Effect of the Electrical Discharge Machining Parameters on Material Removal Rate

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الملخص:

هذه الدراسة استخدمت طريقة (Tagushi and Signal to noise ratio) كمنهجية تجريبية لتحسين مدخلات عملية التصنيع (Input Parameters) والمخرجات (Outputs) لغرض تحسين معدل إزالة المعدن (MRR) كمقياس لاداء عملية التصنيع بالتفريغ الكهربائي (EDM) اثناء تصنيع سبيكة الفولاذ نوع DIN 1.2080. تم إجراء التجارب بناءً على تصميم المصفوفة المتعامدة القياسية (L9) باستخدام أربع مدخلات، وهي قطر الالكترود الكهربائي (D) ، تيار التفريغ (Ip) ، النبض في وقت التشغيل (Ton) وعامل التشغيل (η) ، وذلك استنادًا إلى تحليل (S/N).

من خلال النتائج النهائية لمنهجية التحسين المتبعة تم الحصول على القيم المثلى للمدخلات على النحو التالي: قطر الالكترود عند المستوى3 (25 ملمتر) ، تيار التفريغ عند المستوى3 (25 امبير) ، النبض في الوقت المحدد عند المستوى1 (300 ميكروثانية) وعامل التشغيل عند المستوى1 (0.65)، أي (D3، Ip3 و Ton1 و η1). مع الأخذ في الاعتبار اتباع نهج (Larger is Better). أشارت نتائج مخطط التأثير الرئيسي إلى أن العوامل: النبض في وقت التشغيل، وتيار التفريغ هما أهم المعاملات تاثيرا علي معدل إزالة المعدن ، متبوعًا بقطر الالكترود، وكان عامل التشغيل هو العامل الأقل تأثيرًا.

تم تطوير نموذج رياضي لتقدير وحساب معدل ازالة المعدن باستخدام تحليل الانحدار، و كانت القيم من النموذج والقيم التجريبية قريبة جدًا من بعضها البعض مما يدل على أهمية النموذج المطور.

Abstract:

This study applies Taguchi's Design and Signal to Noise Ratio as an experimental methodology to enhance and improve the process parameters and

the removal rate of the material MRR, to machine the tool steel alloy DIN 1.2080 during discharge machining EDM. Experiments have been carried out in accordance with L9 standard orthogonal array design with four process parameters, namely Electrode Diameter, Discharge Current, Duty Factor and Pulse on time, utilizing the S/N analysis.
The following was discovered to be the best process parameter setting: Electrode Diameter at level 3 (25mm), Discharge Current at level 3 (25A), Pulse on time at level 1 (300 μs) and Duty Factor at level 1 (0.65) i.e. Di3, Ip3, Ton1, and η1 considering larger-better approach. The main effect plot results indicated that Pulse on time, and Discharge Current are the most significant parameters for the material removal rate, followed by Electrode Diameter. The Duty Factor is the least affecting parameter on the response. A Regression analysis was used to construct a mathematical model for the reaction between response and inputs, the predicted value of the developed model and experimental value are very close to each other showing significance of the developed model, it is observed that there is good agreement between the predicted and experimental values.

Keywords: EDM, Taguchi Design Method, Signal to noise Ratio, Material Removal Rate MRR.

1. Introduction

Electrical Discharge Machining defined as the non-traditional process of material removal of the conductive materials to produce parts with desired shapes. This process is done by applying high-frequency current to the sample and the electrode, which melts the material. Positioned very precisely near the workpiece, the electrode never touches the workpiece but discharges its potential current through an insulating dielectric fluid across a very small spark gap. “The spark is reported to be in the range of 8000 to 12000°C, this process is used when the workpiece material is too hard, or the shape cannot easily machined, this makes many formerly difficult projects more practical and many times it can be the only feasible way to machine a part or material” (El-Sheikh and El-Gnemi, 2017).

It is important to find the best parameter setting before start the machining process in order to achieve the best results. A single parameter change will influence the process in a complex way. Once the optimum parameters are obtained, it reduces the machining cost and improved product’s quality.

