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Effect of Profile Geometry and Cutting Speed Override Parameter on Profiling Speed During Tapering Using Wire Electric Discharge Machining

I. V. Manoj and S. Narendranath

Abstract The oblique/tapered form of precise components has many applications like dies, nozzles, inserts, cutting tools, and other components. Wire electric discharge machining is an erosion technique that helps in precise machining of hard materials. In the present study, basic profiles were machined using a novel slant-type fixture to achieve a slant surface on Hastelloy X. The shapes like triangle, square, and circle are machined at different slant angles, namely 0° and 30°. This paper aims to study the effects of the cutting speed override parameter and profile geometry on profiling speed of machined profiles. The basic shapes of 1, 3, and 5 mm sides were machined. The cutting speed override parameter affected the most on profiling speed in both the angles irrespective of profiles. The profile geometry also affects the profiling speed although the machining parameters were maintained constant.

Keywords Slant-type taper profiling · Cutting speed override · Profile geometry

1 Introduction

Wire electric discharge machining (WEDM) works on an electro-thermal mechanism which melts the hard conductive workpiece by sparks generated by the electrode. It proves to be the most beneficent machining process, as conventional machining of hard materials may produce many flaws on tool and workpiece [1, 2]. Many materials like ceramics, nanoceramics, composites, titanium-based alloys, nickel-based superalloys, etc., can be machined with precision using EDM [3–6]. Many studies have been carried out on output parameters like cutting speed, surface roughness, kerf, etc. Mouralova et al. [7] have investigated the effects of machining parameters on cutting speed and surface quality. The optimum cutting speed was experimentally confirmed for efficient machining to get a good surface quality. He et al. [8] have investigated machining speed and surface roughness in machining of wire electrical discharge machining (WEDM) of 2D C/SiC composite. Dey and Pandey [9] have

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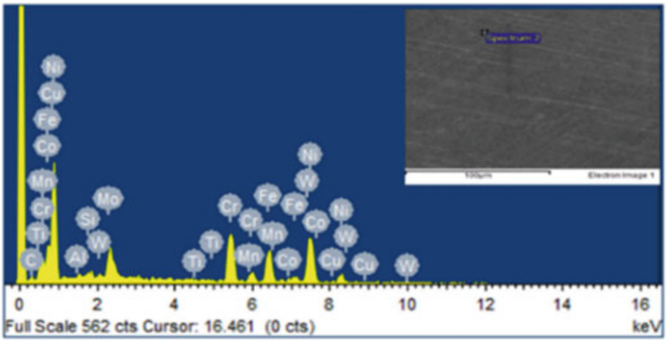
reported optimal settings of machining condition which yields superior performance in machining of aluminum matrix composites. It was reported a boost in cutting speed (3.234%), kerf width (2.7415%), and surface roughness (7.053%). Rajmohan and Senthil [10] have investigated the effect of pulse on time, travel speed, and current on material removal rate, surface finish, and cutting width in the machining of grade 2205 nitrogen-enhanced duplex stainless. Manoj et al. [11, 12] have highlighted the influence of cutting speed during taper machining on various parameters like surface roughness, slant angle, etc., and its effect corner radius during slant profiling. Sharma et al. [13] investigated the effect of WEDM machining parameters on the turbine disk profile.

Oblique and tapered shaped components can also be machined using WEDM, as it has many precision applications [14, 15]. Kinoshita et al. [16] highlighted the drawbacks of the tapering process in WEDM. They also examined the behavior of the wire during taper machining and studied the deviation of machined angle from the programmed angle. Yan et al. [17] designed two types of mechanism to avoid wear, angular error in case of tapering in WEDM. A new guide system was suggested due to the flaws in the designed mechanism, to reduce roundness error without damaging the surface of the workpiece. Sanchez et al. [18] have formulated a FEM model considering the nonlinear phenomenon of the wire to predict and reduce the angular error during tapering in WEDM. With the aid of prediction models, deviations of accuracies were reduced below $4'$ in tapered parts machined by WEDM. Plaza et al. [19] have modeled for prediction of angular error for reducing the experimentation in WEDM. The reduction of angular error below $3'45''$ was reported using the prediction model. Ranjit et al. [20] have reported the variation of cutting speeds and its influence on recast layer thickness during taper machining in WEDM.

