Investigation on corner accuracy in wire cut EDM of AISI D3 tool steel

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Abstract: Wire cut electrical discharge machining (WEDM) of AISI D3 tool steel has been reported in this study. The AISI D3 steel is extensively used in tool and die making industries. The machining of ulta-precision dies with the required corner accuracy and surface finish is only possible through WEDM process. It is known fact that the wire deflection and the wire rupture are the problems associated with the WEDM process (Lin et al., 2001; Sarkar et al., 2011). The wire deflection at the corner is causing corner error. The objective of the present work is to minimise the corner error by modifying the programmed path of the wire. The experiments were conducted based on Taguchi's L-27 orthogonal array. The influence of the control factors namely workpiece thickness, flushing nozzle height, corner angle, pulse on time, pulse off time, peak current and wire tension on the process responses such as area removal rate (ARR), surface roughness (Ra) and corner error (CE) were studied. A set of pilot experiments were carried out by modifying the programmed path (wire path) in view of improving the corner accuracy of the profile. A good improvement in corner accuracy (about 25%) has been achieved.

Keywords: WEDM; AISI D3 tool steel; corner error; CE; wire path modification.

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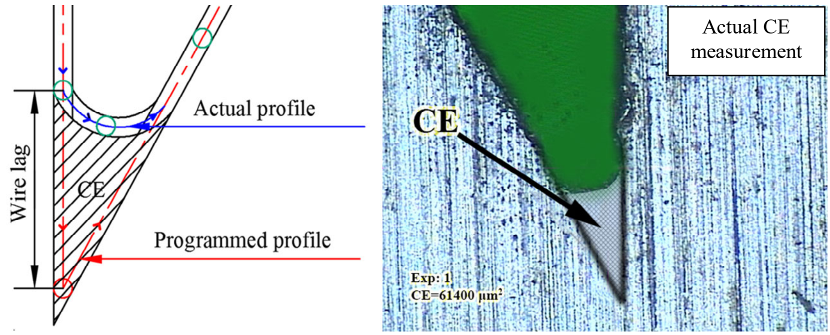
1 Introduction

Wire cut EDM (WEDM) is widely used in tool and die industry for its unique capability of producing complex two dimensional and three dimensional (examples for 3D profiles: frustum of pyramids, prisms having different cross-section at top and bottom and lofted features) profiles. It is known fact that the acute corner cutting using WEDM is highly unstable and stochastic. During corner cutting, the magnitude of the wire deflection (wire lag) is higher and is causing error at the corner region (Sarkar et al., 2011). The uncut area between the actual profile and the programmed profile is termed as corner error (CE) as seen in Figure 1. The minimum CE is preferred in ultra-precision tools and dies. Surprisingly, none of the past researchers have considered the corner accuracy aspects during the WEDM of AISI D3 tool steel. Hence, the present work is formulated with the objectives of identifying the influencing process parameters for CE, area removal rate (ARR) and surface finish and to find an appropriate strategy to minimise the CE.

Figure 1 Schematic of CE for 30° (see online version for colours)



The CE is the inherent process error which cannot be completely eliminated. But, Sanchez et al. (2004) proposed cutting regime modification strategy, multi-pass cutting strategy and profile path modification strategy to minimise the CE. The authors of the present work have made attempts in Monel 400 alloy to minimise CE by using cutting regime modification strategy (Selvakumar et al., 2012) and multi-pass cutting strategy (Selvakumar et al., 2016b) and profile path modification strategy (Selvakumar et al., 2018).

In the area of WEDM, very limited works have been reported on corner accuracy. Hsue et al. (1999) developed a model by considering wire deflection with transformed exponential trajectory of wire centre to estimate material removal rate (MRR) in geometrical corner cutting. Sanchez et al. (2004) developed a user friendly expert system for the improvement of accuracy in corner cutting. Sanchez et al. (2007) reported that the corner accuracy in the successive cuts is influenced by the error generated in the previous cuts. Dodun et al. (2009) quantified the CE in terms of workpiece thickness and corner angle. The taper accuracy aspects during WEDM of AISI D3 steel is reported by Selvakumar et al. (2016a).

