

A study on the effect of tool electrode thickness on MRR, and TWR in electrical discharge turning process

Vikas Gohil¹ and YM Puri²

¹Mukesh Patel School of Technology Management & Engineering, SVKMs, NMIMS University-Shirpur Campus, 425405, MS, India

²CAD-CAM Centre, Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, MS, India

2vikasgohil@gmail.com

Abstract. Turning by electrical discharge machining (EDM) is an emerging area of research. Generally, wire-EDM is used in EDM turning because it is not concerned with electrode tooling cost. In EDM, turning wire electrode leaves cusps on the machined surface because of its small diameters and wire breakage which greatly affect the surface finish of the machined part. Moreover, one of the limitations of the process is low machining speed as compared to constituent processes. In this study, conventional EDM was employed for turning purpose in order to generate free-form cylindrical geometries on difficult-to-cut materials. Therefore, a specially designed turning spindle was mounted on a conventional die-sinking EDM machine to rotate the work piece. A conductive preshaped strip of copper as a forming tool is fed (reciprocate) continuously against the rotating work piece; thus, a mirror image of the tool is formed on the circumference of the work piece. In this way, an axisymmetric work piece can be made with small tools. The developed process is termed as the electrical discharge turning (EDT). In the experiments, the effect of machining parameters, such as pulse-on time, peak current, gap voltage and tool thickness on the MRR, and TWR were investigated and practical machining was carried out by turning of SS-304 stainless steel work piece.

1. Introduction

EDM is a nonconventional thermal machining technique that removes workpiece materials by precisely controlled electrical discharges occurs between the tool electrode and workpiece. Unlike traditional machining processes which depend on tool hardness to erode unwanted work material, EDM utilizes electro thermal energy to erode the workpiece material and produces the required geometry. The main advantage of EDM is that it can cut any material (conductive) regardless of its strength and hardness. Therefore, it is particularly suitable for machining advanced, ultra-hard and high strength materials. It is reported that EDM account for about seven percent of all machine sales in the world [1]. In EDM process there is a gap for sparking in between tool and workpiece, which eliminates chatters, vibration problem and allowing miniature parts to be machined [2]. The flexible manufacture of axisymmetrical components made of high strength materials suitable for aerospace and engine industry applications which are difficult to machine by traditional machining processes, can be produced by EDM machine, so there is a great scope for improving and adapting EDM technology to afford manufacturing such type of components by setting up an external axis (turning spindle) on conventional EDM and feeding shaped



tool electrode against rotary workpiece in order to produce axisymmetrical geometries. The developed process named electrical discharge turning (EDT) can be utilized for producing cylindrical forms and helical profiles on high-strength, advanced materials and alloys widely used in the automotive and aeronautical industries. One application of the EDM is found in turning of honey-comb seals used in aerospace industry [3]. The idea and experimental set-up of EDT process is shown in Figure 1 and Figure 2 respectively.



Figure 1. The idea of EDT process.

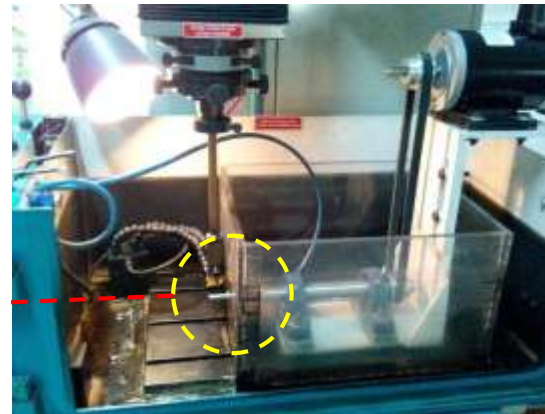


Figure 2. Experimental set up of the EDT process.

