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# Investigation of angular error during taper cutting in Inconel 718 using WEDM process

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**Abstract**— The current research work presents the effect of process parameters on angular error during taper cutting using WEDM process. Taper cutting is an unique operation of WEDM process, which provides an effective way for machining conductive, high strength and temperature resistant materials and has the capability to produce components with complex features and curved surfaces. During this process the wire is subject to deformation, which creates deviation in the inclination angle of the machined part. As a result, the machined part loses its precision. In this paper, the effect of process parameters on angular error (AE) in WEDM taper cutting is presented. Taguchi $L_{27}$ orthogonal array is used to gather information regarding the process with less number of experimental runs. The contribution of each process parameters towards the Angular error is identified. Analysis of Variance (ANOVA) is also conducted to determine the statistical significance of process parameters during taper cutting in WEDM process.

**Key Words**— WEDM, Angular Error, Taper Cutting, Inconel 718.

## 1 Introduction

In the recent era, nickel based supper alloys such as Inconel 718 finds outspread demand in aerospace, automobile, and nuclear industries due to its high strength to weight ratio and wear resistance properties. However, these advanced nickel based alloys with complex shapes are difficult to machine using conventional machining processes due to its superior mechanical properties. Since traditional machining processes hardly meet these requirements, taper cutting operation using wire electrical discharge machining (WEDM) provides an effective solution for producing complicated and tapered profiles using any difficult-to-machine materials, super alloys and composites, especially for aerospace and defence applications. During tapering process the wire is subject to deformation, resulting in deviations in the inclination angle in the machined part. As a result, the machined part loses its precision.

The problem of prediction of angular error was investigated by Kinoshita et al. [1]. They proposed a linear model of wire deformation neglecting the forces produced during the process. Sanchez et al. [2] presented a approach for the prediction of angular error in wire-EDM taper cutting. They analyzed the factors that influence angular error in taper cutting that leads to the development of experimental and numerical methods for the prediction of the error. Plaza et al. [3] developed two models for the prediction of angular error in WEDM taper cutting and found that part thickness and taper angle are most influencing variables. A computer simulation approach is adopted by Sanchez et al. [4] for analysis of angular error in wire-EDM taper cutting to minimize verification by experimentation. Huse et al. [5, 6] has discussed an effective WEDM cornor cutting strategy with appropriate control and tension adjustment and introduced a concept of discharge contact angle and a geometrical analysis for both angular and arc cornor cutting. Chiu et al. [7] carried out an on-line adjustment of the axial force imposed by the machine on the wire in taper cutting. Development of sinking and wire electro discharge machining technology for two ceramics with a promising future (boron carbide and silicon infiltrated silicon carbide) was described by [8]. Formula to calculate the maximum inclination angle of ruling was introduced and coordinates of points on ruled surface have been obtained [9]. However a limited number of studies deal with the effect of process parameters on angular error during taper cutting operation in WEDM process. With a view to alleviate this difficulty, a simple but reliable method based on Taguchi's design of experiment is used in the present work for investigating the effect of various process parameters on angular error and determines optimal process parameter settings. ANOVA analysis is carried out to find out the significant effect of the process parameters during taper cutting in WEDM process.

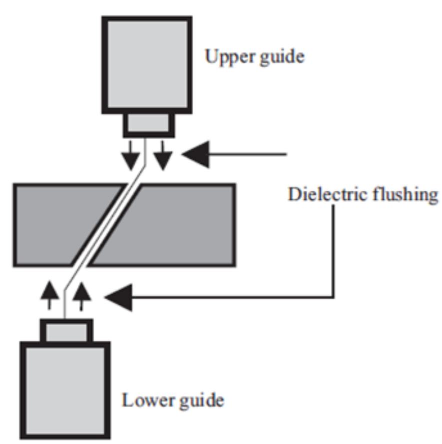


Figure I: Relative displacement of upper guide and lower guide in WEDM taper cutting (Plaza et al. [3])