By implementing fuzzy logic-based control strategy, Lin et al. (2001) reduced the machining error by 50%. Yan and Huang (2004) have developed dynamic models to investigate the performance of the wire tension control system. By using the models, the authors have obtained 50% reduction in geometrical contour error during corner cutting. To improve the corner cut accuracy in rough cut, Han et al. (2007) established relationship between the wire path and the numerical control (NC) path.

Sinha et al. (2015) have carried out multi-objective optimisation in WEDM of AISI D3 tool steel by using Taguchi methodology and principal component analysis. Tosun et al. (2004) have reported the optimisation of parameters on the kerf and the MRR during WEDM of AISI 4140 steel. Yan and Chien (2007) carried out an off-line process optimisation in WEDM of SKD11 tool steel. Spedding and Wang (1997) have used response surface methodology (RSM) and artificial neural network (ANN) techniques to model WEDM of AISI 420 alloy and reported that the prediction capability of the ANN model is better than the RSM model. Hasçalýk and Çaydas (2004) investigated the surface roughness and the metallurgical structure of the WEDMed surfaces in AISI D5 tool steel. Haddad and Tehrani (2008) reported the effects of machining parameters on MRR in cylindrical wire electrical discharge turning of AISI D3 tool steel.

A few works on taper accuracy (Selvakumar et al., 2016a), cylindrical wire electrical discharge turning (Haddad and Tehrani, 2008) and multi-objective optimisation (Sinha et al., 2015) were reported on WEDM of AISI D3 tool steel. From the review of past literature, it is evident that almost no work is reported on WEDM of AISI D3 tool by considering corner accuracy (i.e., CE) aspects.

In this study, a potential material AISI D3 has been considered for the investigation of corner accuracy. Hence, the present work is unique. The AISI D3 tool steel is predominantly used in tool and die industry for its higher wear and deformation resistance. The outcome of the present work could be used in tool and die making industry for processing ultra-precision components. The chemical composition of the workpiece material used in this research is reported in Table 1.

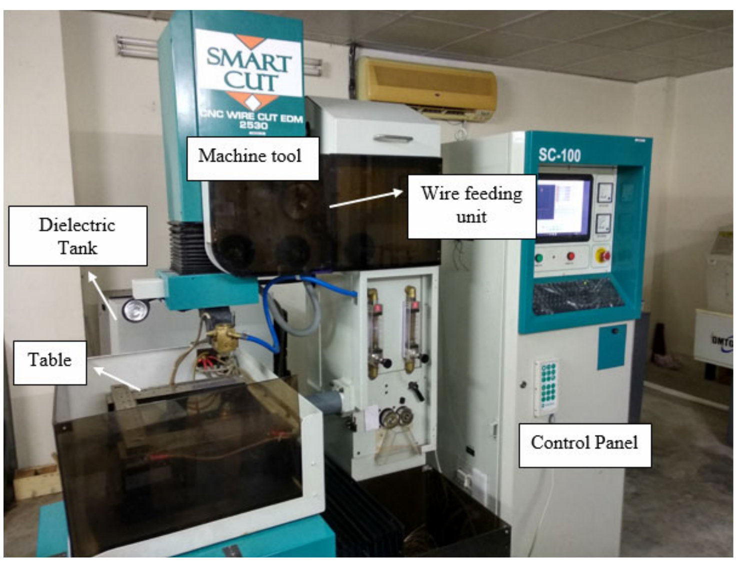
Table 1 Chemical composition (wt. %) of AISI D3 tool steel

C	*Mn*	*Si*	*S*	*P*	*Cr*	*V*	*W*	*Fe*
2.21	0.48	0.40	0.020	0.025	11.40	0.073	0.005	Balance

2 Experimentation

The planned experiments were performed using wire-cut EDM machine manufactured by M/s Ratnaparkhi Electronics (India) Private Limited (model: Smart Cut 2530). The photograph of the machine tool is displayed in Figure 2.