Several experimental studies have been conducted by many researchers to investigate the machining characteristics of the EDM process. Soni and Chakraverty reported a comparative study of output parameters between rotary and stationary tool electrode. They reported that due to better sparking efficiency and flushing action in rotary EDM material removal rate tends to increase. However, this results at a cost surface roughness [4]. Qu et al. worked on the development of cylindrical parts using wire electrical discharge machining process to fabricate cylindrical parts of high-strength materials. The experimentation was performed in two phases; in the first phase, an additional rotary spindle (axis) is added to generate cylindrical geometries. Spindle error can influence rate of material removal, surface finish (R_a) and roundness of the part. In second phase, a mathematical model was derived for MRR. Two experiments were designed and conducted to find maximum MRR on brass and carbide material. Based on the obtained findings they conclude that maximum MRR for CWEDM was higher than that in two-dimensional (2D) WEDM for same machining condition and work material [5]. The same authors further extend their experimental study to investigate roundness and surface finish of the part, produced by the CWEDM process. Two machining parameters, that is, shorter T_{on} and lower feed rate, were to be found most important, and their influence on roundness and surface roughness was investigated. A mathematical model was established for surface integrity and roundness, and a good estimate for the roundness and surface finish of CWEDM parts was found [6]. Y.H. Guu et al. study the effect of rotating workpiece during electro discharge machining of D2 steel using copper tool. They reported that with increase in rotational speed the rate of material removal increases significantly [7]. Ghoreishi and Atkinson studied the influence of rotary, vibratory and vibro-rotary tool on the machining characteristics. Experimental results show that the introduction of ultrasonic vibrations on a rotary tool improves MRR significantly [8]. Yan et al. demonstrated a new magnetic abrasion finishing technique. The results of experimental analysis show that the introduction of vibrations on rotary workpiece reduces micro cracks and the recast layer, thus improves surface quality [9]. Janardhan and Samuel study the influence of the input parameters on the MRR and R_a in wire electrical discharge turning process. According to their report, the MRR increases significantly as the rotational speed increases [10]. Gjeldum et al. study the effects of machining parameter and work material dimensions on MRR. They proposed a mathematical model to predict maximum achievable MRR by employing BFGS back-propagation algorithm based on ANN. Maximum pulse current, spindle rotation, pulse pause time, cutting radius and length of discharge area were used as input machining parameters during CWEDT of X5CrNi18-10 steel. Experimental results show that among the process parameters

maximum IP has a significant impact on MRR; as it increases, MRR increases as well. MRR also improves with an increase in maximum pulse current and discharge area length. However, spindle rotation (up to 1000r/min) has a little effect on MRR [11]. Gohil et. al. Conducted an experimental investigation on EDM turning of titanium alloy. The experimental findings reveal that IP, Ton and voltage are most dominating parameters which affect MRR. With respect to surface roughness, current and pulse-on time show direct proportion to it. That is surface roughness increases as the value of both parameters increases [12]. The same author performed another experimental investigation to study surface integrity of EDM turned part. An experimental result indicates both IP and Ton have the most significant effect on Ra, whereas, duty factor shows an inverse relation to Ra as it increases Ra decreases [13].

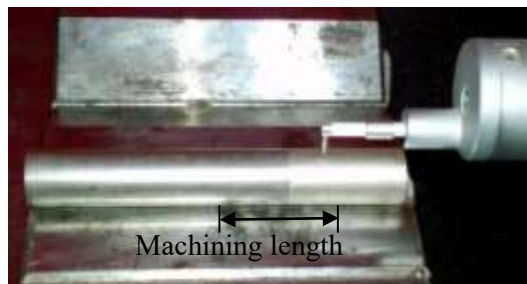


Figure 3. A cylindrical EDT part.



