An Investigation into Dimensional Accuracy Achievable in Wire-cut Electrical Discharge Machining

M. N. Islam, N. H. Rafai, and S. S. Subramanian

Abstract**—Wire-cut electrical discharge machining (WEDM) is a popular choice for machining hard and difficult to machine materials with very close tolerances. However, the widely held assumption of the high accuracy of WEDM needs to be investigated, which is the primary aim of this research. This paper presents the experimental and analytical results of an investigation into the dimensional accuracy achievable in WEDM. Three techniques—traditional analysis, the Taguchi method, and Pareto ANOVA analysis—are employed to determine the effects of six major controllable machining parameters: the discharge current, pulse duration, pulse gap frequency, wire speed, wire tension, and dielectric flow rate on three key dimensional accuracy characteristics of the prismatic component parts—linear dimensional errors, flatness errors, and perpendicularity errors of corner surfaces. Subsequently, the input parameters are optimized in order to maximize the dimensional accuracy characteristics. The results indicate that the dimensional accuracy that is achievable in wire-cut electrical discharge machining is not as high as anticipated.**

Index Terms**—Wire-cut electrical discharge machining, dimensional accuracy, Pareto ANOVA analysis, Taguchi methods.**

I. INTRODUCTION

Wire-cut electrical discharge machining (WEDM) is one of the most widely used non-traditional machining processes in current manufacturing. It involves the removal of metal by discharging an electrical current from a pulsating DC power supply across a thin interelectrode gap between the tool and the workpiece. It is a popular choice for machining hard and difficult to machine materials with very close tolerances. Generally, WEDM is perceived to be an extremely actuate process and there are various reasons for this perception. Firstly, in WEDM, no direct contact takes place between the cutting tool (electrode) and the workpiece; as a result, the adverse effects—mechanical stresses, chatter, and vibration—normally present in traditional machining are eliminated. Secondly, the wire used as a cutting tool has high mechanical properties and small diameters (0.076 to 0.30 mm [1]), which is believed to produce very fine, precise, and clean cuts. Finally, in WEDM, the movements of the workpiece during cutting are controlled by a highly accurate computer numerical controlled (CNC) system (with positioning accuracy up to ± 0.5 μm [1]); as a result, the effects of positioning errors present in conventional machining are significantly diminished. However, this perception of the high accuracy of WEDM needs to be investigated, which the primary objective of this project.

Since its advent in the early 1970s, there have been numerous papers reported on various aspects of WEDM, such as metal removal rate [2, 3], surface finish [3–5], and process modeling [6]. However, there has been less interest in the dimensional accuracy achievable by this process [7–9]. In addition, the reported studies on WEDM concentrated on a single dimensional accuracy characteristic only and, as such, did not take into account their combined effects on machined parts. Therefore, in this paper, an attempt has been made to examine three key dimensional accuracy characteristics of parts produced by WEDM concurrently, and to find the optimum combination major controllable input parameters.

II. SCOPE

The main objective of this project is to investigate the dimensional accuracy characteristics achievable of typical component parts produced by the WEDM process. For the sake of simplicity, in this study, a rectangular block is selected as a test part, details of which are given in the following section. For such a part, the three most important dimensional accuracy characteristics are: (i) linear dimensional error, (ii) the flatness of the surfaces produced, and (iii) the perpendicularity error of the corners. Thus, the characteristics were selected here to monitor the quality of the parts produced by WEDM. The six independent input parameters chosen are: (i) discharge current, (ii) pulse duration, (iii) pulse gap frequency, (iv) wire speed, (v) wire tension, and (vi) dielectric flow rate. A general purpose coordinate machine (CMM) is employed for the measurement of the output parameters. The results are analyzed by three techniques: (i) traditional analysis, (ii) Pareto analysis of variation (ANOVA), and (iii) Taguchi's signal-to-noise ratio (S/N) analysis. The expected outcomes of this project are: (i) to get a clear picture of the machining accuracy achievable in WEDM, (ii) to find out the influences of the six input parameters on the accuracy of a typical component part produced by WEDM, and (iii) to optimize the input parameters.