“Today's manufacturing industry is facing challenges from advanced difficult-to-machine materials (super alloys, ceramics, and composites) traditional machining processes are not satisfactory, economical, or even impossible, due to hardness and strength of the material is very high, the shape of the part is complex, temperature rise and residual stresses in the work piece are not desirable or acceptable” (kozak and gulbinowicz, 2010).

It is clear from previous studies, manufacturers and researches relied on the use of non-traditional manufacturing methods like (EDM) instead of traditional methods like turning and milling in manufacturing the metals with high hardness, that could not be machined in traditional ways because the hardness of the workpiece is higher than the hardness and rigidity of the machine and cutting tool (Idris and Mosrati, 2019).

1.1 Electrical Discharge Machining Applications

There are a lot of applications of EDM in the industry like Automotive industry, figure1 shows some parts machined using EDM, such as: cylinders, Gears, and many other engine parts are obtained from EDM technology (elhofy, 2005).
Also EDM is used to create plastic injection molds with complex shapes, many of today’s products simply could not be produced without it. Some equipment's as cell phones, calculators, cameras, medical devices and some high tech equipments that are made out of plastic and cannot be produced without this technology as shown in Figure 2 (Speeding And Wang, 1997).

Figure1: Examples of Automotive parts

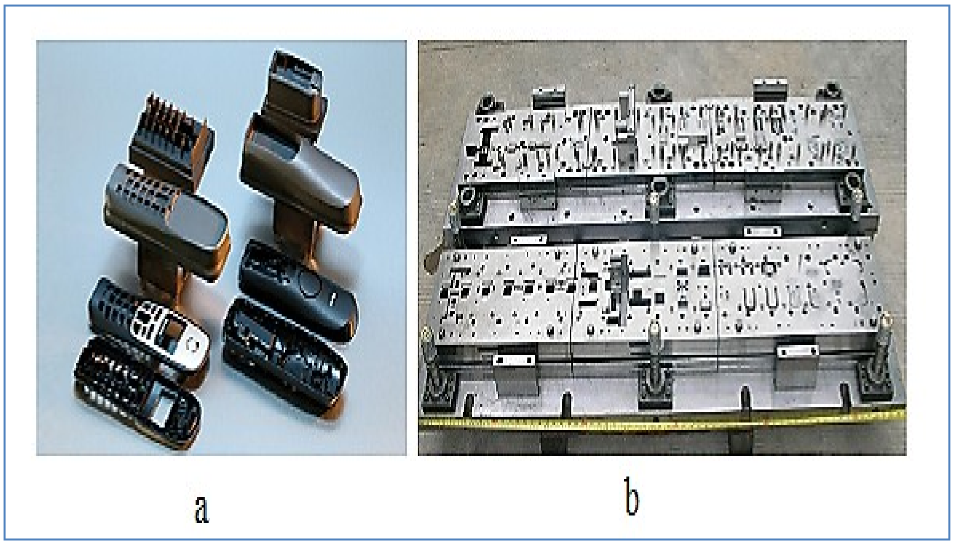

Figure 2: Examples of EDM applications in plastic injection molds

“Wire cut EDM is widely used to machine various molds, such as punch die, squeezing die, powder metallurgy mold” (Sorabh et al., 2013). Other Applications are found in military applications and medical applications and aerospace applications.

1.2 EDM Process Parameters

As explained earlier, some of the important process parameters which influence the responses are:

1.2.1 Electrical Parameters

Generator power supply produces the pulse current at the machining gap. The control of the generator is important because they directly determine the power applied to the working gap (Hewidy et al., 2005). Discharge voltage (V) is applied between the electrodes. It depends upon the electrode gap (Speeding, and Wang, 1997). Pulse-on time (Ton) It is the time during which actual machining takes place and it is measured in μs. In each discharge cycle, there is a pulse on time and pause time/Pulse off time, and the voltage between the electrode and workpiece is applied during Ton duration. Pulse-off time (Toff) In a cycle, there is a pulse off time or pause time during which the supply voltage is cut off as a consequence the Ip drop to zero. It is also the duration of time after which the next spark is generated and is expressed in µs, figure 3 shows the EDM pulses cycle (Parshar et al., 2009).

