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Performance Evaluation of Slotted Tool Electrodes in Electric Discharge Drilling of Inconel 718

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***Abstract*— Electric discharge machining (EDM) is gaining considerable industrial importance due to its potential of machining difficult to machine materials, such as super alloys, composites, ceramics, etc.**

During EDM, poor debris removal may occur under certain conditions, and the flushing becomes ineffective causing excessive arcing and short circuiting in the machining zone, thereby, leading to poor material removal and inferior quality of machined surface. In an effort to improve the flushing of accumulated debris, electrode rotation and shaped tool electrodes, can simply evacuate the debris from the machining zone.

In the present experimental investigation, electrical discharge drilling (EDD), is applied using cylindrical copper electrodes to make hole features on Inconel 718. The different types of tool electrodes used were non-slotted (NS), single-slotted (SS), and double-slotted (DS). The experiments were conducted using Taguchi's L9 (3^4) OA and results analysed using regression. The experimental results exhibited that among the three types of tool electrodes, the single slotted electrode engendered good debris removal capability.

Keywords*— *Electric discharge drilling, advance materials, slotted tool electrode, debris removal, performance measures

I. INTRODUCTION

Advanced materials such as super alloys, composites, ceramics, etc. are difficult to machine materials, have enhanced properties that are intentionally designed for superior performance. The demand for Inconel 718 is quickly rising in the current manufacturing environment to meet the requirements of advanced technologies in the aerospace, aircraft, nuclear, marine, and chemical industries. Inconel 718 is demandable due to its high oxidation-corrosion-temperature resistance, high strength, durability, toughness, and dimensional stability and has wide application in gas turbines, aircraft, nuclear reactors, submarines, etc. [1]. Although Inconel 718 has high hardness, toughness, work hardening tendency, chemical affection to tool material, and high thermal resistance it is very difficult to be machined by traditional methods [1, 2].

As the conventional machining process makes changes in the shape of the work material using a hard tool material which requires more time and energy and hence results in increased cost, in some cases [3]. Therefore, the machining world has shown advancement in non-conventional machining technologies. In non-conventional machining processes, there is no direct contact between the work material and the tool. It uses different forms of energy such as mechanical, thermo-electric, chemical, and electro chemical for performing the machining process on the work material [4, 5].

Electric Discharge Machining (EDM) has evolved as one of the methods to machine hard and difficult to machine materials. EDM, a non-conventional machining process, works on thermo-electrical energy in which the tool electrode shape is replicated on the work material mirror-wise. The replicated shape defines the area in which the spark erosion occurs. The series of repetitive electric sparks that continuously strikes on the work material and removes the material by heating, melting and vaporizing. The melted material is flushed away by the means of dielectric fluid. As there is no contact between the work material and the tool material the mechanical stresses are eliminated, as are caused in conventional machining processes. Fig. 1 shows the schematic of EDM process. Review of the published literature finds that high-performance EDM is a key technology for manufacturing high-precision components in a broad range of industrially relevant applications.

Drilling holes can be a major requirement in the application of super alloy that finds application in fuel injectors, tool coolant holes, punch ejectors and small hole diameters, etc. [7]. During drilling using die sinking EDM, the accumulated machining debris finds difficult to be flushed away from the machining zone, contaminating the inter electrode gap. Formation of debris in the inter-electrode gap leads to arcing and short-circuits on the surface as well as related inaccuracies and process instabilities. This leads to poor material removal rate and inferior quality of machined surface [8]. Further, in drilling through EDM, high aspect ratios reduce the efficiency of flushing and in consequence, the material removal rate (MRR) and increase the formation of recast layer thickness. Literature identifies that the machining of super alloys with electrode rotation while drilling holes using EDM is more accurate and optimal, as compared to the conventional die-sinking process.

Electric discharge drilling (EDD), a variant of the electric discharge machining process, works on the same principle as EDM, but in addition to the tool sinking, there is tool electrode rotation. In EDD, the material is removed by the means of electric discharges produced by a rotating tool by melting the work surface [9], as shown in the Fig. 1. The melted material is removed from the surface by the means of dielectric fluid which is continuously flowing between the tool and the work material [10] Fig. 2. Dielectric fluid works as an electric medium between the tool and work material by applying voltage [11]. The electric energy is converted to thermal energy which generates a plasma channel in the gap that results in localized heating, melting, and vaporizing [12].