From the literature, it was highlighted cutting speed (profiling speed) was an important parameter as major researchers have considered for investigation. Analyzing the profiling speed during taper machining in WEDM was very essential. In the present studies, a fixture was used to avoid disadvantages of conventional tapering by WEDM like guide wear, wire bending, insufficient flushing and inaccuracies in taper, etc. Almost all literature concentrates on machining parameters affecting profiling speed; but in this paper, an attempt is made to show that the geometric profile shapes also affects the profiling speed. The effects and variation of profiling speed were investigated while machining different profiles like triangular, square, and circular. The input parameters were wire guide distance (WGD), corner dwell time (CDT), wire offset (WO), and cutting speed override (CSO) for all the profiles. Different profiles of 1, 3, and 5 mm were machined at two different slant angles, namely 0° and 30°. All the profiles were machined using L_{16} Taguchi orthogonal array at two different slant angles. It was found that CSO has a major influence on profiling speed and different profiles geometry also affected profiling speed.



Element	Weight%
C	7.75
Al	0.41
Si	0.11
Ti	0.13
Cr	18.33
Mn	0.75
Fe	17.34
Co	0.48
Ni	44.53
Cu	1.41
Mo	7.83
W	0.95
Totals	100.00

Fig. 1 Energy dispersive X-ray analysis of Hastelloy X

2 Material and Experimental Procedure

2.1 Machining Parameters

Hastelloy X is a nickel-based superalloy having high mechanical properties, oxidation resistance, fabricability, and high-temperature strength. It has many applications in various industries like defence, aerospace, petrochemical, and dies making. The composition of the as-received alloy is shown as in Fig. 1 which was examined by energy dispersive X-ray analysis (EDX). It was solution heat-treated at 2150 °F (1177 °C) and rapidly cooled holding time of 1 h per inch of the section.

2.2 Experimental Particulars

The dimension of the profile that was programmed was as shown in Fig. 1a, b using ELPULS software, and the necessary G&M codes were generated based on machining conditions. The generated codes were exported to Electronica 'ELPULS 15 CNC WEDM' which was used to machining the material. The zinc coated copper wire electrode and deionized water as dielectric fluid were employed through the experimental runs. In WEDMs, the sparks are generated between the wire and workpiece due to voltage difference which melts the material that is required to the machine. The dielectric fluid cools the workpiece and flushes the debris outside the machining area. The machining was performed on the workpiece at different slant angles as shown in Fig. 2a. The slant machining was achieved by the unique fixture that is made of aluminum H9. The workpiece was fixed to the angle plate which would be rotated for the required slant angle. This angle plate would be locked with the help of slots on the side plate to a required angle. The whole fixture is fixed on the table of WEDM as shown in Fig. 2b.

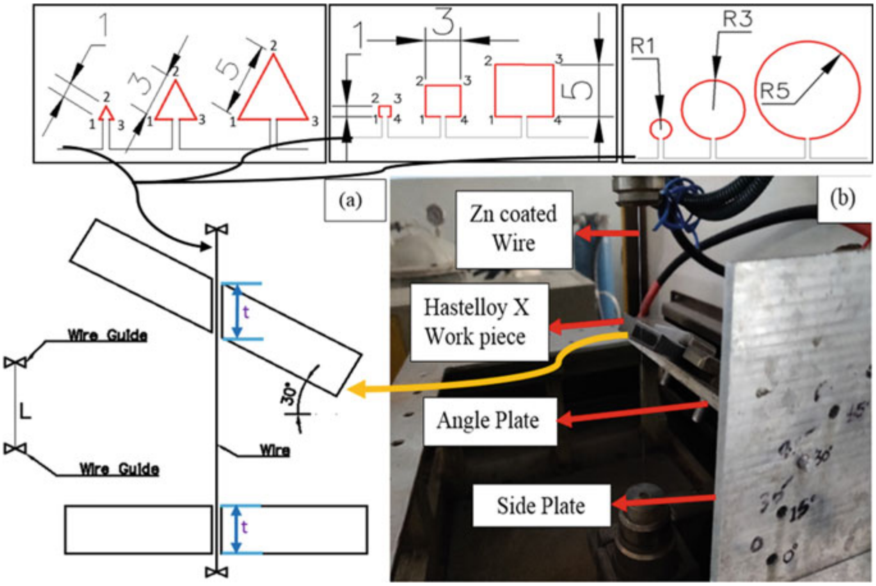


Fig. 2 **a** Workpiece at different slant angle by slant fixture, **b** slant fixture

