Experimental study of electrical discharge drilling of stainless steel UNS S30400

E A H Hanash and M Y Ali
Department of Manufacturing and Materials Engineering
Faculty of Engineering, International Islamic University Malaysia
P.O.Box 10, 50728 Kuala Lumpur, Malaysia
E-mail: mmyali@iium.edu.my

Abstract. In this study, overcut and taper angle were investigated in machining of stainless steel UNS S30400 against three different electrical discharge machining parameters which are electric current ($I_p$), pulse on-time ($T_{on}$) and pulse off-time ($T_{off}$). The electrode used was of 1 mm diameter with aspect ratio of 10. Dimensional accuracy was measured by evaluating overcut and taper angle. Those two measurements were performed using optical microscope model (Olympus BX41M, Japan). The experimentation planning, evaluation, analysis and optimization have been carried out using DOE software version 10.0.3 RSM based method with total number of twenty experiments. The research reveals that, discharge current was found to have the most significant effect on overcut and taper angle followed by pulse on-time and pulse off-time. As the discharge current and pulse on-time increase, overcut and taper angle are increased. However, when pulse off-time increases, overcut and taper angle decrease. The outcome result of this study will be very useful in the manufacturing industry to select the appropriate parameters for the selected work material. The model has shown a great accuracy with percentage error of less than 5%.

1. Introduction
The current demand of miniaturized parts with high quality output is growing rapidly due to the fast development of technology in all fields such as aerospace, automotive, medical, biomedical and electronic industry. Moreover, Machining of hard materials such as stainless steel requires, high friction force between the cutting tool and the workpiece; provided that the cutting tool is stronger and harder than the work material. Therefore, the traditional machining operations, machining of hard materials with high accuracy and in the micro-level is seemed to be impossible. However, with the development of the non-traditional machining operations, it is made possible with considerable precision and accuracy. Among the non-conventional machining processes to achieve a good accuracy of the drilling of small holes is electrical discharge machining (ED-Drilling). Therefore, in this study, presents general overview of the main categories of the machining operations and the main study focuses on the electrical discharge machining (EDM) specifically ED-Drilling. Therefore, non-conventional processes such ultrasonic machining, ion beam machining, water jet machining, laser machining, electrical discharge machining; just to name few among others, are processes which have the ability to machine complex geometrical shapes on difficult-to-cut materials such as tungsten carbide, diamond and steel alloys [1].

Researchers have investigated the machinability of the stainless steel and different machining performances such as MRR, EWR, surface roughness and other EDM machining characteristics [2, 3]. The study of machining performance, the researchers study the MRR, EWR and surface tribology and quality. Rajmohan, Prabhu [4] have investigated the effect of pulse on-time ($T_{on}$), pulse off-time ($T_{off}$), voltage (V) and the current (I) on the MRR in 304 stainless steel. They used Taguchi method and
ANOVA to analyse the results and it was found that the pulse of time and current have the most significant effect on MRR. However, dimensional accuracy has not been investigated.

Dimensional accuracy is considered of great importance in machining the different parts for different applications. It is more sensitive in the applications such as nozzles or on the cooling fans of turbines whereby high accuracy is required. The dimensional accuracy can be measured by the amount of overcut and taper angle [5]. Many researchers have done analysis of the quality, performance and dimensional analysis of the EDM-Drilling holes of different work materials with different hole diameters [2, 5-14]. As previous researchers focused on the measurement of machining performance, this study investigates the dimensional accuracy of the drilled hole made by electrical discharge drilling so that the quality of machined parts is maintained. Therefore, the effect of different electrical discharge parameters are investigated.

1.1 Hole Overcut
Hole overcut is defined as the difference of the average diameter of the entrance and exit hole with respects to the electrode diameter. The diameter of the hole will always be larger than the diameter of the electrode. This phenomenon is due to the spark gap and due to the secondary spark formation, which is generated by the debris that are removed by the pressurized liquid. Overcut can be calculated from figure 1. From the figure, the formula for overcut can be easily deduced. It is the difference between the hole diameter and the electrode diameter and divide by two, as expressed by Equation 1.

\[ OC = \frac{(d_a - d_e)}{2} \]  

(1)

1.2 Hole Taper Angle
Hole taper is also one of the characteristics to measure the dimensional accuracy of the small drilled hole. It is occurred due to the wear of the electrode and debris issue that made the entrance diameter larger than the exit diameter. Therefore, taper is the angular measurement between the opening and the end of the drilled hole. There is a strong relationship between taper angle of the hole and the corner wear of the electrode. Taper can be calculated using equation 2 where \( \theta \) is the taper angle; \( D_h \), \( D_e \), and \( D_{ex} \) are hole diameter at entry, electrode diameter, hole diameter at the exit respectively and \( t \) is the thickness of the workpiece. Figure 2 shows the schematic diagram representing taper angle occurrence.

\[ \theta = \tan^{-1}\left(\frac{d_h - d_{ex}}{2t}\right) \]  

(2)