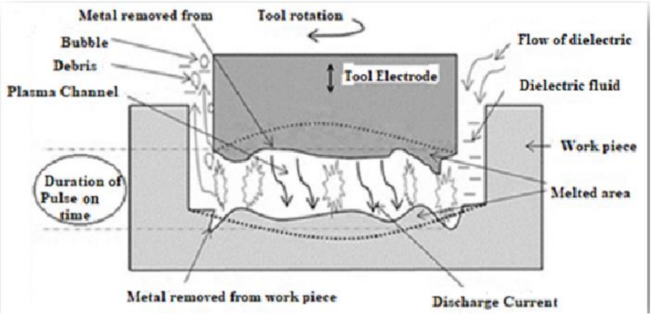

Fig.1 Mechanism of material removal in EDD during pulse on time (After Singh et al., 2019) [18]

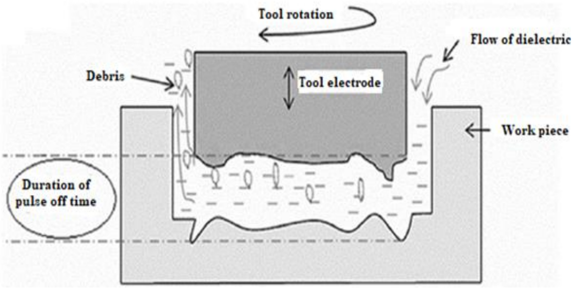

Fig. 2 Mechanism of material removal in EDD during pulse off time *(After Kachhap et al., 2019)* [19]

In EDD, the tool and work material wear simultaneously, due to which the shape of the tool electrode also changes which can affect the diameter of desired hole and surface finish. An overcut in the drilled hole is seen due to the gap between the tool and the work material. On investigation, the creation of holes in aerospace titanium alloy using static electrode machining & electrical discharge drilling process found that surface roughness increased with an increase of gap current and duty factor due to better and stabilized flushing of eroded debris [13]. Performance of dry EDM using slotted electrodes found that using slotted tools reduces the TWR and occurrence of debris attachment on the tool electrode [14]. In an analysis and performance of slotted tools in electrical discharge drilling, it was found that an increase in the removal rate in slotted electrode corresponding to the conventional cylindrical electrode [15].

It was observed that flushing of removed material is important to obtain high-quality results and good productivity, but also the increase in gap flushing can also result in a negative process [16]. Published work during drilling highlights that cylindrical electrodes incorporated with the slots and helices along with the electrode rotation effectively remove the debris from the sparking zone, thus preventing the occurrence of arcing and short circuiting, resulting in improved process performance [17].

In the present experimental investigation, an attempt has been made to compare the performance characteristics using various types of tool electrodes, namely cylindrical tool electrode without slots (NS), single longitudinal slotted tool electrode (SS), and double longitudinal slotted tool electrode (DS), during electric discharge drilling of Inconel 718.

A rotary attachment was fabricated to impart rotation to the tool electrode with variable speed. The slots on the tool electrode were fabricated by Wire Electric discharge machining. Experiments were conducted using the three types of tool electrodes with the variation in pulse current, I_p (A), pulse ON time, T_{ON} (µs) and tool electrode speed (rpm). The responses namely material removal rate (MRR), tool wear rate (TWR), electrode consumption ratio (ECR) and surface roughness (SR) were evaluated to study the influence of slotted tools.

II. EXPERIMENTATION

A. *Work material*

Inconel 718 plate has been chosen as work material because of its mechanical properties that are listed below in Table I. In addition to its mechanical properties, it also provides high resistance to corrosion, oxidation, creep, and fatigue. The required dimension of work material is cut using wire electric discharge machining (Exeteck S&T EX series CNC wire EDM machine model EX 40) with process parameter [20].

The work material before machining is shown in the Fig. 3a, and work material after machining in Fig. 3b.