Figure 2 Photograph of WEDM machine tool (see online version for colours)



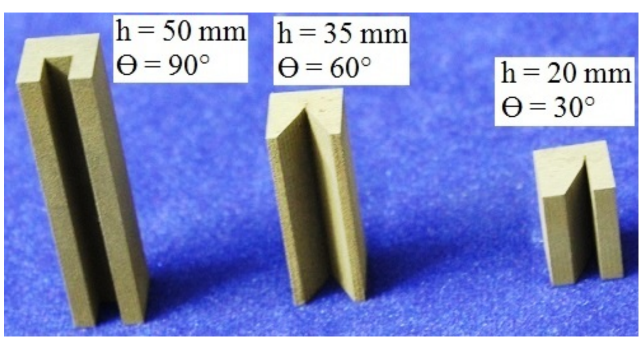
Based on the literature and trial runs, the control factors as listed in Table 2 were considered for the present study. A well planned experimentation, by varying the salient process parameters (as listed in Table 2) over a specified range is performed by using Taguchi's L-27 orthogonal array. The full factorial design, by involving all parameters and its level is ought to be conducted to produce desired data. However, the full factorial design is not used in this study in order to reduce the material cost, time and energy. Supposing full factorial design is used, the authors would have conducted $[(\text{level})^{\text{no. of parameters}} = 3^7 = 2{,}187)$ 2,187 experiments. The Taguchi's orthogonal arrays give minimum variance for experimentation with optimum setting for the process parameters. The Taguchi's signal-to-noise ratios (S/N) is serving as 'objective function' and is used for analysis of data and the prediction of optimum results. Therefore, the choice of L-27 array is obvious to generate the desired set of scientific data with 27 experiments.

Table 2 Control factors with its levels

Sl. no.	*Control factors*	*Level – 1*	*Level – 2*	*Level – 3*	*Units*
1	A: Workpiece thickness (h)	20	35	50	mm
2	B: Flushing nozzle height (a)	35	45	55	mm
3	C: Corner angle (θ)	30	60	90	Degree
4	D: Pulse on time (T_{on})	12	22	32	μs
5	E: Pulse off time (T_{off})	4	5	6	μs
6	F: Peak current (I_p)	2	3	4	A
7	G: Wire tension (WT)	45	65	85	g

During experimentation, a few factors [workpiece material: AISI D3 tool steel, cutting tool: molybdenum wire (diameter 0.25 mm), flushing pressure: 15 kg/cm^2, dielectric fluid: tap water + coolant oil, conductivity of the dielectric: 15 to 20 mho, wire feed: 3 m/min] having little influence on the responses were kept constant. In this study, three profiles as displayed in Figure 3 were created using CNC software in-built with the WEDM machine tool.

Figure 3 Photographic display of the machined specimen (see online version for colours)

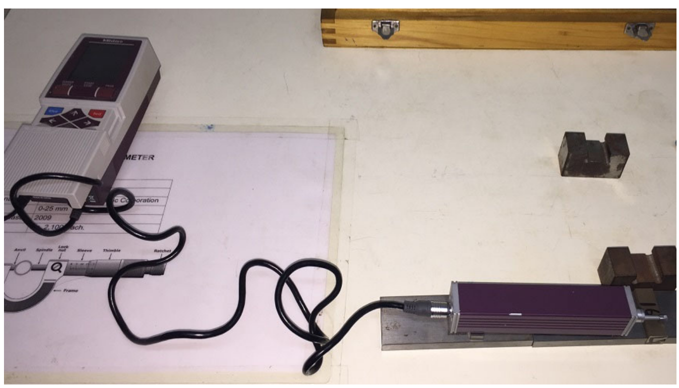


In the present study, ARR, surface roughness (Ra) and the CE were considered as performance measures. The ARR is referring to the productivity (cutting speed) of the WEDM process, expressed in mm^2/min. The influence of the workpiece thickness on the cutting speed is taken care by the ARR. The MRR can be obtained by multiplying the kerf width and density of the workpiece material with the ARR. Hence, the use of ARR is equivalent to that of MRR. Further, the recent versions of WEDM machine display the cutting speed in mm²/min, i.e., ARR. Therefore, ARR has been considered in this study and is measured by using equation (1). The length of the profile is measured by using AUTOCAD software and the machining time is measured by using stopwatch.

$$\text{ARR} = \frac{(\text{Length of the profile}) * (\text{Workpiece thickness})}{\text{Machining time}} \tag{1}$$

The surface roughness (Ra) of the machined specimen was measured by using surface roughness tester (make: Mitutoyo, model: SJ-210, headquarters: Kanagawa, Japan). The photographic exhibit of the instrument is presented in Figure 4. For each specimen, four measurements were made and the average is reported in Table 3.