2. Experimental Setup
The experiment is planned using the response surface method to design, analyse and optimise the results with total numbers of 20 experimental runs. These runs have been executed in the ED-Drilling machine model OCT3525NA (Taiwan) to investigate the effect of the input machining parameters such as electric current, pulse on-time, and pulse off-time on the dimensional accuracy of the drilled hole measures by the hole overcut and taper angle. The electrode that have been used in this experiment is made of a brass tube material with 1mm outer diameter and inner diameter of 0.3 mm. prior to the measurement of the machining characteristics such as hole overcut and taper angle, the set of holes in one line in the 304-stainless steel were cut exactly from the middle of the holes by the aid of the wire electric discharge machining, so that more accurate results is obtained. The measurement of the hole overcut and taper angle were done using the optical microscope (Olympus BX41M, Japan). The electrode discharge condition are shown in table 1.
Table 1. Electro discharge drilling condition

| Fixed Parameters                  | Value               |
|-----------------------------------|---------------------|
| Workpiece Material               | stainless steel UNS 30400  |
| Electrode tool material           | Brass               |
| Electrode diameter (mm)           | 1                   |
| Capacitance (F)                   | 0                   |
| Polarity                          | -ve                 |
| Dielectric flushing pressure (Mpa)| 6                   |
| Hole depth (mm)                   | 9.65                |
| Voltage gap (v)                   | 22                  |
| Feed rate (mm/s)                  | 2                   |
| Spark power (VDC)                 | 105                 |

Figure 1. Hole overcut schematic diagram [5]

Figure 2. Schematic diagram of taper angle [15]

2.1 Work Materials
The work material is selected based on the application of the material itself in the industry. After studying different literature studies, different materials have been investigated such as D2 steel, SS316, SS 304, Inconel 718, and various types of ceramic based materials. The investigation was mainly to measure the machining performance such as surface roughness, MRR, EWR and dimensional accuracy such as overcut, taper angle, and circularity, however, the examining of the dimensional accuracy of 1mm holes have not been done before on UNS 30400.
Table 2. Process parameters and level using RSM

| Variable Parameters | Lower Level | Upper Level | Response   |
|---------------------|-------------|-------------|------------|
| Pulse Current (I<sub>p</sub>) | 5           | 21          | Overcut    |
| Pulse on-time (T<sub>on</sub>) | 15          | 75          | Taper Angle |
| Pulse off-time (T<sub>off</sub>) | 5           | 45          |            |

Figure 3. Electrode made of brass tube [8]

Therefore, in this study, UNS 30400 has been selected to investigate the dimensional accuracy of the drilled holes. UNS 30400 enters into various applications in aerospace, automotive, biomedical, biotechnology, and home appliance manufacturing industry. It is mostly used in valves, refrigeration equipment, skyscraper trim, turbine blades, evaporators, sinks, splash back, a basic machining method for the manufacturing industries of aerospace, automotive, nuclear, medical and die-molding industry.

2.2 Electrode Materials
Brass electrode was used to perform drilling holes on 304 stainless steel due to its good physical properties and it is relatively cheap. Figure 3 shows the electrode which made of brass. It is a hollow electrode which allow the pressurized water to go through the internal diameter of the electrode to remove the debris from the hole while drilling.

2.3 Experimental Procedures
The experimental procedures were implemented on stainless steel grade 304 using different machining parameters such as electric current, pulse on-time and pulse off-time with 1mm electrode diameter made of a brass tube. The experimental design, evaluation and analysis were done using the response surface method (RSM) with total number of 20 experiments with three factors and 5 levels. Table 2 depicts the process parameters and their levels.

3. Results and Discussion
The effect of the different parameters such as electric current, pulse on-time and pulse off-time on the dimensional accuracy of the drilled hole were studied. Different parameters have different effect on overcut and taper angle. As it can be seen from figure 4 and figure 5 that electric current has the significant effect on overcut and taper angle because it has the largest factor which is a small change in electric current can directly affect the change in overcut and taper angle as can be seen in the models equations 3 and 4 where A, B, C are electric current, pulse on-time and pulse off-time respectively.

\[
OC = 0.028 + 0.008219A + 0.005056B - 0.002156C - 0.001149A2 - 0.001374B2 \quad (3)
\]
\[
\theta = 0.40 + 0.085A + 0.042B - 0.024C \quad (4)
\]
This is because a small change in the electric current will cause higher change in these two criteria. In the case of overcut and taper angle, the result is also confirmed with previous researchers’ results [2, 5, 15]. This is due to the higher spark gap, which melts and vaporizes more material from surface and this also could be explained due to the material properties of the SS304 work material. However, this is an opposite to some of the researchers which states that with the increases of the discharge current overcut and taper angle decrease [16]. The effect of pulse on-time on overcut and taper angle is that with the increasing of the pulse on-time, taper angle increases in a way less than what electric current does. This is because the pulse on-time and pulse off-time affect the formation of the secondary spark during removal of the debris by pressurized liquid. The pulse off-time was with the least effect on both responses so that as the pulse off-time

**Figure 4.** The effect of the three different EDM parameters namely electric current, pulse on-time and pulse off-time on overcut
Figure 5. The effect of the three different EDM parameters namely electric current, pulse on-time and pulse off-time on taper angle

Figure 6. Optical microscope image (current = 9A, pulse on time = 30 µs and pulse off time = 35 µs)
3.1 Study of Hole Morphology

Figure 6 depicts that when the machine tool is running at current 30 A, pulse on time 30 µs, pulse off time 35 µs, it achieves lower overcut and reduced the taper angle. It can be observed also some sharp edges appeared in the hole and this could be because of the flushing pressure need to be studied and adjusted.