TABLE I. Mechanical Properties of Inconel 718

Yield strength MPa	**Density g/cm3**	**Hardness HRc**	**Thermal conductivity W/m.K**	**Ultimate tensile strength MPa**	**Melting range**
1100	8.19	36	11.4	1375	1260°C-1336°C

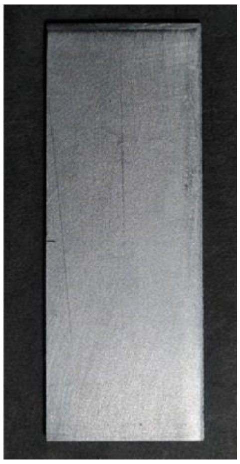

Fig. 3(a) Work material Inconel 718

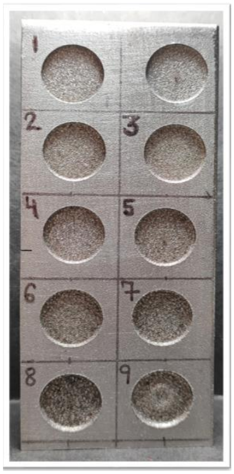

Fig. 3(b) Work material after machining

B. Tool electrode material

Cylindrical copper tool electrode of diameter 12mm has been taken as tool material due to its various properties that are listed below in the Table II. Fig. 4 shows different shapes of the electrode i.e., non-slotted tool electrode (NS), single-slotted tool electrode (SS), and double-slotted tool electrode (DS) used in present study. Slots on the tool electrode were made by using wire electric discharge machining (Exeteck S&T EX series CNC wire EDM machine model EX 40).

TABLE II. MECHANICAL PROPERTIES OF COPPER

Specific gravity (g/cm3)	Melting range (°C)	Thermal conductivity (W/m.K)	Specific heat Kg (J/K)	Thermal expansion Coefficient (1/°C)	Electrical resistivity (Ωcm)
8.94	1065-1083	388	385	16.7×10^{-6}	1.7×10^{-6}

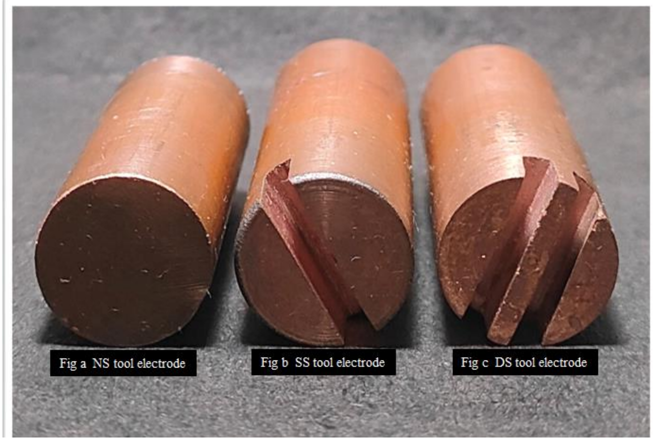

Fig. 4 Tool Electrode Copper, (a) non-slotted tool electrode, (b) Single-slotted tool electrode and (c) Double-slotted tool electrode

C. Electric discharge drilling setup

The experiments were performed on E-ZNC S-50 (Sparkonix India Ltd.), which has a sinking motion, and for the rotational motion, of tool electrode a self-developed setup was installed on the ram of the EDM machine as shown in Fig. 5. In this setup, a DC motor of 0.5 HP, a spindle, a drilling chuck, a v-belt, and a speed regulator are used to add a rotational motion in sinking motion. For the rotation of the tool electrode, the rotational motion from the DC motor is transferred to the spindle by means of a V-belt. For a controlled speed (rpm) of the tool electrode, a speed controller is connected in line to the DC motor and provides the desired speed. the rpm is measured using proximity sensor connected to rpm monitor.

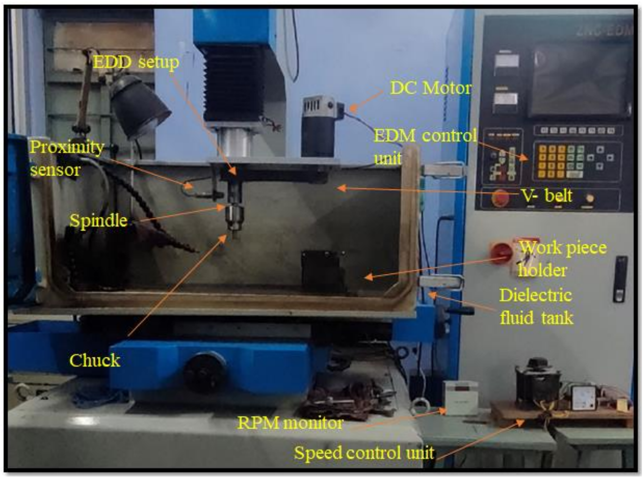

Fig.5 EDM machine with rotary setup

D. Experimental procedure

The required experiments were performed using Electric Discharge Drilling on the basis of L9 (3^4) Taguchi's orthogonal array having four factors and three levels each [21]. This has 9 rows and 4 columns in orthogonal array. The process parameters used for this study are Number of slots (NoS), Pulse current (I_p, A), Pulse ON time (T_{ON}, μs), Electrode rotation speed (N, rpm). Copper cylindrical tool electrode of 12mm diameter were used. The slots having width 2mm, depth of 6 mm, and at a distance of 2 mm same slot is made on double slotted tool). Process parameters and their values are shown in Table III.