Figure 4 Photographic exhibit of the Ra measuring instrument (see online version for colours)



The magnitude of the CE was measured by using non-contact video measurement system (make: ARCS, model: KIM-2010CU, headquarters: Taichung, Taiwan). A few snap shot of corners are displayed in Figure 5 and a sample CE measurement is exhibited in Figure 1. The results of the entire experiment were reported in Table 3.

Figure 5 Graphical display of corners (see online version for colours)

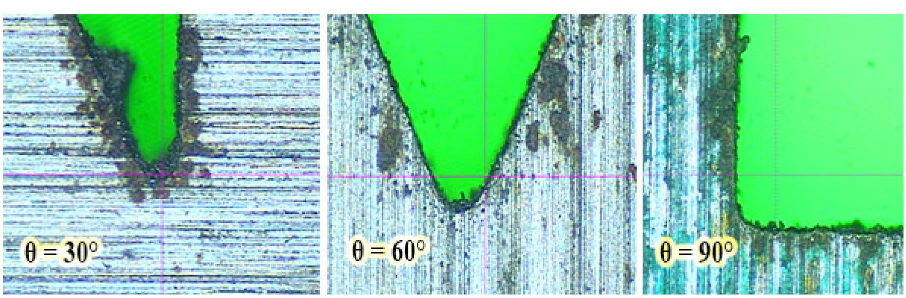


Table 3 Experimental results

Sl. no.	*Control factors*							*Responses*		
	A	*B*	*C*	*D*	*E*	*F*	*G*	*ARR (mm²/min)*	*Ra (µm)*	*CE (µm)²*
1	1	1	1	1	1	1	1	16.27	2.59	61,400
2	1	1	1	1	2	2	2	24.41	2.94	252,600
3	1	1	1	1	3	3	3	30.51	6.76	248,200
4	1	2	2	2	1	1	1	21.10	2.61	175,100
5	1	2	2	2	2	2	2	29.01	4.88	57,600
6	1	2	2	2	3	3	3	29.01	7.60	139,800
7	1	3	3	3	1	1	1	19.08	7.19	14,600
8	1	3	3	3	2	2	2	27.55	8.10	54,300
9	1	3	3	3	3	3	3	31.00	6.53	47,500
10	2	1	2	3	1	2	3	27.08	4.28	47,000
11	2	1	2	3	2	3	1	28.21	9.45	278,600
12	2	1	2	3	3	1	2	16.92	2.61	25,300
13	2	2	3	1	1	2	3	26.14	2.82	24,200
14	2	2	3	1	2	3	1	24.11	5.85	59,000
15	2	2	3	1	3	1	2	13.56	2.01	65,900
16	2	3	1	2	1	2	3	28.47	4.26	74,700
17	2	3	1	2	2	3	1	24.27	7.57	157,300
18	2	3	1	2	3	1	2	15.82	3.96	229,800
19	3	1	3	2	1	3	2	28.18	7.62	83,200
20	3	1	3	2	2	1	3	20.67	2.54	38,100
21	3	1	3	2	3	2	1	21.38	9.71	81,900
22	3	2	1	3	1	3	2	27.73	7.79	107,000
23	3	2	1	3	2	1	3	20.34	2.84	142,600
24	3	2	1	3	3	2	1	20.34	5.75	70,900
25	3	3	2	1	1	3	2	27.63	3.37	174,100
26	3	3	2	1	2	1	3	17.27	1.64	129,800
27	3	3	2	1	3	2	1	17.59	3.64	29,100

3 Results and discussions

The parametric analysis is carried out in Minitab software by considering Ra and CE as smaller is better and ARR as larger is better type problem. The signal-to-noise (S/N) ratio for Ra and CE is calculated by using equation (2). The equation (3) is used for calculating S/N ratio for ARR. The outcome of the parametric analysis in terms of S/N ratio for ARR, Ra and CE are presented in Figures 6, 7 and 8 respectively. The most influencing parameters are identified by conducting ANOVA test as reported in Table 4.