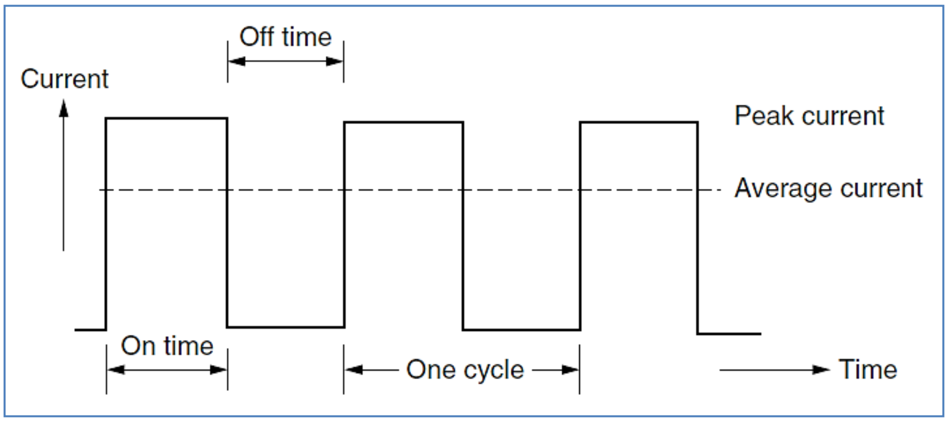

Figure 3: Typical EDM pulses time.

Discharge Current Ip is the most important machining parameter in EDM because it relates to power consumption of power while machining directly proportional to the Material removal rate. Duty cycle (τ) It is on-time period divided by total cycle time, It is defined in the equation1.

$$\tau = \frac{T_{on}}{T_{on}+T_{off}} \qquad (1)$$

Where:

T_{on} is pulse on-time.

T_{off} is pulse off-time.

A New input parameter called (pulse cycle time Tc) was introduced in (Idris and Imad Mokhtar, 2019) its effect on the EDM process responses was investigated, it was proven that Tc has an important effect, which affects material properties and process responses.

1.2.2 Non- Electrical Parameters

Electrodes Material**:** EDM electrodes must be good electrical conductors. Commonly used materials include graphite, brass, copper, copper-graphite, copper-tungsten, and zinc alloys. The EDM process causes much greater tool wear than conventional machining processes. Therefore, tool materials which provide the best wear ratio are used whenever possible (Hsue et al., 1999). All

EDM electrode materials must possess certain properties in order to perform economically in a given application (Qu. et al., 2002). Dielectric Fluid**:** It is an insulator applied at machining medium for cooling and remove the metal away.

1.3 EDM Responses

Performance Responses are used to evaluate the machining process, namely material removal rate, surface roughness, over cut, tool wear rate, white layer thickness and surface crack density (Mahapatra et al., 2007). The task of this article is to optimize the material removal rate using Tagushi approach. MRR is expressed by following equation 2:

$$\boldsymbol{MRR} = \frac{WRW=(W_b-W_a)}{t_m}\ (g/min) \qquad (2)$$

where:

WRW= Workpiece Removal Weight.

W_b = Weight of workpiece material before machining (g)

W_a = Weight of workpiece material after machining (g)

t_m = machining times (min)

1.4 Taguchi Design and Optimization Method

Taguchi approach is a design and optimization methodology, it is known as a widely used tool for the improvement of quality. Compared to classical experimental design, "Taguchi method uses orthogonal arrays to design the experiments which utilize the least. To achieve desirable product quality" (Konda et al., 1984).