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In the traditional analysis, the mean values of the measured variables were used. For the Taguchi method, the *signal-to-noise ratio* was calculated using the following formula [10]:

$$S/N = -10 \log \frac{1}{n}\left(\sum_{i=1}^{n} \frac{1}{{y_i}^2}\right) \qquad (1)$$

where *S/N* is the signal-to-noise ratio (in *dB*), *n* is the number of observations, and *y* is the observed data.

The above formula is suitable for quality characteristics in which “the smaller the better” holds true. This is the case for all three quality characteristics considered. The higher the value of the S/N ratio, the better the result is because it guarantees optimum quality with minimum variance. A thorough treatment of the Taguchi method can be found in [10]. Pareto ANOVA is a simplified ANOVA analysis method that does not require an ANOVA table; further details of Pareto ANOVA can be found in [11].

III. EXPERIMENTAL WORK

The experiments were planned using Taguchi’s orthogonal array methodology and a three-level L_{27} (3^{13}) orthogonal array was selected for our experiments. A total of 27 experimental runs were conducted. Besides the six main effects (A to F), two interaction effects were also selected for analysis. The selected interactions are between the discharge current and pulse duration (AxB) and between the discharge current and dielectric flow rate (AxF).

Even though one of the main advantages of using WEDM is its ability to cut hard and difficult to machine materials with low machinability ratings, in this study, mild steel 1040 was chosen as the work material because of its low cost and availability. Nevertheless, it is anticipated that hard and difficult to machine materials will produce inferior machining accuracy. The designed sizes for the rectangular test part (L×W×H) were 20×10×15 mm. Cutting was performed on a 15 mm plate and the rectangular block was extracted from the plate by means of cutting along the contour. The height remains as it is because machining was not done on the height.

A total of twenty-seven test parts marked TP1 to TP27 were produced on a FANUC ROBOCUT α oiD, manufactured by FANUC, Japan. It is a high performance wire-cut EDM equipped with digital servo technology. The available machining space for this machine is 370×270×255 mm along the *X*-, *Y*-, and *Z*-axes, respectively. The wire used is an EDM brass wire with a 0.25 mm diameter, well-known for its excellent mechanical properties and its capability to achieve high dimensional accuracy.

The six most important input variables were selected after an extensive literature review and subsequent preliminary investigations. Their limits were set on the basis of the capacity and limiting cutting conditions of the WEDM, ensuring continuous cutting by avoiding the breakage of the wire; details are given in Table 1.

The precision measurements were taken by a Discovery Model D-8 coordinate measuring machine (CMM), manufactured by Sheffield, UK. The probes used were spherical probes with a star configuration, manufactured by Renishaw Electrical Ltd. The linear size of the test parts was calculated using the standard built-in software package of the CMM. For each length feature, 14 measurements were taken at a 1 mm height step. The difference between the measured size and the designed size is the linear dimensional error, thus, a positive error indicates over sizing of a feature. A large number of points, 5×14 on the long faces and 3×14 on the short faces, respectively, were measured to determine the flatness error and to monitor the surface profile at different cross-sections. Additional measurements were taken at three different heights to determine the perpendicularity error of each corner angle. A positive perpendicularity error indicates that the corner angle is larger than 90^{o}.

Table 1. Input variables

Input parameters	Unit	Symbol	Levels		
			Level 0	Level 1	Level 2
Discharge current	amp	A	16.00	20.00	24.00
Pulse duration	msec	B	3.00	6.00	9.00
Pulse gap frequency	kHz	C	40.00	50.00	60.00
Wire speed	m/min	D	7.00	8.00	9.00
Wire tension	g	E	1000	1150	1300
Dielectric flow rate	MPa	F	0.14	0.20	0.26

IV. RESULTS AND ANALYSIS

An enormous amount of data was obtained and subsequently analyzed. Due to space constraints, only a few are illustrated, although in the analysis of the work, all these relationships were considered at different stages. In the traditional analysis, the mean values of the measured variables were used. For the Taguchi method, the *signal-to-noise ratio* was calculated using the following formula [10]:

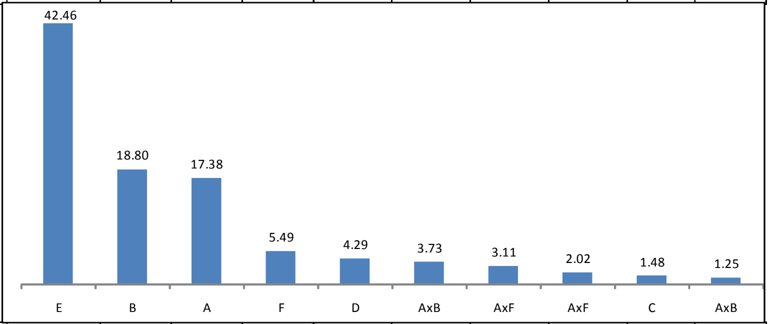
A. *Linear Dimensional Errors*

The results of the linear dimensional errors are shown in Table 2. It is noted that in all cases, the measured mean linear dimension size is less than the designed size. This indicates that the test parts have been overcut. Overcutting is a common problem in WEDM [13]. The main reason behind this is that during WEDM operation, the size of the cavity created in the workpiece is larger than the wire diameter. The exact size of the overcut is difficult to predict, but it is known to be proportional to the discharge current [13]. This explains the higher contributing effect of the discharge current (A) on the linear dimensional errors shown in the Pareto ANOVA analysis (Table 3). While most of the modern WEDMs are equipped with inbuilt overcut error compensation means, it appears that those measures were not enough to overcome this problem.

Table 2. Linear dimensional error results

Input parameters	Unit	WEDM		End Milling [9]	
		Length	Width	Length	Width
Design size	mm	20	10	200	75
Measured mean size	mm	19.787	9.902	199.966	74.963
Linear dimensional error	μm	-203	-98	-34	-37
Range of measurement	μm	97	193	36	35
6 x Standard deviation	μm	146	136	51	53
Calculated IT grade		11.352	11.713	7.277	8.146

Table 3. Pareto ANOVA analysis for dimensional error

Sum at factor level	Factor and interaction									
	A	B	AxB	AxB	F	AxF	AxF	C	D	E
0	300.99	316.83	298.50	295.52	299.02	306.48	295.56	297.84	307.38	264.938
1	313.46	292.76	307.02	301.62	292.37	294.78	305.09	297.16	298.82	297.008
2	285.18	290.04	294.10	302.50	308.23	298.37	298.99	304.63	293.43	307.442
Sum of sq. of difference (S)	1204.71	1303.73	258.96	86.65	380.56	215.84	139.75	102.32	297.14	2943.92
Contribution ratio (%)	17.38	18.80	3.73	1.25	5.49	3.11	2.02	1.48	4.29	42.46
										
Cumulative contribution	42.46	61.26	78.64	84.13	88.41	92.15	95.26	97.27	98.75	100.00
Check on significant interaction			AxB two-way table							
Optimum combination of significant factor level			A1 B0 C2 D2 E0 F2							

The International Tolerance (IT) grade is often used as a measure to represent the precision of a machining process, where the higher is the IT grade number and the lower is the precision of a process. The following formula has been utilized by several authors [14–16] to estimate the process capability tolerance achievable through various manufacturing processes:

$$PC = \left(0.45\sqrt[3]{X} + 0.001X\right) 10^{\frac{IT-16}{5}} \qquad (1)$$

where PC is the process capability tolerance (mm), X is the manufactured dimension (mm), and IT is the International Tolerance grade number.

The expected IT grades for WEDM and end milling are calculated applying Eq. (1), where six times standard division values shown in Table 2 represent the process capability tolerances. The calculated values demonstrate that in terms of linear dimensional accuracy, the WEDM performed poorly and its precision level is far less than CNC end milling.

The Pareto ANOVA analysis for linear dimensional errors given in Table 3 illustrates that wire tension (E) has the most significant effect on linear dimensional errors (P = 42.46%). The wire tension influences dimensional errors by a phenomenon known as *wire lag*, caused by the static deflection of the wire electrode. The effect of the wire lag on surface errors is discussed in the following subsection. The two other major contributing factors to linear dimensional errors are: pulse duration (B) (P = 18.80%) and discharge rate (A) (P = 17.38%). It is worth pointing out that the total of all of the individual effects (P ≅ 90%) is much higher than the total of all the interaction effects (P ≅ 10%). Therefore, it will be relatively easy to control the linear dimensional error through proper selection of the independent input parameters.