2.3 Machining Parameters

The initial trial experiments were conducted the machining parameters and constant cutting parameters were chosen as shown in Table 1 [11, 12]. Based on the trial runs, the levels were fixed for input parameters like WGD, CDT, WO, and CSO as shown

Table 1 WEDM parameters

EDM parameters	Settings			
Constant parameters				
Pulse off time (µs)	44			
Servo feed (mm/min)	20			
Wire feed (m/min)	6			
Pulse on time (µs)	115			
Servo voltage (V)	40			
Machining parameters				
Wire guide distance (mm) (WGD)	40	50	60	70
	100	110	120	130
Cutting speed override (%) (CSO)	31	54	77	100
Wire offset (µm) (WO)	0	40	80	120
Corner dwell time (s) (CDT)	0	33	66	99

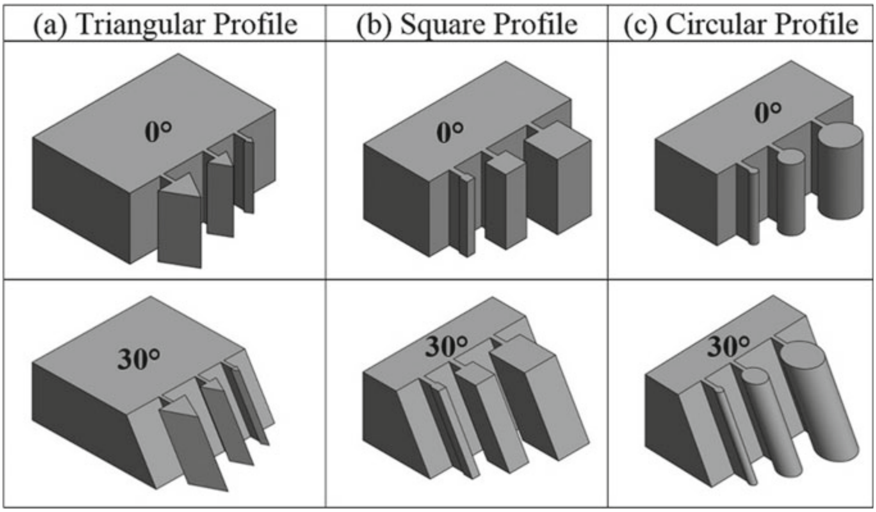


Fig. 3 Machined **a** triangular, **b** square, and **c** circular taper profiles

in Table 1. Taguchi's L16 orthogonal array was employed in the present investigation based on different parametric level set for slant angles at 0°, and 30°. Figure 3a–c shows the different profiles machined of 10 mm thickness at different slant angles.

3 Results and Discussion

3.1 Profiling Speed of Different Profiles at 0° and 30° Angle

The profiling speed was recorded during profiling provided by WEDM during profiling all the profiles, and the average of the values is taken as profiling speed. Table 2 shows the profiling speed calculated for triangular, square, and circular forms at 0° and 30° slant angles, respectively. It can be observed that the trials 12 and 28 yielded the least profiling speed and trials 15 and 31 produced the maximum profiling speed for all the slant angles. It can be observed that the square profile produced higher profiling speed than the circular and triangular profiles.