The Taguchi method uses signal-to-noise ratio (S/N) to turn the trials result data into a value of the characteristics to analyze. The S/N reflects both the average and the variety of the quality characteristics. The standard S/N ratios generally used are as follows: Larger-the-better, smaller-the-better and nominal-the-best. The optimal setting is the parameter combination, which has the highest S/N ratio, in this study, Larger-the-better way is used to optimize MRR.

2.Methodology

A series of experiments on electrical discharge machining (EDM) of tool steel (DIN 1.2080) was conducted to examine the effects of input machining parameters such as current intensity Ip, pulse on time Ton, duty factor η, and electrode diameter on the output variable metal removal rate MRR.

2.1 Machine

Charmilles Roboform FORM 2-LC EDM die sinking machine was used for experiments as shown in figure 4.

Figure 4: Charmilles Roboform 2-LC Electrical Discharge Machine.

2.2 Workpiece Material

The workpiece material used in this study was tool steel (DIN1.2080) alloy, chemical composition is shown in table 1.

Table1: Chemical Composition.

Elements	C	Si	Mn	Cr	Mo	V	Ni
Composition	2.2	0.42	0.32	12.25	0.03	1	0.3

A Three shafts (Ø 25 mm x 31 mm length), (Ø 20 mm x 31 mm length) and (Ø 15 mm x 31 mm length), with nine pieces for each shaft were used.

2.3 Electrode Material

The electrode materials investigated in this research were copper, it is an important metal since it is widely used in industry, three shaft bars at different diameters are used, shafts has (Ø 30 mm x 71 mm length), (Ø 20 mm x 71 mm length) and (Ø 15 mm x 71 mm length). Electrode material properties are shown in table 2.

Table 2: Electrode Material Properties.

Composition	99.9% Copper
Density	8.904 g/cm^3
Melting point	1083°C
Electrical resistivity	9 μΩ cm
Hardness	100 HB

2.4 Dielectric Fluid

The dielectric fluid has been used is mineral kerosene. The quality, viscosity and composition of the dielectric are important for guaranteeing optimum spark erosion conditions.

2.5 Digital Balance

Its model is Precisa 202A, it is used to measure the weight of the workpiece and electrode before and after machining, Maximum, precision is 4 digits, figure 5 show the digital balance.

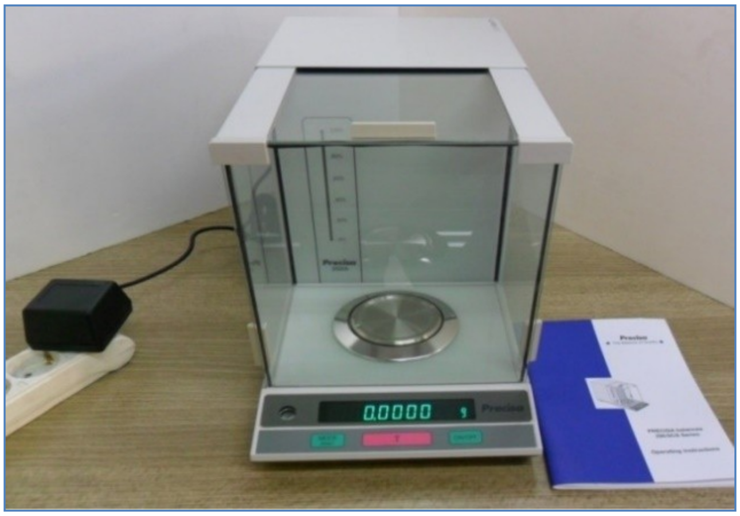

Figure 5: Digital Balance

2.6 Machining Performance Evaluation

The material removal rate is used to evaluate machining performance (MRR). It is defined as material removal weight (WRW) divided by the machining time in minutes (T).

2.7 Design of Experiments

The Taguchi method is used to design the experiments to establish optimum process settings, signal to noise ratio approach is used for the optimization purpose. Analysis of variance ANOVA is utilized to evaluate and analyze the effect of input parameters on the material removal rate, Minitab software is used for this purpose. Four control factors: electrode diameter, current, pulse on time, and duty factor, are selected for the study. Each control factor is treated at three levels, as shown in table3.