The response graphs for the dimensional errors are shown in Figure 2a. Based on the S/N ratio and Pareto ANOVA analysis, it was found that the combination for achieving a low linear dimensional error value was $A_1B_0C_2D_2E_0F_2$; that is, a medium discharge current, low pulse rate, high pulse gap frequency, high wire speed, low wire tension, and high dielectric flow rate.

B. Flatness Errors

For prismatic components, a flatness error is another important quality characteristic, which is geometric in nature. It is particularly important for parts where mating takes place across a surface area in an air-tight or liquid-tight manner. The flatness tolerances are also applied on all *principle datum surfaces* to ensure the integrity of measurement. *Flatness* is the condition of a surface having all elements in one plane [17]. A flatness error specifies a zone defined by two parallel planes between which the entire surface must lie.

The flatness error results given in Table 4 illustrate that the surfaces produced by WEDM have flatness errors about ten times higher compared to surfaces produced by CNC end milling.

Table 4. Flatness error results

Input parameters	Unit	WEDM	End Milling [9]
Feature size (LxH)	mm	20x15	200x12
Measured mean flatness error	mm	48	17
Range of measurement	mm	189	19
6 x Standard deviation	mm	271	28

It is worth noting that the flatness data does not give any indication of the shape of the cross-sectional profile. Therefore, in this study, in addition to flatness data, the cross-sectional profile of the test parts are monitored, which may help in understanding the flatness error-forming mechanics. A typical surface profile created by WEDM is depicted in Figure 1, where z = 0 represents the bottom of the cut. Similar drum-shaped surface profiles have been observed in [8], which are believed to be caused by wire bending and vibration.

It is worth pointing out that in a vertical plane, the surface errors for WEDM and CNC end milling are comparable, however, the main source for the high flatness error values in WEDM were caused by the errors at the corners. The problem of erosion of the corner shapes has been identified by a number of researchers [7–9], and is also a result of the wire lag phenomenon. The combined effects of erosion of corners and the drum-shaped surfaces produced resulted in high flatness errors for the surfaces produced by WEDM.

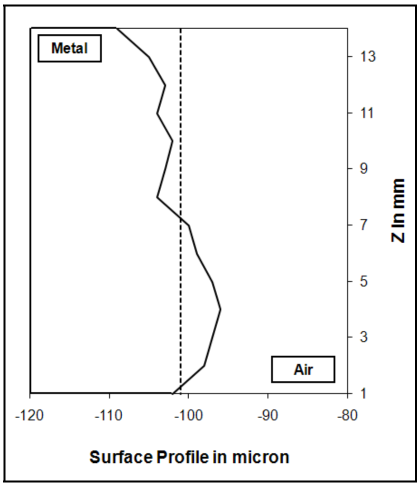


Figure 1. A typical surface profile created by WEDM

The Pareto ANOVA analysis shown in Table 5 illustrates that the most significant impendent parameter affecting the flatness error was the discharge current (A) (P = 30.23%), followed by wire tension (E) (P = 15.70%) and pulse duration (B) (P = 11.02%). The total of all interaction effects on flatness errors is relatively higher (P ≅ 24.7%) compared to the total of all interaction effects on dimensional errors (P ≅ 10%). Therefore, it will be more difficult to control flatness errors through the individual selection of input parameters. The response graphs for flatness errors are shown in Figure 2b. Based on the S/N ratio and Pareto ANOVA analysis, it was found that the combination for achieving a low linear dimensional error value was $A_0B_2C_0D_0E_2F_1$; that is, a low discharge current, high pulse rate, low pulse gap frequency, low wire speed, high wire tension, and medium dielectric flow rate.

C. Perpendicularity Errors

The perpendicularity of the surfaces at each corner of the test part was checked. For prismatic components, a perpendicularity error of the surfaces is another important dimensional accuracy characteristic, which is also geometric in nature.

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The perpendicularity error results given in Table 6 illustrate that the surfaces produced by WEDM have about five times higher perpendicularity errors compared to surfaces produced by CNC end milling. The wire lag phenomenon is believed to be responsible for increasing the perpendicularity error of all corners.