Table 4 ANOVA test

Factor	*DF*	*ARR*		*Ra*		*CE*	
		Sum of squares	*% contribution*	*Sum of squares*	*% contribution*	*Sum of squares*	*% contribution*
A: Workpiece thickness (h)	2	6.401	5.9	11.098	2.1	150.27	12.32
B: Flushing nozzle height (a)	2	0.299	0.3	4.481	0.9	106.97	8.77
C: Corner angle (θ)	2	0.239	0.2	25.235	4.8	563.27	46.18
D: Pulse on time (T_{on})	2	5.844	5.4	121.28	23.2	104.65	8.58
E: Pulse off time (T_{off})	2	8.492	7.8	5.354	1.0	52.45	4.30
F: Peak current (I_p)	2	72.246	66.8	255.63	48.9	128.31	10.52
G: Wire tension (WT)	2	10.645	9.8	40.245	7.7	17.49	1.43
Error	12	4.047	3.7	59.236	11.3	96.36	7.90
Total	26	108.213	100	522.56	100	1,219.72	100

Figure 6 Factor effects on *S/N* ratio of ARR (see online version for colours)

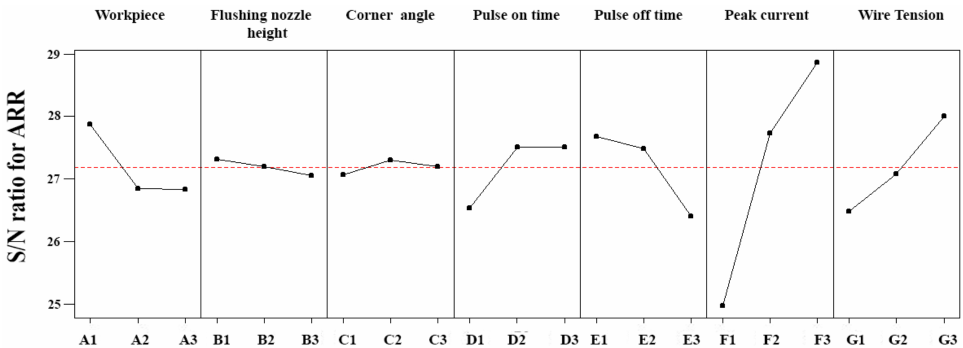


Figure 7 Factor effects on *S/N* ratio of Ra (see online version for colours)

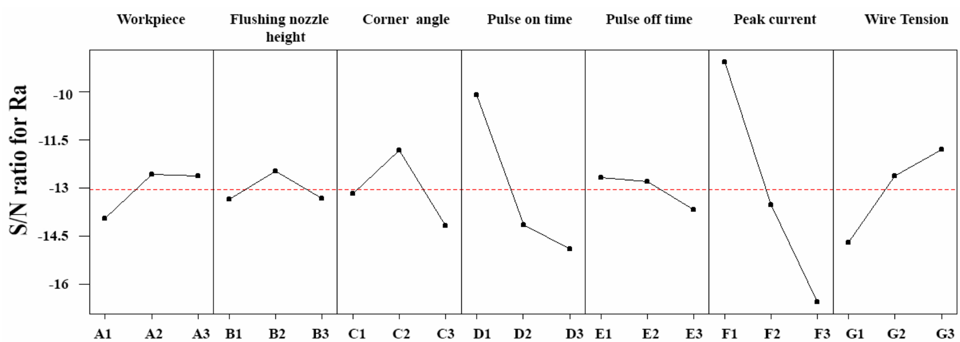
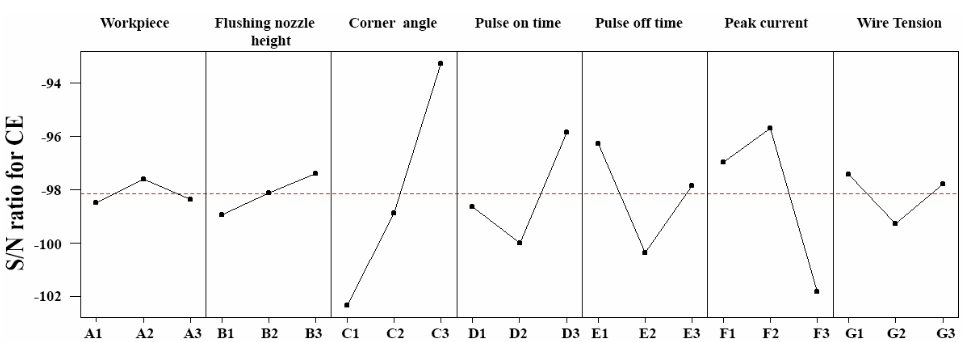