Figure 4. Tool used in EDT process

Song et al. produced a new turning method which utilizes a conventional EDM machine. The authors reported that strip EDM removes 74% more material than WEDT and produces a cusp-free surface [14]. Yan and Hsieh proposed a new pulse discrimination system for process monitoring of WEDT. This system can provide better output for online evaluation of spark gap throughout wire EDM turning process [15]. Gohil et. al. optimized surface roughness in EDT of SS-304 stainless steel using an electrolytic copper electrode. Experimental findings show that only pulse on time has the most significant and direct effect upon surface roughness. The interaction effect of Ton and current is more significant than spindle rotational speed. Also, the value of surface roughness increases as spindle rotational speed increases [16]. Aravind Krishnan and Samuel have optimized machining parameters in wire electrical discharge turning process by considering MRR and Ra as output parameters [17]. Recently Puri et. al. performed straight turning on Ti-6Al-4V alloy. They found that the IP, Ton, and V have the most significant effect on material removal. Furthermore, IP and Ton show a direct relation to MRR, i.e. as IP and Ton increase, MRR increases significantly. However, higher MRR can be obtained at a lower value of voltage [18].

From the above literature study, one can conclude that many researchers and scientists have worked to the progress of electro-discharge turning process. But, to the best of our knowledge, very less research has been reported on electrical discharge turning of SS-304 utilizing a conventional EDM machine. The current research work presents a study on EDM turning of SS-304 stainless steel using a pre-shaped solid copper electrode. Statistical analysis was conducted on the experimental data obtained through DOE technique. This was done by characterizing significant factors by means of ANOVA technique.

2. Experimental equipment's

In the current research work, all experiments were performed on 500×300 ZNC Electronica EDM machine at normal polarity. Industrial grade EDM oil was used as the dielectric fluid. The experimental runs are conducted to study the effects of several factors upon MRR, and TWR. SS-304 stainless steel workpiece (10 mm dia. × 75 mm length) chosen for turning (machining length 25 mm) with fixed machining time 15 min. Turning has been done at 50 RPM with constant flushing pressure 0.05 kg/cm². To determine the MRR and TWR, the specimen and tool were weighed before (w_i) and after

(w_f) machining using a digital precision balance. The MRR and TWR were calculated using equation (1):

$$MRR(mg / min.) = \frac{W_i - W_f}{t} \times 1000 \quad (1)$$

In order to study the influence of all possible combinations of parameters and their levels the experimental sheet was designed using full factorial DOE method. Four input machining parameters involving, Ton and IP are assigned with three levels, whereas voltage and tool thickness are with two levels, thus 36 experiments are performed as shown in Table 1.

3. Data analysis

3.1 Influence of EDT parameters on MRR

Figure 7 show the main effects plot of current, gap voltage, Ton, and tool thickness on the MRR. It is noted that the rate of material removal increases significantly with increase in Ton and IP. This result is expected as higher current and high pulse-on time generates more intense electrical discharges and consequently, more material melted and removed from the workpiece. In addition IP and Ton also show direct proportion to the MRR; i.e., MRR can be increased by increasing the value of these two parameters. Similar results are presented by Natarajan [19] Gap voltage as indicated shows inverse relation to MRR; that is at the lower voltage value higher material removal can be obtained. The effect of tool thickness on MRR is depicted in the Figure 7. As indicated MRR increases significantly with increase in tool thickness. Similar conclusion reported by Song [20] by area effect concept. As indicated in Table 2 only Ton and IP shows a strong interaction effect (with $p < 0.05$) over MRR. However the interaction of voltage and tool thickness is seems significant only.