TABLE III. PROCESS PARAMETERS AND THEIR LEVELS

Factors	Process Parameters	Symbol (Unit)	Levels		
			1	2	3
A.	Number of slots	NoS	NS	SS	DS
B.	Pulse current	I (A)	12	15	21
C.	Pulse ON time	Ton (μs)	8	9	10
D.	Electrode rotation speed	N (rpm)	200	300	400

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E. *Measurement of performance characteristics*

The performance measure that has been studied in this proposed study are as follows.

1. Material Removal Rate (MRR): MRR is the rate of material removed from the work material during the machining process and can be calculated by using an equation that is

$$MRR= w_1\text{-}w_2/t_m \text{ (mm3/min)} \qquad (1)$$

   where w_1 is the initial weight of work material before machining, w_2 weight of work material after machining, t_m time for the machining process.

2. Tool Wear Rate (TWR): TWR is the rate of material removed from the tool during the machining process and can be calculated by using an equation that is

$$TWR= W_{t1}\text{-}W_{t2}/tm \text{ (mm3/min)} \qquad (2)$$

   where w_{t1} is the initial weight of tool before machining, w_{t2} is the weight of the tool after machining, t_m is the time for the machining process.

3. Electrode Consumption Ratio (ECR): ECR is the ratio between material removal to the electrode consumption. Mathematically

   ECR= Material removal/Electrode consumption

4. Surface Roughness (SR): The irregularities on the surface texture were measured using Surface Roughness Tester Surtronic 25 (Make: Taylor Hobson

III. EXPERIMENTAL RESULT AND ANALYSIS

A. *Experimental results*

Table IV shows experimental results obtained by performing EDD operation on Inconel 718 and being analysed using Taguchi's method.

Table IV EXPERIMENTAL DATA

NoS	I (A)	Ton (µs)	N (rpm)	MRR (g/min)	S/N ratio MRR	TWR (g/min)	S/N ratio TWR	ECR	S/N ratio ECR	SR (µm)	S/N ratio SR
1	12	8	200	0.1243	-18.11057743	0.0069	43.22301819	41.4	-32.34000682	7.32	-17.29022162
1	15	9	300	0.1747	-15.1541419	0.0058	44.73144013	32.36068966	-30.20035537	5.78	-15.23855677
1	21	10	400	0.2266	-12.89480189	0.0055	45.19274621	28.11449275	-28.97860505	3.74	-11.45743204
2	12	9	400	0.1612	-15.85269925	0.0061	44.2934033	35.02636364	-30.88790104	4.91	-13.82162984
2	15	10	200	0.1762	-15.07988192	0.0072	42.85335007	26.67222222	-28.52118402	6.79	-16.63739549
2	21	8	300	0.1832	-14.74149061	0.0044	47.13094647	31.25622951	-29.89873174	5.05	-14.06582756
3	12	10	300	0.1478	-16.60651132	0.0065	43.74173287	29.80612245	-29.48610963	5.5	-14.80725379
3	15	8	400	0.1551	-16.18776404	0.0041	47.74432287	29.82926829	-29.49285201	4.39	-12.8492904
3	21	9	200	0.1632	-15.74559691	0.0049	46.1960784	20.23846154	-26.12354992	5.94	-15.4757289

B. *Analysis of Material Removal Rate*

Fig 6 shows main effect plot for S/N ratio larger is better. It shows that MRR using single slotted tool is higher as compared to non-slotted and double slotted tool. Table V shows regression analysis for MRR, it show that Nos, I (A), Ton (µs), and N (rpm) are found to be significant at confidence level of 95% because their P values < 0.005. Table VI shows ANOVA for MRR, P values shows a significant correlation between the variables (at confidence level 95%), since it is preferred, a larger S/N ratio has been chosen for MRR.