3.2 ANOVA and Main Effects Plots

Table 3 shows ANOVA for different profiles at 0° and 30° slant angles, respectively. It can be clearly noticed that the CSO parameter was the most significant factor influencing the profiling speed. The ANOVA also showed that CSO contributed the

Table 2 Profiling speed of different profiles at 0° and 30° angle

Trial No	WGD (mm)	CDT (s)	WO (μm)	CSO (%)	Profiling speed		
					Triangle (mm/min)	Square (mm/min)	Circular (mm/min)
0°							
1	40	0	0	31	0.749	0.769	0.756
2	40	33	40	54	0.952	1.126	0.990
3	40	66	80	77	1.256	1.427	1.392
4	40	99	120	100	1.425	1.616	1.537
5	50	0	40	77	1.266	1.501	1.337
6	50	33	0	100	1.409	1.599	1.510
7	50	66	120	31	0.659	0.898	0.748
8	50	99	80	54	0.801	1.000	0.881
9	60	0	80	100	1.403	1.558	1.501
10	60	33	120	77	1.371	1.523	1.398
11	60	66	0	54	0.812	0.890	0.879
12	**60**	**99**	**40**	**31**	**0.631**	**0.740**	**0.718**
13	70	0	120	54	0.750	0.908	0.898
14	70	33	80	31	0.602	0.750	0.729
15	**70**	**66**	**40**	**100**	**1.508**	**1.719**	**1.677**
16	70	99	0	77	1.326	1.495	1.393
30°							
17	100	0	0	31	0.483	0.695	0.620
18	100	33	40	54	0.566	0.718	0.703
19	100	66	80	77	1.000	1.160	1.106
20	100	99	120	100	1.384	1.467	1.411
21	110	0	40	77	0.977	1.297	1.089
22	110	33	0	100	1.361	1.499	1.383
23	110	66	120	31	0.494	0.698	0.682
24	110	99	80	54	0.571	0.779	0.718
25	120	0	80	100	1.383	1.450	1.405
26	120	33	120	77	1.046	1.369	1.074
27	120	66	0	54	0.586	0.834	0.696
28	**120**	**99**	**40**	**31**	**0.470**	**0.693**	**0.607**
29	130	0	120	54	0.586	0.856	0.708
30	130	33	80	31	0.500	0.698	0.614
31	**130**	**66**	**40**	**100**	**1.450**	**1.469**	**1.457**
32	130	99	0	77	1.006	1.406	1.088

The lowest and highest profiling parameters are indicated in the bold format

Table 3 ANOVA at for different profiles geometries at 0° and 30° angle

Sl No.	Factor	DF	Adj SS	Adj MS	*F*-value	*P*-value	% contribution
0°							
Triangular profile							
1	WGD	3	0.009	0.003	0.34	0.798	0.521
2	CDT	3	0.004	0.001	0.15	0.921	0.233
3	WO	3	0.012	0.004	0.47	0.725	0.711
4	**CSO**	**3**	**1.656**	**0.552**	**63.92**	**0.003**	**97.017**
5	Error	3	0.026	0.009			
6	Total	15	1.706				
Square profile							
1	WGD	3	0.012	0.004	0.40	0.761	0.582
2	CDT	3	0.010	0.003	0.34	0.802	0.486
3	WO	3	0.021	0.007	0.74	0.595	1.065
4	**CSO**	**3**	**1.905**	**0.635**	**67.03**	**0.003**	**96.428**
5	Error	3	0.028	0.010			
6	Total	15	1.976				
Circular profile							
1	WGD	3	0.010	0.003	1.21	0.440	0.559
2	CDT	3	0.006	0.002	0.77	0.581	0.357
3	WO	3	0.007	0.002	0.83	0.559	0.383
4	**CSO**	**3**	1.778	**0.593**	**212.72**	**0.001**	**98.240**
5	Error	3	0.008	0.003			
6	Total	15	1.810				
30°							
Triangular profile							
1	WGD	3	0.003	0.0009	1.14	0.459	0.136
2	CDT	3	0.002	0.0006	0.69	0.617	0.082
3	WO	3	0.001	0.0003	0.30	0.823	0.035
4	**CSO**	**3**	**2.106**	**0.702**	**838.11**	**0.0001**	**99.628**
5	Error	3	0.003	0.0009			
6	Total	15	2.114				
Square profile							
1	WGD	3	0.02099	0.007	13.38	0.030	1.181
2	CDT	3	0.00462	0.002	2.94	0.199	0.260
3	WO	3	0.02085	0.007	13.30	0.031	1.174
4	**CSO**	**3**	**1.72868**	**0.576**	**1102.48**	**0.0001**	**97.297**
5	Error	3	0.00157	0.0005			