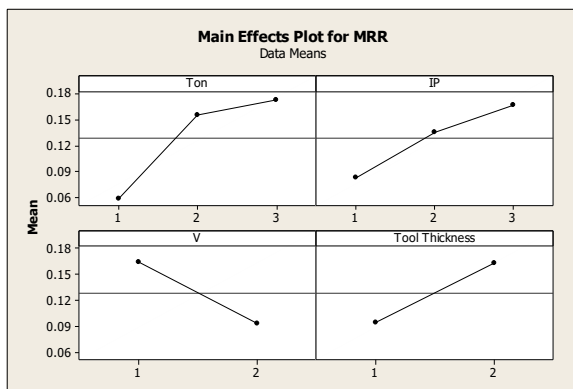


Figure 7. Main effect plot of factors for MRR

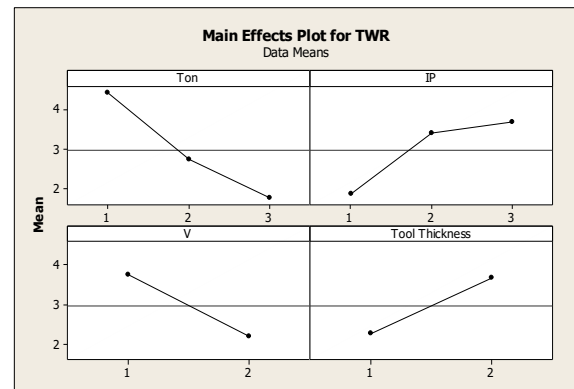


Figure 6. Main effect plot of factors for TWR

Although the inference made based on graphical assessment is not accurate. So, ANOVA is used here to find the significance effects of the factor based on a 95% confidence interval. Before any conclusion is made based on ANOVA table, the assumptions are verified as follows.

To evaluate the experimental data for the problems such as outliers, non normality, etc. residual plots are used. The histogram plot, normal probability plot, and residual versus observation plot of these residuals do not reveal any abnormality. In the above discussion, ANOVA proved not to be violated through these experimentations, so ANOVA can be performed. As indicated in the Table 2 Ton is the most influencing parameter because of its contribution is 30.38%, followed by V, tool thickness, IP and interaction of Ton*IP, IP*Tool thickness, V*Tool thickness and Ton*V and with percentage contributions 18.64, 18.08, 11.67, 8.04, 2.11, 1.87 and 1.11 respectively.

Table 1. Experimental layout using full factorial design

Run Order	Std Order	Ton	IP	V	Tool Thickness	MRR (mg/min)	TWR (mg/min)
1	35	65	35	99	5	0.149	1.267
2	27	65	5	99	5	0.03	0.4
3	29	65	20	50	5	0.215	1.733
4	8	5	20	99	10	0.009	5.067
5	32	65	20	99	10	0.157	1.953
6	15	35	5	99	5	0.046	0.2
7	31	65	20	99	5	0.104	0.667
8	1	5	5	50	5	0.013	4.933
9	6	5	20	50	10	0.119	8.067
10	13	35	5	50	5	0.078	0.333
11	10	5	35	50	10	0.133	6.715
12	11	5	35	99	5	0.012	2.333
13	4	5	5	99	10	0.011	3.767
14	33	65	35	50	5	0.26	3.667
15	3	5	5	99	5	0.008	2.267
16	22	35	35	50	10	0.303	5.467
17	30	65	20	50	10	0.278	1.95
18	34	65	35	50	10	0.348	4.467
19	17	35	20	50	5	0.217	3.6
20	19	35	20	99	5	0.112	2.267
21	14	35	5	50	10	0.197	0.6
22	7	5	20	99	5	0.019	1.867
23	9	5	35	50	5	0.059	3.267
24	26	65	5	50	10	0.158	1.793
25	16	35	5	99	10	0.168	0.333
26	20	35	20	99	10	0.167	3.267
27	18	35	20	50	10	0.229	5.267
28	24	35	35	99	10	0.191	4.4
29	2	5	5	50	10	0.229	6.167
30	28	65	5	99	10	0.093	1.3
31	12	5	35	99	10	0.093	3.667
32	21	35	35	50	5	0.123	4.033
33	36	65	35	99	10	0.189	1.7
34	23	35	35	99	5	0.134	2.967
35	5	5	20	50	5	0.051	4.933
36	25	65	5	50	5	0.073	0.333

