L27 orthogonal array presented in Table 3. Using this approach, the mean performance characteristic and the confidence intervals for the predicted mean were determined. The analysis of variance (ANOVA) was performed in MINITAB-17 software. For SR, results for Means and S/N ratios are presented in Figure 12 and Table 4, whereas for MRR rate, the results are presented in Figure 13 and Table 5.

3. RESULTS AND DISCUSSION

3.1 Influence of Input Parameters on Surface Roughness

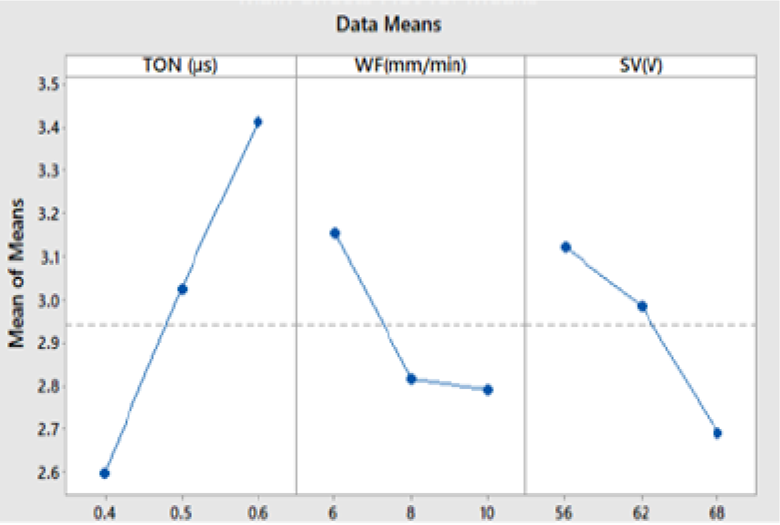


Fig. 12: Main effects plot for Means

From Figure 12, it can be seen that the Means are minimized when the TON is 0.4 µs, WF is 10 mm/min and SV is 68 V.

Fig. 13. Main effects plot for S/N ratios

As shown in Figure 13, the S/N ratios are maximized at TON of 0.4 µs, WF of 8 mm/min and SV of 68 V. ANOVA results for Means are presented in Table 4.

Table 4: ANOVA results for Means

Source	*DF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
TON (µs)	2	2.2530	1.7531	0.87656	10.81	0.039
WF (mm/min)	2	0.3622	0.4393	0.21967	2.71	0.046
SV (V)	2	0.5851	0.5851	0.29254	3.61	0.031

S=0.7369 R-Sq=98.5% R-Sq (adj) =91.17%

Table 5: ANOVA results for S/N ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
TON (µs)	2	20.47	16.371	8.1856	9.34	0.023
WF(mm/min)	2	3.993	4.836	2.4179	2.76	0.049
SV (V)	2	6.042	6.042	3.0212	3.45	0.037

S=0.1671 R-Sq=98.7% R-Sq (adj) =95.1%

The results presented in Tables 4-5 show that TON, WF, and SV are significant on SR and MRR by 95% confidence level since their respective P-values are less than 0.05 for Means and for S/N ratios.

3.2 Influence of Input Parameters on Material Removal Rate

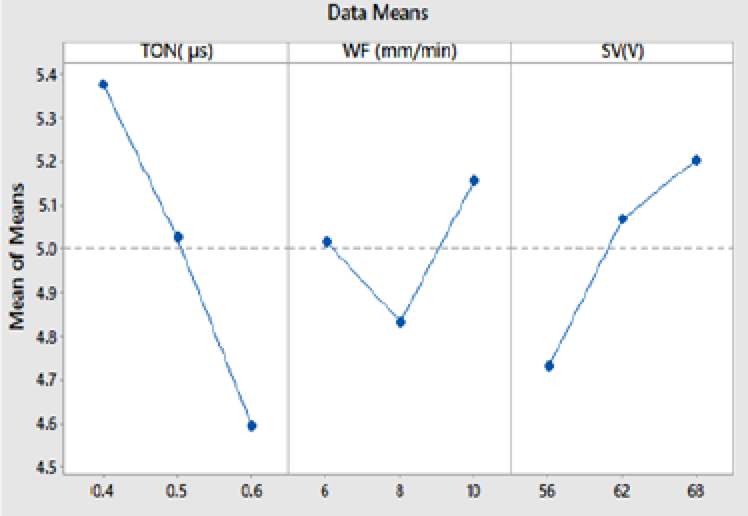


Fig. 14: Main effects plot for Means

As shown in Figure 14, the level averages of the means were maximized when the TON was 0.4 µs, WF was 10 mm/min and SV was 68 V.