Table 3: Control Factors and Their levels.

Controllable Factors	Factors Designation	Levels		
		Level 1	Level 2	Level 3
Electrode Diameter	D	15	20	25
Current	Ip	9	16	25
Pulse on time	Ton	300	1200	2400
Duty Factor		0.65	0.8	0.9

In this study, an L9 orthogonal array is used. The experimental layout for machining factors is shown in table 4.

Table 4: Layout of Experimental Design L_9.

Experiment No.	A Electrode Diameter	B Current	C Pulse on	D Duty Factor
1	15	9	300	0.65
2	15	16	1200	0.80
3	15	25	2400	0.90
4	20	9	1200	0.90
5	20	16	2400	0.65
6	20	25	300	0.80
7	25	9	2400	0.80
8	25	16	300	0.90
9	25	25	1200	0.65

2.8 Experiments Running:

An EDM machine (FORM 2-LC) was used in this study, the electrode is cylindrical pure copper with diameters of (15,20,25) mm to erode a workpiece of 1.2080 (according to DIN standard) with diameters (15,20,25) mm, kerosene was used as the dielectric fluid. The schematic diagram of the experimental setup is shown in Figure 6. Machining time for each workpiece in the experiments was 45 minutes and each experiment is repeated three times, the electrode and specimen were weighed before and after machining in each experiment using the digital balance.

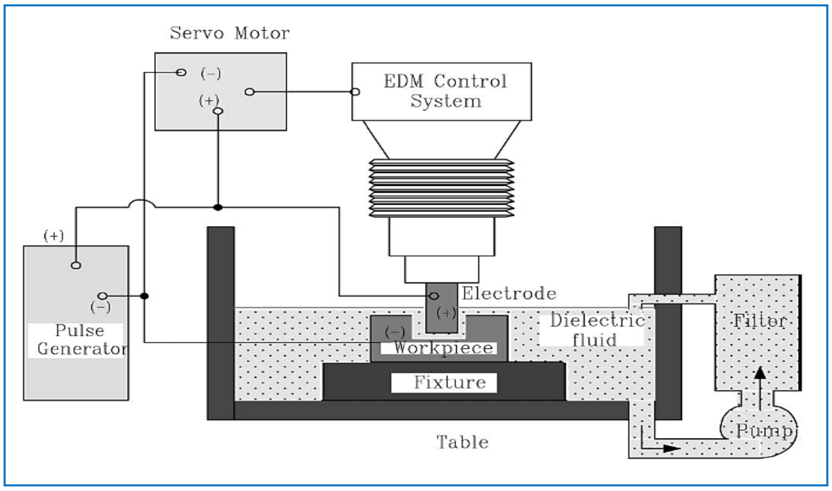

Figure 6: Schematic diagram of the EDM process.

3.Results and Analysis

After finishing each experiment, MRR was calculated by weighing the specimen on the digital single pan balance with an accuracy of ± 0.0001g, then equation (2) was employed to determine MRR, table 5 shows the experimental and calculated results.

$$\boldsymbol{MRR} = \frac{WRW=(W_b-W_a)}{T_m}\ (g/min) \qquad (2)$$

where:
WRW= Workpiece Removal Weight.
W_b = Weight of workpiece material before machining (g).
W_a = Weight of workpiece material after machining (g).
T_m = Machining Times (min).

Table 6: Experimental Results for Material Removal [MRR].