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## 2 EXPERIMENTAL DETAILS

The experiments have been carried out on AC Progress V2 high precision CNC WEDM, which is manufactured by Agie-Charmilles Technologies Corporation. Coated Broncocut-W (by Bedra), diameter 0.2mm, has been used for the experiment. Deionized water is used as di-electric medium. Inconel 718 [69% Iron (Fe), 19% Chromium (Cr), 10% Nickel (Ni), 2% Manganese (Mn) and less than 0.08% Carbon (C)] of diameter 25mm and thickness of 20mm, 30mm and 40 mm respectively has been chosen as work piece material. The input parameters used in the present study are shown in Table 1. These were chosen through review of literature, experience, and some preliminary investigations.Their limits were set on the basis of capacity and limiting conditions of the WEDM, ensuring continuous cutting by avoiding the breakage of the wire.

TABLE 1 Input parameters with different levels

| Input Parameters | Unit | Sym-bol | Levels | | |
|---|---|---|---|---|---|
| | | | I | II | III |
| Part Thickness | mm | A | 20 | 30 | 40 |
| Taper Angle | Degree | B | 5 | 6 | 7 |
| Pulse Duration | µs | C | 24 | 28 | 32 |
| Discharge Current | Amp | D | 14 | 16 | 18 |
| Wire Speed | mm/s | E | 90 | 120 | 150 |
| Wire Tension | N | F | 12 | 14 | 16 |

In the present work, Taguchi's $L_{27}$ orthogonal array is used to gather maximum information regarding the process with less number of experimental run. The factors and their interaction are assigned to the columns by using the standard linear graph [10-11]. According to the Taguchi design concept, a $L_{27}$ orthogonal array was chosen for the experiments as shown in Table II. Angular error is chosen as the most important response for tapering process in wire electrical discharge machining process. The angular errors can be expressed in minute and calculated by using the following formula.

Angular error = β-α

where α is the programmed angle and the angle expected in the machined part.

β is the measured angle after machining.

After machining, the angle of the inclined surface (β) is measured with respect to the top surfaces using a Zeiss 850 CNC coordinate measuring machine. The angle is measured at four different places of the tapered surface and the average is taken as the final value for angle of the inclined surface. Then the angular error is calculated which is shown in Table 2.

TABLE 2 Experimental Results

| Expt.NO. | A | B | C | D | E | F | Angular Error (min) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 30.221 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 34.447 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 39.119 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 41.546 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 42.485 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 45.824 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 46.616 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 48.847 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 52.145 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 50.255 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 58.654 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 33.526 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 50.398 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 53.254 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 44.658 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 25.257 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 32.542 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 27.568 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 28.356 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 24.736 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 26.845 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 34.628 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 45.265 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 35.548 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 33.667 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 41.529 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 34.289 |

## 3 RESULTS AND DISCUSSIONS

The experiments were performed as per Taguchi's $L_{27}$ orthogonal array considering Inconel 718 as the work piece material with coated Broncocut-W wire electrode. Experimental results as shown in Table 2 are analysed to determine the influence of various process parameters on angular error using the popular statistical software package MINITAB 16. Analyses of the results presented in Fig. 2 lead to the conclusion that the third level of part thickness ($A_3$), first level of taper angle ($B_1$), third level of pulse duration ($C_3$), first level of discharge current ($D_1$), second level of wire speed ($E_2$) and first level of wire tension ($F_1$) provide the minimum value of angular error. Analysis of variance (ANOVA) is carried out to investigate the significant effect of each parameter and their interaction in relation to angular error. From the Table 3 it is evident that part thickness, taper angle, pulse duration, discharge current, wire tension are the significant parameters for angular error during tapering process of WEDM. A significant interaction between factors A and B, A and C is also observed. The normal probability plot presented in Fig. 3 shows that the set of values of responses are very close to median of set values and not deviate from mid value. The point on this plot forms nearly a linear pattern, which indicates that the normal distribution is a good model for this data set. From Fig. 2, it is evident that increase of part thickness causes decrease in angular error because a longer length of the wire electrode in a thicker work piece provides more opportunities for the spark to occur and enough space for movement in U-V axes using upper guide and lower guide.