(continued)

Table 3 (continued)

Sl No.	Factor	DF	Adj SS	Adj MS	*F*-value	*P*-value	% contribution
6	Total	15	1.77671				
Circular profile							
1	WGD	3	0.001	0.0004	1.14	0.458	0.081
2	CDT	3	0.004	0.0013	3.38	0.172	0.238
3	WO	3	0.001	0.0004	0.96	0.513	0.067
4	**CSO**	**3**	**1.582**	**0.5274**	**1412.68**	**0.0001**	**99.543**
5	Error	3	0.001	0.0004			
6	Total	15	1.590				

CSO is the highest contributing and significant factor so it is indicated in bold format

highest irrespective of slant angle and profile geometry. Figures 4 and 5 show the main effects plots for triangular, square, and circular profiles at both angles. It can be concluded that CSO is the most influencing factor on profiling speed, and as the CSO percentage increases, the profiling speed also increases. In Figs. 4 and 5 at 54–77%, there is variation in profiling speed. This increase was observed due to the flexible nature of wire which vibrates and leads to variation in the profiling speed [21, 22], whereas other parameters like WGD, CDT, and WO has very minimal effect

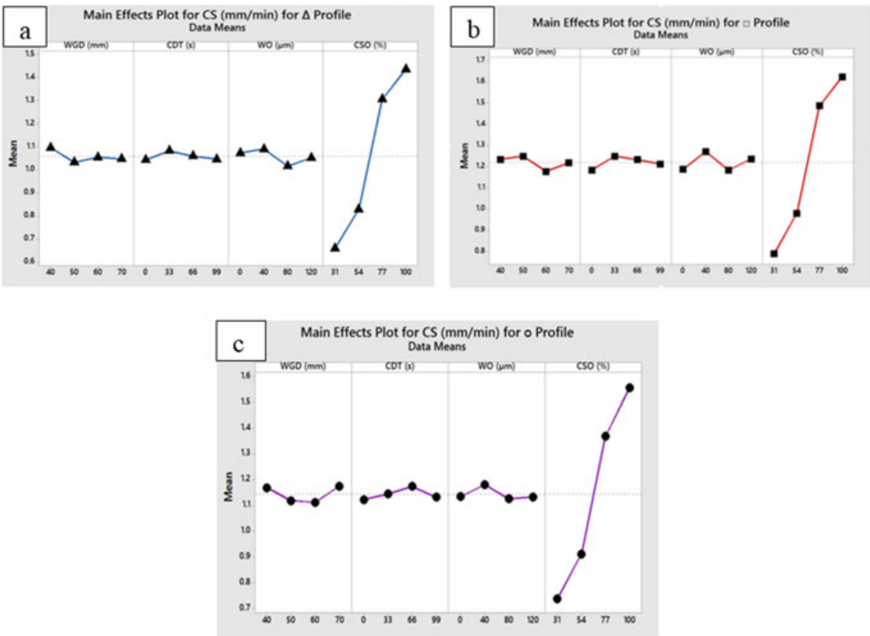


Fig. 4 Main effects plots for **a** triangular, **b** square, and **c** circular profiles at 0°