Run No	Sample No	Tm (min)	Wb Before (g)	Wa After (g)	WRW (g)	Average W/P.R.W (g)	MRR (g/min)
1	A1	45	39.6273	37.2407	2.3866	2.4922	0.0554
	B1		40.4907	37.9544	2.5363		
	C1		39.9324	37.3788	2.5536		
2	A2	45	40.2205	38.4958	1.7247	1.4924	0.0332
	B2		39.2434	37.8791	1.3643		
	C2		39.6592	38.2711	1.3881		
3	A3	45	38.7077	37.2057	1.502	1.5269	0.0339
	B3		39.5768	38.0969	1.4799		
	C3		39.2024	37.6036	1.5988		
4	A4	45	71.636	71.2453	0.3907	0.3844	0.0085
	B4		71.1324	71.1018	0.0306		
	C4		71.4908	70.759	0.7318		
5	A5	45	71.6328	71.0641	0.5687	0.5371	0.0119
	B5		71.9464	71.3463	0.6001		
	C5		71.7682	71.3256	0.4426		
6	A6	45	71.313	61.7581	9.5549	9.1655	0.2037
	B6		71.5058	62.5781	8.9277		
	C6		71.7566	62.7426	9.014		
7	A7	45	110.3162	109.8512	0.465	0.4023	0.0089
	B7		111.3724	110.945	0.4274		
	C7		111.6164	111.3018	0.3146		
8	A8	45	110.0918	105.3122	4.7796	5.2238	0.1161
	B8		111.5592	106.1912	5.368		
	C8		111.1724	105.6487	5.5237		
9	A9	45	112.0502	107.4446	4.6056	4.5840	0.1019
	B9		111.6136	106.9325	4.6811		
	C9		111.2084	106.7432	4.4652		

Development of The Regression Model: Utilizing the experimental data, a model for material removal rate has been developed using multiple linear regression. The material removal rate (MRR) as dependent variable, the independent variables, namely electrode diameter, pulse on time, current, and duty factor. The data were analyzed by Minitab 16 software. The adequacy of model has been checked using correlation coefficients (R^2). Developed models can be used to predict values of material removal rate (MRR). A regression analysis is applying the least squares method to the experimental data in order to obtain the coefficients of this equation, the following equation 3 is attained for material removal rate.

$$\mathrm{MRR} = -0.035 + 0.00348\mathrm{D_i} + 0.00561\mathrm{I_p} - 0.000049\mathrm{T_{on}} + 0.000\eta \qquad (3)$$

$S = 0.0323689$, $R^2=87.8\%$, $R^2\ (adj) = 75.7\%$

ANOVA is useful for identifying the level of significance of the developed model. If the P - value of a term appears less than 0.05 (for 95% confidence level) then it is concluded that the model is significant. The result of ANOVA is shown in table 7. From Anova table regression is significant because P-value is less than 0.05. The regression model presented high determination coefficient (R^2= 87.8%) which indicates goodness and high significance of the model.

Table 7: Analysis of variance for MRR model.

Source	DF	SS	MSS	F	P	Remarks
Regression	4	0.030235	0.007559	7.21	0.041	Significant
Residual Error	4	0.004191	0.001048			
Total	8	0.034425				

Optimization of Material Removal Rate (MRR): To optimize the process parameters and the output response, the experimental results are transferred to signal-to-noise ratio (S/N ratio), to measure the quality characteristics deviating from the desired values. Signal-to-noise ratio for material removal rate (MRR) is calculated with consideration of larger-the-better (LB) characteristics according to equation (4). Experimental Results and their corresponding S/N ratio are shown in table 8. The S/N ratio for each level of process parameters was calculated, the optimal combination of process parameters for the response has been predicted.

$$\boldsymbol{Larger\ the\ better\ LB}\ (\boldsymbol{S.N}\ \mathbf{ratio}) = -10\ log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{1}{{y_i}^2}\right) \qquad (4)$$

Table 8: Experimental Results and S/N for MRR.

Run No	MRR (g/min)	S/N MRR
1	0.0554	-25.1298
2	0.0332	-29.5772
3	0.0339	-29.3960
4	0.0085	-41.4116
5	0.0119	-38.4891

6	0.2037	-13.8202
7	0.0089	-41.0122
8	0.1161	-18.7034
9	0.1019	-19.8365

The mean S/N response table for material removal rate is shown in table 9.

Table 9: Mean S/N ratio for MRR.