Table 6. Perpendicularity error results

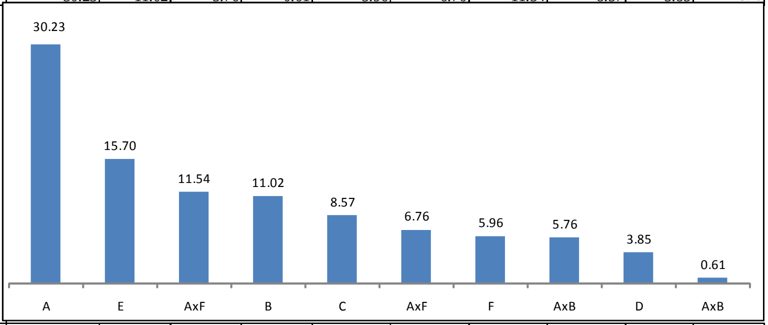
Input parameters	Unit	WEDM	End Milling [9]
Feature size (LxWxH)	mm	20x10x15	200x45x12
Measured mean perpendicularity error	deg	-0.524	0.072
Range of measurement	deg	2.766	0.527
6 x Standard deviation	deg	4.317	1.089

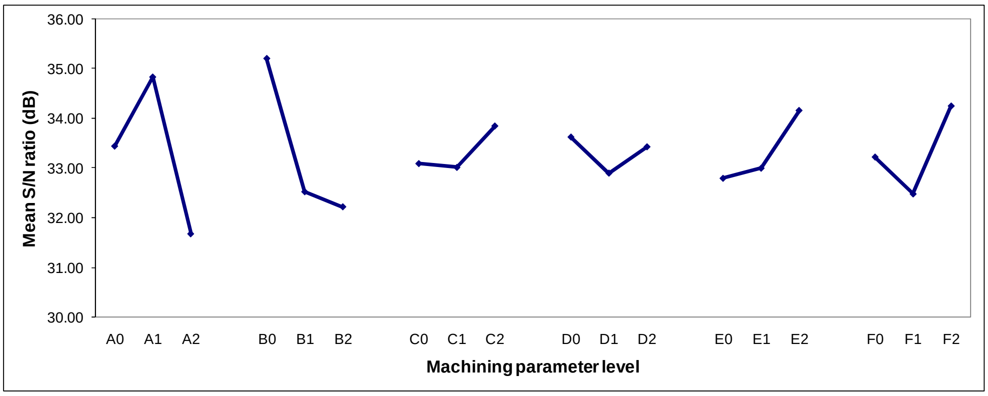
The Pareto ANOVA analysis shown in Table 7 illustrates that the most significant impendent parameter affecting the flatness error was wire tension (E) (P = 27.94%), followed by pulse gap frequency (C) (P = 24.62%) and wire speed (D) (P = 15.51%). The total of all interaction effects on flatness errors is relatively higher (P ≅ 27.5%) compared to that of dimensional errors (P ≅ 10%). Therefore, it will be more difficult to control flatness errors through the individual selection of input parameters.

The response graphs for perpendicularity errors are shown in Figure 2c. Based on the S/N ratio and Pareto ANOVA analysis, it was found that the combination for achieving a low linear dimensional error value was $A_2B_1C_1D_0E_1F_0$; that is, a high discharge current, medium pulse rate, medium pulse gap frequency, low wire speed, medium wire tension, and low dielectric flow rate.

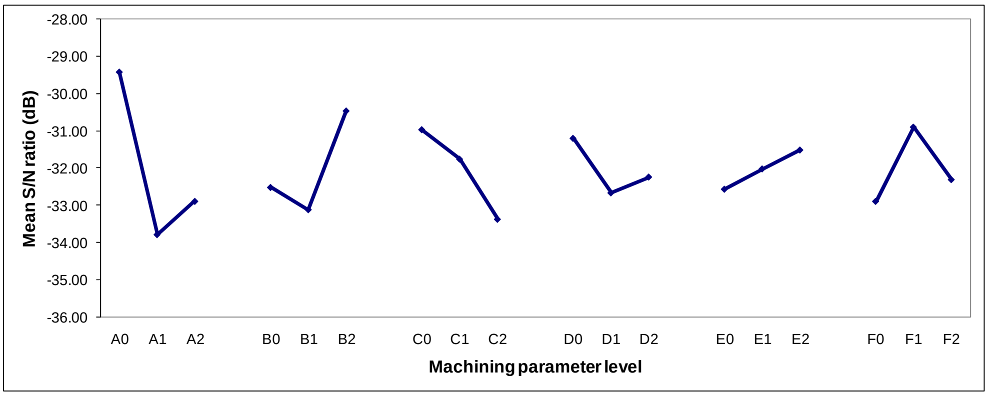
A summary of the optimum levels for the WEDM input parameters is given in Table 8. It is clear from the information shown in Table 8 that different input parameters are required to be kept at different levels in order to optimize each dimensional accuracy characteristic. This emphasizes the problem of optimizing all three dimensional accuracy characteristics all at once.