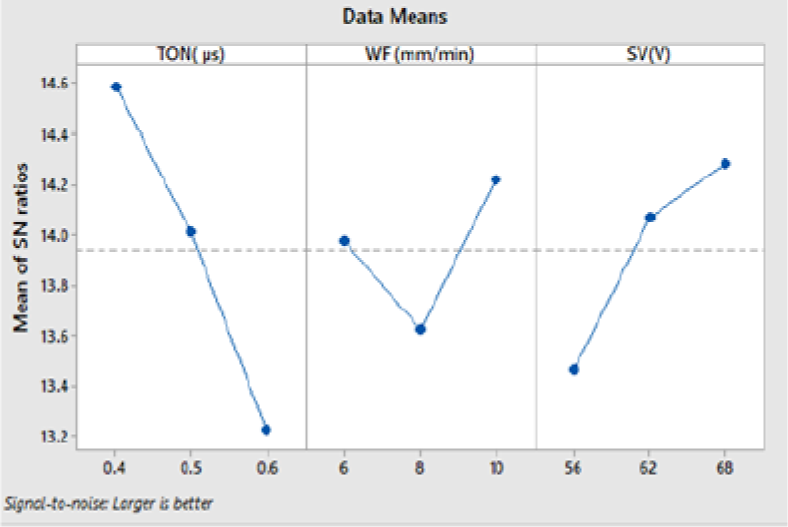
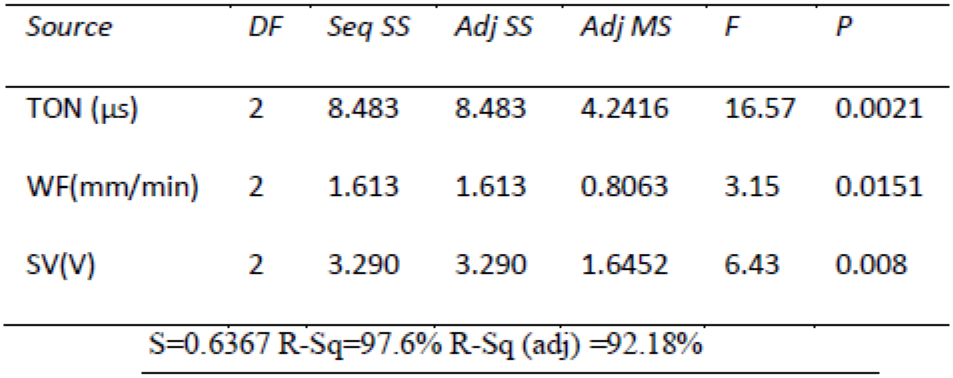


Fig. 15: Main effects plot for S/N ratios

From Figure 15, it can also be seen that for MRR, the S/N ratios were maximized when the TON was 0.4 μs, WF was 10 mm/min and SV was 68 V.

Table 6: ANOVA results for Means



Source	*DF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
TON (μs)	2	8.483	8.483	4.2416	16.57	0.0021
WF(mm/min)	2	1.613	1.613	0.8063	3.15	0.0151
SV(V)	2	3.290	3.290	1.6452	6.43	0.008

S=0.6367 R-Sq=97.6% R-Sq (adj) =92.18%

Table 7: ANOVA results for S/N ratios

Source	*DF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
TON (µs)	2	7.482	7.472	4.2315	17.46	0.0422
WF(mm/min)	2	1.512	1.714	0.7062	3.16	0.0242
SV (V)	2	3.281	3.291	1.5451	6.42	0.0171

S=0.7357 R-Sq=98.3% R-Sq (adj) =92.11%

The results presented in Tables 6-7 show that, as it is seen for Means, the TON, WF, and SV are also significant on MRR by 95% confidence level since their respective P-values are less than 0.05 for Means and S/N ratios.

4. CONCLUSION AND RECOMMENDATION

In this study, investigation was conducted on the influence of TON, WF, and SV on MRR and SR. Taguchi's technique was applied for design of experiments and optimization of the process for high MRR and improved SR. The following are key highlights of the results of the study.

1. The confidence level for ANOVA for Means and for S/N ratios were found at 95% and therefore the TON, WF, and SV are significant to machining process in terms of MRR and SR.
2. The optimum value of SR and MRR was obtained at a TON of 0.4 µs, WF of 10 mm/min, and SV of 68 V. This study investigated the influence of input machining parameters on MRR and SR. It is recommended that the investigation can be extended to cover other performance parameters such as kerf width.

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