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

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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 honeycomb seals used in aerospace industry [3]. The idea and experimental set-up of EDT process is shown in Figure 1 and Figure 2 respectively.

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 increases. 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 (Ra) 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 Ton 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 input parameters on the MRR and Ra 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 parameter which affects 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 that IP and Ton has a most significant effect on Ra whereas, duty factor shows inverse relation to Ra as it increases Ra decreases [13].

![Figure 3. A cylindrical EDT part.](image)

![Figure 4. Tool used in EDT process](image)

Song et al. produced a new turning method which utilizes conventional EDM machine. The authors reported that strip EDM removes 74% more material than WEDT and produces 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 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 has 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 has most significant effect on material removal. Furthermore IP and Ton shows direct relation to MRR i.e. as IP and Ton increases MRR increases significantly. However, higher MRR can be obtained at lower value of voltage [18].

From the above literature study one can conclude that many researchers and scientists has 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 conventional EDM machine. The current research work presents a study on EDM turning of SS-304 stainless steel using preshaped 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 weighted before (w₁) and after
(w_i) machining using a digital precision balance. The MRR and TWR were calculated using equation (1):

\[
MRR (mg / min.) = \frac{W_f - W_i}{t} \times 1000
\]  

(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 shows 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 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.

![Main Effects Plot for MRR](image1)

**Figure 7.** Main effect plot of factors for MRR

![Main Effects Plot for TWR](image2)

**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| 5              | 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  | 50| 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  | 50| 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 forms 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 thicker 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 of 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 shows 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|         |         |        |         |       |

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