Figure 8 Factor effects on *S/N* ratio of CE (see online version for colours)



Smaller is better:

$$\text{S/N ratio} = \eta = -10\log\left\{\frac{1}{n}\sum_{i=1}^{n} y_i^2\right\} \tag{2}$$

Larger is better:

$$\text{S/N ratio} = \eta = -10\log\left\{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right\} \tag{3}$$

where

y_i i^{th} reading of 'y' in a treatment

n total number of readings in the same treatment.

From Table 4, it is learnt that ARR is influenced by the I_p, WT, T_{off}, T_{on} and h. The Ra is influenced by T_{on} and I_p. The CE is influenced by h, a, θ, T_{on} and I_p. Figure 6 shows that the ARR is exhibiting increasing trend with T_{on}, I_p and WT. The increase in T_{on} and I_p increases the energy content of the pulse. The increase in pulse energy melts and evaporates more workpiece material. Hence, the increase in T_{on} and I_p increases the ARR. As the increase in WT facilitates the better sparking at the inter electrode gap, increase in WT increases the ARR. The T_{off} is representing the time duration during which the pulse voltage is not applied between the workpiece and the wire electrode. The increase in T_{off} facilitates stable sparking and better cooling of the wire electrode and the workpiece material. However, the increase in T_{off} increases the duty cycle which in turn reduce the ARR. The machining time required for higher thickness job is naturally higher. Hence, the increase in T_{off} and h decreases the ARR as shown in Figure 6.

The increase in T_{on} and I_p produces higher energy pulses which melts and evaporate relatively higher amount of material. During the high pulse erosion, a huge amount of intense plasma is generated amid the workpiece and the wire electrode owing to the breakdown of dielectric media. Due to this, intensive bubbles are produced and collapsed in the sparking region. This makes the machined surface rougher than the surfaces machined with lower energy pulses. Hence, the increase in T_{on} and I_p exhibits decreasing trend with the surface finish (i.e., Ra increases) as shown in Figure 7.

The corner accuracy of the profile is predominantly influenced by 'θ' (46.18%), 'h' (12.32%) and 'a' (8.77%). The increase in 'θ' increases the corner accuracy (i.e., decrease in CE) as the geometry of the acute angle inherently possesses higher CE. The increase in 'h' and 'a', decreases the corner accuracy (i.e., increase in CE). The increase in 'h' and 'a' increases the magnitude of the wire deflection which has been the prime cause for CE. Hence, the increase in 'h' and 'a' decreases the corner accuracy. The employment of higher pulse energy pulses at the corner deteriorates the corner accuracy of the profile Increasing T_{on} and I_p increases the energy content of the pulses. Hence, the increase in T_{on} and I_p decreases the corner accuracy as shown in Figure 8.