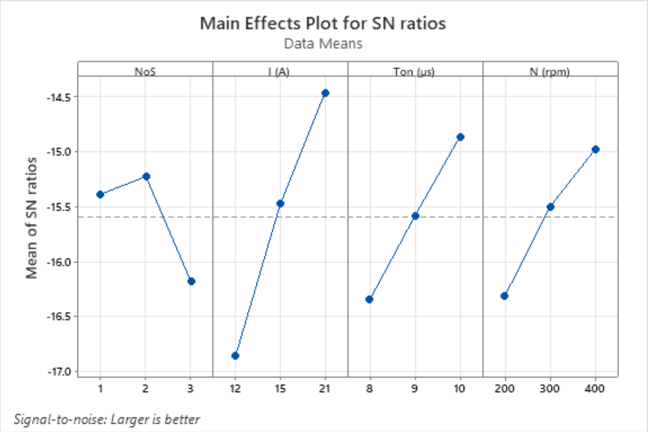

Fig. 6 Main Effect Plot for S/N ratio of MRR

TABLE V REGRESSION ANALYSIS FOR MRR

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.0632	0.0363	-1.74	0.157	

NoS	-0.00992	0.00351	-2.82	0.048	1.00
I (A)	0.004967	0.000767	6.48	0.003	1.00
Ton (µs)	0.01467	0.00351	4.17	0.014	1.00
N (rpm)	0.000132	0.000035	3.76	0.020	1.00

TABLE Ⅵ ANOVA FOR MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.006034	0.001509	20.37	0.006
Error	4	0.000296	0.000074		
Total	8	0.006331			

C. *Analysis of Tool Wear Rate*

Fig 7 shows main effect plot for S/N ratio smaller is better. It shows that TWR using double slotted tool is higher as compared to non-slotted and single slotted tool. Table VII shows regression analysis for TWR, it show that Nos, I (A), Ton (µs), and N (rpm) are found to be significant at confidence level of 95% because their P values < 0.005. Table VIII shows ANOVA for TWR, P values shows a significant correlation between the variables (at confidence level 95%), since it is preferred, a smaller S/N ratio has been chosen for TWR.

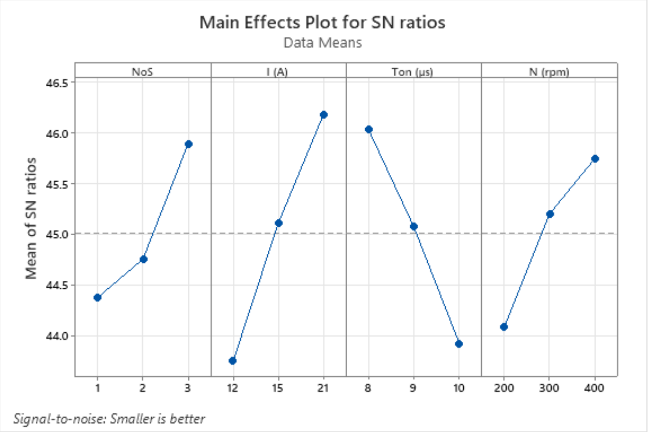

Fig. 7 Main Effect Plot for S/N ratio of TWR

Table VII Regression Analysis for TWR

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.00524	0.00143	3.67	0.021	
NoS	-0.000450	0.000138	-3.25	0.031	1.00
I (A)	-0.000167	0.000030	-5.55	0.005	1.00
Ton (µs)	0.000633	0.000138	4.58	0.010	1.00
N (rpm)	-0.000005	0.000001	-3.98	0.016	1.00

Table VIII ANOVA for TWR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.006034	0.001509	20.37	0.006
Error	4	0.000000	0.000000		
Total	8	0.000009			

D. *Analysis of Electrode Consumption Ratio*

Fig 8 shows main effect plot for S/N ratio smaller is better. It shows that ECR using double slotted tool is higher as compared to non-slotted and single slotted tool. Table IX shows regression analysis for ECR, it show that Nos, I (A),and Ton (µs) are found to be significant at confidence level of 95% because their P values < 0.005.Table X shows ANOVA for ECR, P values shows a significant correlation between the variables (at confidence level 95%), since it is preferred, a smaller S/N ratio has been chosen for ECR.