Table 2. ANOVA for MRR, using Adjusted SS for Tests

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	%
Ton	2	0.087	0.087	0.043	33.3	0.000	30.38
IP	2	0.033	0.033	0.016	12.8	0.000	11.67
V	1	0.053	0.053	0.053	40.9	0.000	18.64
Tool thickness	1	0.052	0.052	0.052	39.7	0.000	18.08
Ton*IP	4	0.023	0.023	0.005	4.41	0.014	8.04
Ton*V	2	0.003	0.003	0.001	1.25	0.314	1.11
Ton*Tool thickness	2	0.001	0.001	0.000	0.40	0.679	0.35
IP*V	2	0.000	0.000	0.000	0.35	0.710	0.31
IP*Tool thickness	2	0.006	0.006	0.003	2.35	0.127	2.11
V*Tool thickness	1	0.005	0.005	0.005	4.13	0.059	1.87
Error	16	0.021	0.021	0.001			
Total	35	0.288					

3.2 Influence of EDT Parameters upon TWR

The effect of electrical discharge machining parameters on tool wear rate is shown in Figure 3. It shows that current is in direct relation with the tool wear. As the value of current increases, it leads to increased melting of workpiece surface. As depicted in the figure, Ton shows an inverse relation to TWR. At higher Ton, more carbon particles are released and form a protective layer on the electrode that reduces tool wear. Similar results are presented by Habib [21]. While, tool wear tends to decrease with increase in gap voltage. This is because when the gap voltage increases the distance between workpiece and tool electrode also increases, which reduces the intensity of electrical discharges, as a result TWR decreases. As indicated in figure tool wear is found higher with thickened tool, possibly due to large machining area. From the interaction plot study it was found that with the increase of interaction of IP*Ton the tool wear rate decreases, because the higher combination of current with pulse duration possibly forces the metal particles to stick on the tool surface, which develops a shield against wear, with a possibility of less tool wear. Ton*Tool thickness and Ton*voltage are found to be less significant than the earlier terms in respect to TWR. Before any inference can be made based on Table 3, the assumptions are verified through residual plots which do not reveal any abnormality. As indicated in the Table 3 Ton is the most significant parameter because its contribution is 30.38%, followed by IP, V, interaction of Ton*IP, tool thickness, interaction of Ton*V and Ton*Tool thickness with percentage contributions 15.72, 14.90, 14.56, 12.08, 3.08 and 2.73 respectively.

4. Conclusion

In the current study, the effect of input parameters i.e. IP, Ton, tool electrode thickness, gap voltage, and their interaction over MRR and TWR was investigated. The study has been made for SS-304 stainless steel because of its increasing applications in various industries. The full factorial design of experiments method has been used to design the experiments. Experimental findings show that Ton is the most influencing factor that affects MRR and TWR. Voltage and tool thickness also identified as significant parameters, however, its effect is less than pulse-on time. Among all interactions of the factors, the interaction of Ton*IP shows a significant effect over MRR and TWR. These results can also be verified through ANOVA tables which show the percentage contribution of various factors and their interactions.

Table 3.ANOVA for TWR, using Adjusted SS for Tests

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	%
Ton	2	43.2658	43.2658	21.6329	51.88	0.000	30.38
IP	2	22.3863	22.3863	11.1931	26.84	0.000	15.72
V	1	21.2157	21.2157	21.2157	50.88	0.000	14.90
Tool thickness	1	17.1953	17.1953	17.1953	41.24	0.000	12.08
Ton*IP	4	20.7344	20.7344	5.1836	12.43	0.000	14.56
Ton*V	2	4.3801	4.3801	2.1900	2.25	0.018	3.08
Ton*Tool thickness	2	3.8887	3.8887	1.9443	4.66	0.025	2.73
IP*V	2	1.4057	1.4057	0.7028	1.69	0.217	0.99
IP*Tool thickness	2	1.0890	1.0890	0.5445	1.31	0.298	0.76
V*Tool thickness	1	0.1657	0.1657	0.1657	0.40	0.537	0.12
Error	16	6.6720	6.6720	0.4170			
Total	35	142.3985					