Table 3 Anove Table

| Factor | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Part thickness (A) | 2 | 423.8 | 423.8 | 211.9 | 45.2 | 0.00 |
| Taper angle (B) | 2 | 257.2 | 257.2 | 128.6 | 27.4 | 0.00 |
| Pulse duration (C) | 2 | 146.9 | 146.9 | 73.48 | 15.6 | 0.00 |
| Discharge current (D) | 2 | 101.9 | 101.9 | 50.96 | 10.8 | 0.01 |
| Wire speed (E) | 2 | 24.89 | 24.89 | 12.44 | 2.66 | 0.14 |
| Wire tension (F) | 2 | 65.61 | 65.61 | 32.80 | 7.00 | 0.02 |
| A×B | 4 | 1068.94 | 1068.94 | 267.23 | 57.03 | 0.00 |
| A×C | 4 | 210.4 | 210.4 | 52.6 | 11.2 | 0.00 |
| Error | 6 | 28.11 | 28.11 | 4.68 | | |
| Total | 26 | 2328.2 | | | | |

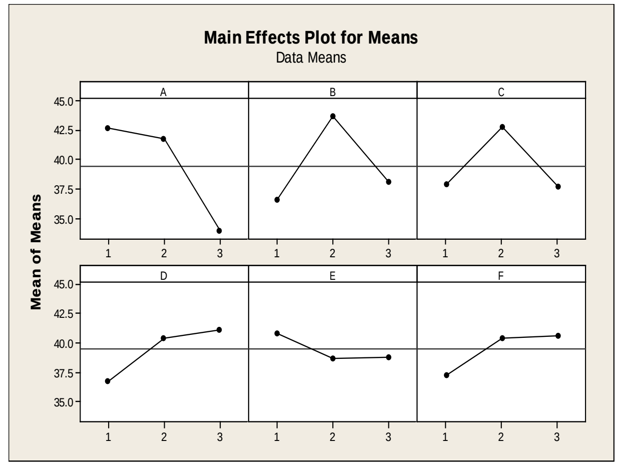


Fig. 2. Main effect of plot for angular error

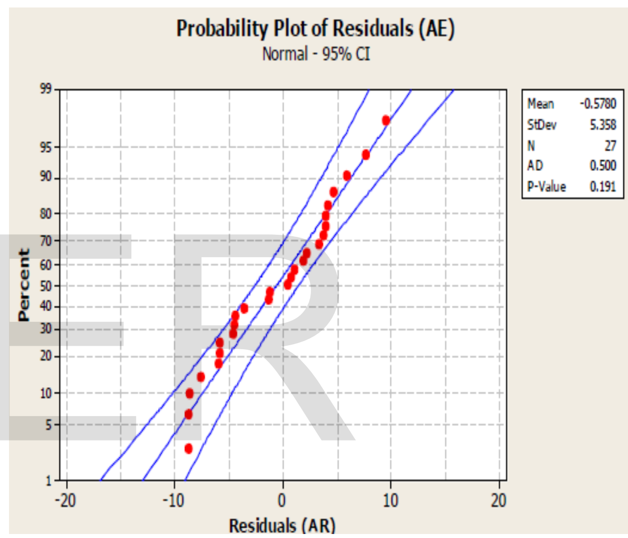


Fig. 3. Normal Probality Plot

## 4 CONCLUSIONS

Angular error is a major concern among the tool engineers while producing tools and dies for complex parts using wire electrical discharge machining process. The Taguchi method seems to be an efficient methodology to find out the optimum cutting parameters for taper cutting operation as experiment was based on minimum number of trails conducted to obtain optimum setting for cutting parameters. For minimizing the angular error the recommended parametric combination is part thickness 40mm, taper angle 5 degree, pulse duration 32 µs, discharge current 14 Amp, wire speed 120 mm/s and wire tension 12N for taper cutting of Inconel 718 using wire electrical discharge machining process.

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