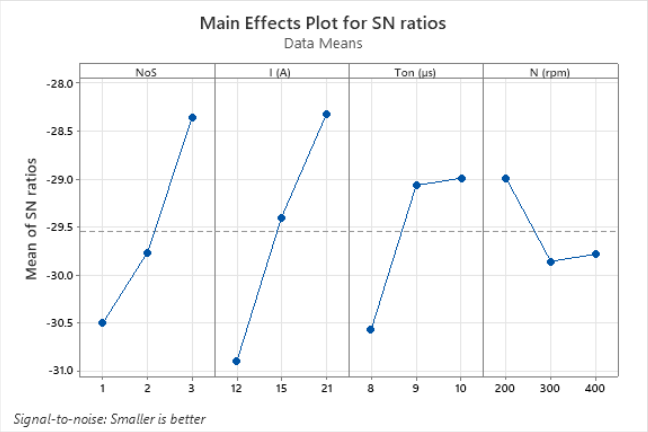

Fig. 8 Main Effect Plot for S/N ratio of ECR

TABLE Ⅸ REGRESSION ANALYSIS FOR ECR

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	77.1	10.7	7.17	0.002	
NoS	-3.67	1.04	-3.53	0.024	1.00
I (A)	-0.919	0.227	-4.05	0.015	1.00
Ton (µs)	-2.98	1.04	-2.87	0.045	1.00
N (rpm)	0.0078	0.0104	0.75	0.496	1.00

TABLE Ⅹ ANOVA FOR ECR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	243.980	60.995	9.41	0.026
Error	4	25.921	6.480		
Total	8	269.900			

E. *Analysis of Surface Roughness*

The surface generated in electrical discharge machining process is mainly due to the discharge energy. The Ra (µm) was measured using roughness tester.

Fig 9 shows main effect plot for S/N ratio smaller is better. It shows that TWR using double slotted tool is higher as compared to non-slotted and single slotted tool.

Table XI shows regression analysis for TWR. It displays that NoS, I (A), Ton (µs), and N (rpm) are found to be significant at confidence level of 95% because their P values

< 0.005. Table XII shows ANOVA for SR, P values shows a significant correlation between the variables (at confidence level 95%), since it is preferred, a smaller S/N ratio has been chosen for SR.

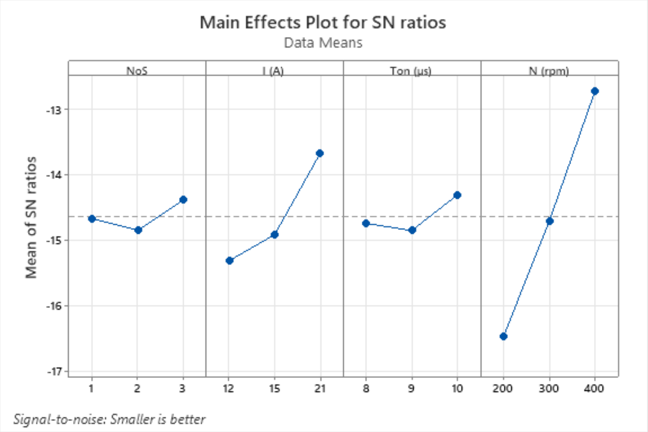

Fig. 9 Main Effect Plot for S/N ratio of SR

Table XI REGRESSION ANALYSIS FOR SR

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	12.235	0.567	21.59	0.000	
NoS	-0.1683	0.0548	-3.07	0.037	1.00
I (A)	-0.1129	0.0120	-9.44	0.001	1.00
Ton (µs)	-0.1217	0.0548	-2.22	0.091	1.00
N (rpm)	-0.011683	0.000548	-21.31	0.000	1.00

Table XII ANOVA FOR SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	10.0559	2.51398	139.37	0.000
Error	4	0.0722	0.01804		
Total	8	10.1281			

IV. CONCLUSION

In the present experimental investigation, the process performance of electric discharge drilling by using various electrodes has been analysed. Blind holes were drilled in Inconel 718 work material to evaluate the effectiveness of the designed tool electrodes. The effect of slots and tool speed on MRR was evaluated.

The following conclusions can be drawn from the present experimental investigation:

1. The internal flushing channel diameter is less in single slotted tool as compared to double slotted tool and showed a significant effect with respect to speed and therefore a relevant effect on debris removal.
2. The single slotted copper tool electrode was found to result in significant debris removal, and thus an increase the MRR.
3. Double slotted tool electrode during rotation develops a turbulence, and hence debris removal becomes difficult.
4. In addition, the TWR of single slotted tool is low as compared to that of double slotted tool.
5. In double slotted tool at high current and low rpm irregularities can be seen in the current flow, which eventually leads to improper sparking zone.
6. Relative to the cylindrical tool electrodes, the improvised tool shows improvement in performance.

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