References

- [1] Leão F N and Pashby I R 2004 A review on the use of environmentally-friendly dielectric fluids in electrical discharge machining, *J Mater Process Technol.* **149**(1) 341-6.
- [2] Mohammadi A, Tehrani A F, Emanian E and Karimi D 2008 Statistical analysis of wire electrical discharge turning on material removal rate, *Journal of materials processing Technology.* **205**(1) 283-289.
- [3] Gohil V and Puri Y M 2017 Turning by electrical discharge machining: A review, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture.* **231**(2) 195-208.
- [4] Soni JS and Chakraverti G 1994 Machining characteristics of titanium with rotary electro-discharge machining, *Wear.* **171** 51-8.
- [5] Qu J, Shih A J and Scattergood R O 2002 Development of the cylindrical wire electrical discharge machining process, part 1: concept, design, and material removal rate. *Journal of Manufacturing science and engineering.* **124**(3) 702-707.
- [6] Qu J, Shih A J and Scattergood R O 2002 Development of the cylindrical wire electrical discharge machining process, part 2: surface integrity and roundness, *Journal of manufacturing science and engineering.* **124**(3) 708-714.
- [7] Guu YH and Hocheng H 2001 Effects of workpiece rotation on machinability during electrical-discharge machining, *Mater Manuf Processes.* **(16)** 91-101.
- [8] Ghoreishi M and Atkinson J 2002 A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining, *Journal of Materials Processing Technology.* **120**(1) 374-384.
- [9] Yan B H Chang, GW Chang, J H and H su R T 2004 Improving electrical discharge machined surfaces using magnetic abrasive finishing, *Machining science and technology.* **8**(1) 103-118.
- [10] Janardhan V and Samuel GL 2010 Pulse train data analysis to investigate the effect of machining parameters on the performance of wire electro discharge turning (WEDT) process, *International Journal of Machine Tools and Manufacture.* **50**(9) 775-788.
- [11] Gjeldum N Bilic B and Veza I 2015 Investigation and modelling of process parameters and workpiece dimensions influence on material removal rate in CWEDT process, *International*

- Journal of Computer Integrated Manufacturing*. **28(7)**715-728.
- [12] Gohil V and Puri Y M 2016 Statistical analysis of material removal rate and surface roughness in electrical discharge turning of titanium alloy (Ti-6Al-4V), *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 0954405416673104.
- [13] Gohil V and Puri Y M 2017 Experimental Investigation on Surface Roughness in Electrical Discharge Turning of Ti-6Al-4V Alloy, *Transactions of FAMENA*. **40(4)**1-10.
- [14] Song K Y, Park MS and Chu CN 2013 EDM turning using a strip electrode, *J Mater Process Technol*. **213** 1495-1500.
- [15] Yan M T and Hsieh P H 2015 An on-line monitoring system for wire electrical discharge turning process, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. **229(11)**1945-1954.
- [16] Gohil V and Puri YM 2016 Experimental investigation of surface roughness in electrical discharge turning process, In *AIP Conference Proceedings* (**1769**) 050001. AIP Publishing.
- [17] Krishnan S A and Samuel G L 2013 Multi-objective optimization of material removal rate and surface roughness in wire electrical discharge turning, *The International Journal of Advanced Manufacturing Technology*. (**67**)2021-2032.
- [18] Puri YM and Gohil V 2017 Experimental Study of Material Removal Rate in Electrical Discharge Turning of Titanium Alloy (Ti-6al-4v), In *IOP Conference Series: Materials Science and Engineering* (**187**) 012036. IOP Publishing.
- [19] Song K Y and Chu C N 2015 Effect of machining area on material removal rate in strip EDM, *Int. J. Precis. Eng. Manuf.* **16(12)**2435-2440.
- [20] Natarajan N, Arunachalam R M and Thanigaivelan R 2013 Experimental study and analysis of micro holes machining in EDM of SS 304, *International Journal of Machining and Machinability of Materials*. **13(1)**1-16.
- [21] Habib S S 2009 Study of the parameters in electrical discharge machining through response surface methodology approach, *Applied Mathematical Modelling*. **33(12)**4397-4407.