3.2 Model Validation

Two sets of experimental runs were performed several times and the average data were taken and compared against the predicted data obtained from the model equations presented previously. Table 3 presents the data used to confirm the validity of the model. Two set runs are performed. The first run is 7 A, 25 µs, and 30 µs for Current, Ton and Toff respectively and the second run are 12 A, 40 µs and 20 µs. The percentage error were calculated and was found to be less than 5% which is promising result.

Table 3. Conformation runs for overcut and taper angle models with percentage errors

| No. | Overcut (mm) | Taper Angle° | % Error Overcut | % Error Taper |
|-----|--------------|--------------|-----------------|---------------|
|     | Predicted    | Actual       | Predicted       | Actual        |
| 1   | 0.0028       | 0.0029       | 0.199           | 0.203         | 3.929         | 2.061 |
| 2   | 0.0251       | 0.0258       | 0.372           | 0.374         | 2.789         | 0.403 |

4. Conclusion

In this study, overcut and taper angle are investigated in machining of stainless steel 304, against three different parameters such as electric current (I_p), pulse on-time (T_on) and pulse off-time (T_off). The electrode is made of a brass tube with diameter of 1mm. Dimensional accuracy was measured by evaluating overcut and taper angle. Those two measurements were performed using optical microscope. The experimentation planning, evaluation and analysis had been carried out by the RSM with total number of 20 runs. According to the experimental outcomes, followings are the specific conclusions that have been drawn.

1. The research reveals that, discharge current was found the most significant factor affecting overcut and taper angle as well followed by pulse on-time and pulse off-time. This is due to the higher spark gap, which melts and vaporizes more material from surface and this also could be explained due to the material properties of the SS304 work material.

2. As the discharge current and pulse on-time increase, overcut and taper angle are increased. In the case of the pulse off-time, as it increases, overcut and taper angle decreases.

3. The optimized parameters that give the minimum overcut and taper angle response are 9 A current, 30 µs Pulse on-time and 35 µs Pulse off-time which gives 0.010 mm overcut and 0.244° taper angle.

4. The validation of the model has been performed and it was found that the percentage errors are about 3.36% for overcut and 1.23% for taper angle.

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References

[1] Venkatesh, V., N. Swain, G. Srinivas, P. Kumar, and H.C. Barshilia. 2016. Materials and Manufacturing Processes

[2] Natarajan, N. and P. Suresh. 2015 The International Journal of Advanced Manufacturing Technology, 77(9-12), 1741-1750

[3] D’Urso, G., G. Maccarini, and C. Ravasio 2015 The International Journal of Advanced Manufacturing Technology, 1-13

[4] Rajmohan, T., R. Prabhu, G.S. Rao, and K. Palanikumar 2012 Procedia Engineering, 38, 1030-1036

[5] Eyercioğlu, O., M.V. CAKIR, and G. Kursad 2013 Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 0954405413498730

[6] Sultan, T., A. Kumar, and R.D. Gupta 2014 International Journal of Manufacturing Engineering

[7] Parmar, K.V. and R. Patel. 2014. Experimental Investigation of Process Parameters of Micro EDM Drilling on Carbide (K20) material

[8] Janmanee, P. and A. Muttamara 2011 International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 2(4), 471-481

[9] Tamang, S., N. Natarajan, and M. Chandrasekaran 2016 Journal of the Brazilian Society of Mechanical Sciences and Engineering, 1-11

[10] Bozdana, A.T., O. Yilmaz, M.A. Okka, and I.H. Filiz 2010 Paper presented at the Responsive Manufacturing-Green Manufacturing (ICRM 2010), 5th International Conference on

[11] Singh, B., P. Singh, G. Tejpal, and G. Singh 2012 Int. J. of Adv. Engg. Tech, 3(4), 130-133

[12] Singh, H. and E. Singh. 2013. Effect of Pulse on/Pulse Off on Machining of Steel Using Cryogenic Treated Copper Electrode

[13] Li, Y., W. Hou, J. Xu, and H. Yu. 2016 IEEE

[14] Bhaumik, M., K. Maity, and K.D. Mohapatra. 2016 Paper presented at the Applied Mechanics and Materials

[15] Jahan, M.P., Y. San Wong, and M. Rahman. 2010 The International Journal of Advanced Manufacturing Technology, 46(9-12), 1145-1160

[16] Siva, M., M. Parivallal, and M.P. Kumar. 2014 Procedia Materials Science, 5, 1829-1836