Symbol	Process parameters	Mean S/N ratio				
		Level 1	Level 2	Level 3	Max-Min	Rank
D_i	Electrode Diameter	-28.03	-31.24	**-26.52**	4.72	3
I_p	Discharge Current	-35.85	-28.92	**-21.02**	14.83	2
T_{on}	Pulse on time	**-19.22**	-30.28	-36.30	17.08	1
η	Duty Factor	**-27.82**	-28.14	-29.84	2.02	4
Total mean S/N ratio = -28.5973						

Figure 7 shows the main effects on material removal rate, it is clear that the parameters: pulse of time, discharge current and electrode diameter have a significant effect, duty factor is found to be insignificant. Optimal results could be got from the main effect plot, selecting the highest levels of S/N ratio values. Therefore, based on the S/N analysis, the optimal process parameters for material removal rate are as follows: Electrode Diameter at level3 (25mm), Discharge Current at level3 (25A), Pulse on time at level1 (300 µs) and Duty Factor at level1 (0.65) i.e. D_i3- I_p3- $T_{on}1$-$\eta 1$.

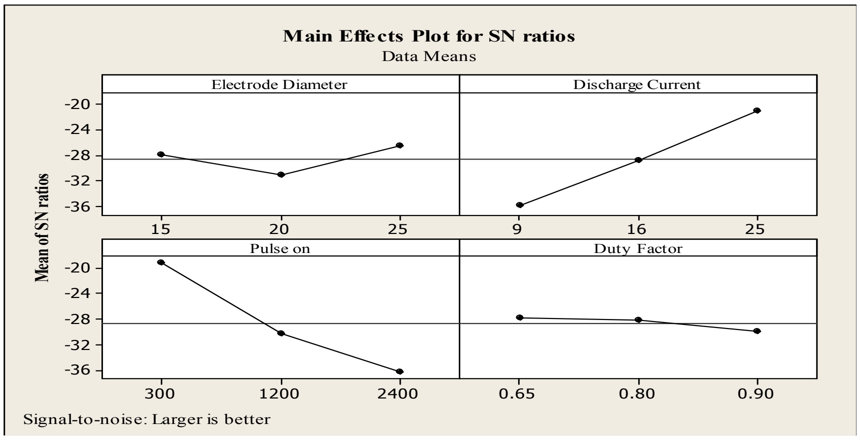

Figure 7: Main effect plot for S/N ratio MRR.

Confirmation tests: Conformation experiment has been carried out to verify the improvement of the response using the optimal combination of the process parameters. Results of conformation experiment using the optimum process parameters and initial process parameters are shown in Table 10. Good agreement exists between predicted and experimental values. The increase of the S/N ratio from the initial process parameters to the optimal process parameters is 25.34 dB. Based on the results of the confirmation test, the material removal rate is increased 18.49 times.

Table 10: Results of confirmation experiment for MRR.

Level/Response	Initial process parameters	Optimal Process Parameters	
		Prediction	Experiment
Level	D_i2-I_p2-$T_{on}3$-$\eta1$	D_i3-I_p3-$T_{on}1$-$\eta1$	D_i3-I_p3-$T_{on}1$-$\eta1$
MRR [g/min]	0.0119	0.3635	0.2201
S/N Ratio [dB]	-38.4891	-8.7881	-13.14
Improvement of S/N Ratio		25.34	

4.Conclusion

Taguchi's robust design and optimization methodology are utilized for maximizing the material removal rate during EDM machining of DIN 1.2080. From the study, its concluded that: Based on ANOVA analysis, the developed regression model is statistically significant, pulse on time and discharge current have the dominant effect on material removal rate, electrode diameter and duty factor has less effect.

According to the S/N analysis and main effect plot, the optimal process parameters for material removal rate are as follows: Electrode Diameter at level 3 (25mm), Discharge Current at level 3 (25A), Pulse on time at level 1 (300 µs) and Duty Factor at level 1 (0.65) i.e. Di3- Ip3- Ton1-η1. Where the value of the material removal rate is increased 18.49 times at the optimized process parameters than the initial process parameters, whereas it is increased from 0.0119 mm3/min to 0.2201 mm3/min.

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