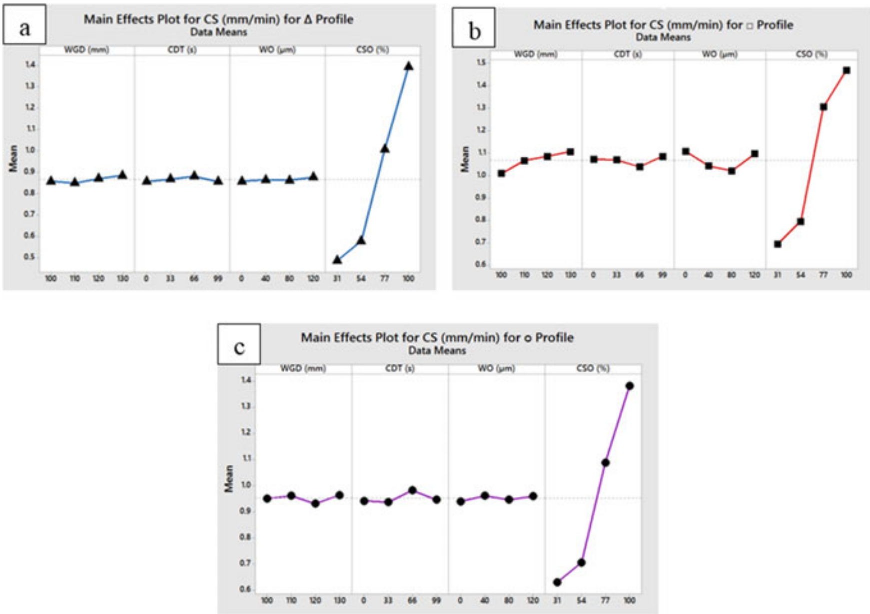


Fig. 5 Main effects plots for **a** triangular, **b** square, and **c** circular profiles at 30°

on profiling speed irrespective of angle and profile geometry. There are very small variations observed which is due to errors during machining. It can also be noticed that the highest profiling speed parameter has the highest CSO percentage (100%), and lowest profiling speed parameter has the lowest CSO percentage (31%). The profiling speed also decreased as the angles increased from 0° to 30° because of the increase in cutting thickness.

3.3 Variation of Profiling Speed for Different Profiles Geometry

Figure 6 shows the variation of profiling speed at 0° and 30° slant angle, respectively. It can be observed that the triangular profile has the minimum profiling speed, and the square profile had the maximum profiling speed. During machining the profiles, the instantaneous profiling speed increases or decreases gradually at the corners of the profile, and then, it comes back to the original profiling speed at straight edge cuts due to the CSO parameter. The CSO parameter detects the corners (acute-angled corners or right-angled corners) in the profile geometry and changes conditions during machining. It automatically tunes the speed to increases or decreases for obtaining the sharp corners in case of square and triangular profiles without changing the machining parameters [23]. Acute-angled corners (triangular shape) need more

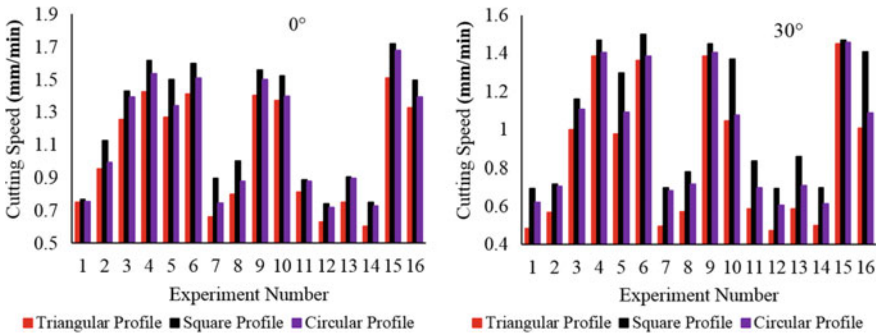


Fig. 6 Variation of profiling speed for different profiles

time and lesser speed for its machining in order to avoid corner errors [23, 24]. So, the square profiles have the highest profiling speed due to geometry, as it has a higher number of corners compared to triangular profiles. In the case of circular profiles, the wire has to traverse by changing the direction at every point. This movement of the wire in a curved way changes the direction very instant that decreases the cutting speed. This makes the cutting speed of the circular profiles lower compared to the square profile. But comparing the triangular profile, the circular profile has a higher cutting speed due to the geometry of the profile and CSO parameter. Similar trends are found all the profiles which were machined at 30° slant angle.

4 Conclusions

Form the above investigation, the CSO parameter was analyzed for different profile geometries at 0° and 30° slant angles. The following conclusions are drawn.

1. The CSO parameter is the most significant and highest contributing factor (96.428–99.628%) that influences and controls the profiling speed for all the profile at both 0° and 30° slant angles.

2.All the profiles indicated that profiling speed decreased as the slant angle increased from 0° to 30°. The greatest decrease of 40.55%, 36.26%, and 28.98% was observed in triangular, square, and circular profiles, respectively.

3.For the same parameters, there was an increase of 1.29–31.54% observed in profiling speed due to its geometry. The triangular profile was found to have least profiling speed compared to all profiles.

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