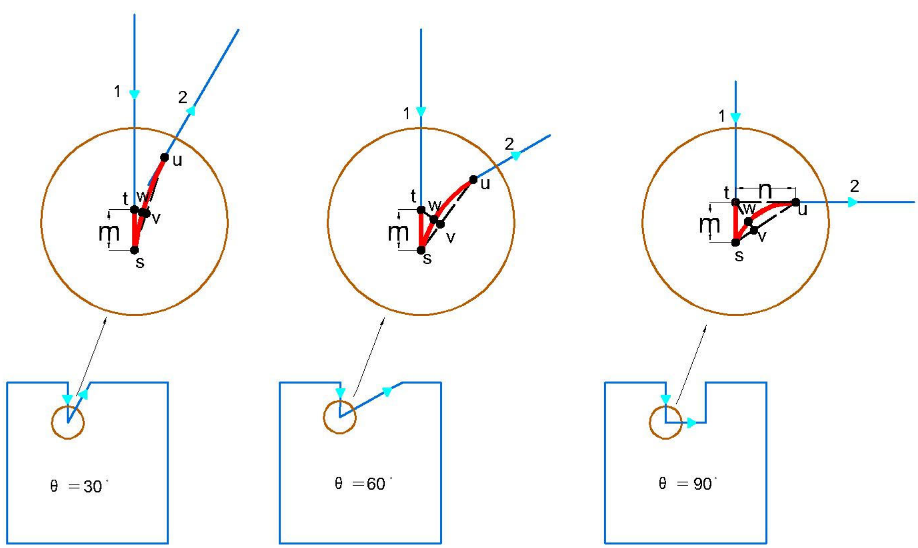
From Table 4, it is evident that the corner accuracy of the profile cannot be improved simply by varying the machine controllable factors (T_{on} and I_p) as the CE is greatly influenced by 'θ', 'h' and 'a'. The values of 'θ', 'h' and 'a' are decided by the nature of the product or mostly by the customers. Improving corner accuracy has been a complex stochastic phenomenon rarely attempted by the researchers. The only alternative to improve the corner accuracy without sacrificing productivity has been the profile path modification strategy (Selvakumar et al., 2018). The wire is not following the programmed path owing to the wire lag as seen in Figure 1. Due to this, a huge CE is generated especially while cutting acute profile in higher workpiece thickness by keeping flushing nozzle at higher elevation.

A set of pilot experiments were conducted by modifying the wire path (programmed path) in an appropriate manner. The programmed wire path (1-t-u-2) and the modified wire path (1-t-s-w-u-2) used in this study are distinctly shown in Figure 9. The magnitude of the maximum deviation of the modified path from the programmed path has been kept as 300 μm (i.e., m = 300 μm). The variables indicated in Figure 9 has to be read as: m = length ‘ts’ = 300 μm; length ‘tu’ = n = 1.5 * m (clearly indicated in Figure 9 for θ = 90°) ; the line ‘tv’ is perpendicular to line ‘su’; $vw = \frac{1}{3} * vt$; a three point circular arc passing through the points ‘s’, ‘w’ and ‘u’ is created. The modified path 1-t-s-w-u-2 is distinctly shown in Figure 9. The results reported in Table 5 reveal that a significant improvement in corner accuracy is achieved by using the wire path modification strategy proposed in this study. The precise prediction of the modified wire path mathematically and optimising the modified path shall be the future direction of the present work.

Table 5 Comparison of CE achieved in modified wire path against the programmed path

Experiment no.	*CE in programmed wire path (μm)²*	*CE in modified wire path (μm)²*	*% reduction in CE*
2. (θ = 30°)	252,600	201,500	20.23
11. (θ = 60°)	278,600	205,800	26.13
19. (θ = 90°)	83,200	57,500	30.89

Figure 9 Schematic of modified wire path (see online version for colours)



4 Conclusions

In the present work, WEDM of AISI D3 tool steel is reported. The salient contributions of the present work to the existing literature are presented hereunder:

1 Based on Taguchi methodology, an extensive parametric analysis is carried out on the performance measures namely ARR, surface roughness and corner accuracy.

2 The ARR and the surface roughness were influenced by the machine controllable factors such as pulse on time and peak current.

3 The corner accuracy of the profile is predominantly influenced by the machine uncontrollable factors like workpiece thickness, flushing nozzle height and corner angle. From this conclusion, it is evident that by simply varying the WEDM process parameters, corner accuracy cannot be improved. Hence, wire path modification strategy is attempted to improve the corner accuracy of the profile.

4 The programmed wire path is suitably modified with respect to the corner angles and a set of pilot experiments carried out. The outcome of the pilot experiments revealed that the wire path modification in respect of corner angle had improved the corner accuracy by 25%.

5 The 'wire path modification' strategy could be a potential approach to enhance the corner accuracy of the profiles during difficult machining conditions.

5 Future scope

In the present work, the expertise of the authors has played a major role in modifying the path of the wire. The development of analytical model and accurate prediction of the modified wire path shall be the future direction of the present work.

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