Table 5. Pareto ANOVA analysis for flatness error

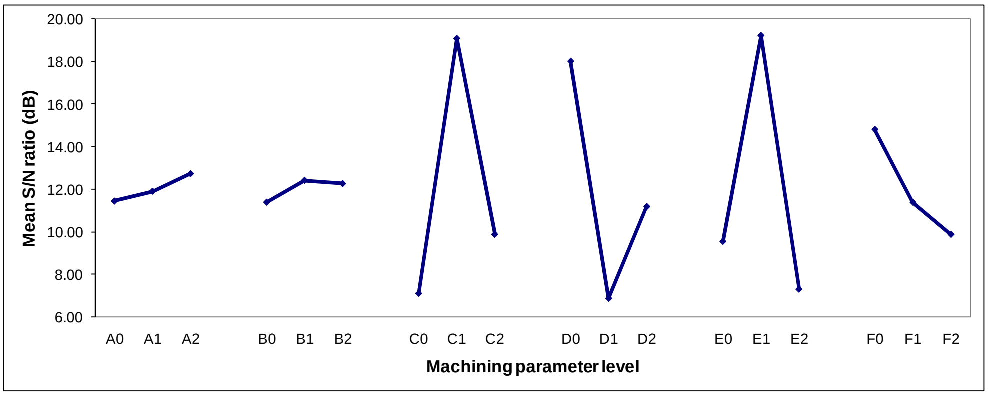
Sum at factor level	Factor and interaction									
	A	B	AxB	AxB	F	AxF	AxF	C	D	E
0	-264.80	-292.62	-285.41	-291.40	-295.97	-299.25	-274.28	-278.68	-293.02	-260.311
1	-304.02	-298.00	-280.99	-285.56	-278.09	-285.10	-299.41	-285.80	-292.02	-288.134
2	-295.97	-274.16	-298.38	-287.83	-290.72	-280.44	-291.09	-300.31	-279.74	-283.603
Sum of sq. of difference (S)	2574.54	938.00	490.29	51.98	507.09	575.88	982.81	729.44	328.07	1337.15
Contribution ratio (%)	30.23	11.02	5.76	0.61	5.96	6.76	11.54	8.57	3.85	15.70
										
Cumulative contribution	30.23	45.94	57.48	68.49	77.06	83.82	89.78	95.54	99.39	100.00
Check on significant interaction		AxB two-way table								
Optimum combination of significant factor level		A0 B2 C0 D0 E2 F1								



(a) Linear Dimensional Error



(b) Flatness Error



(c) Perpendicularity Error

Fig. 2. Response graphs for WEDM

Table 7. Pareto ANOVA analysis for perpendicularity error

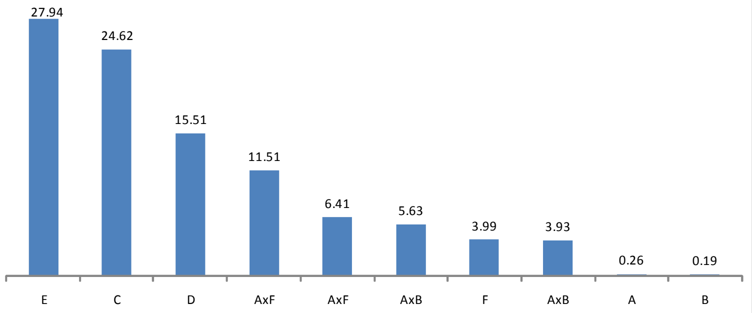
Sum at factor level	Factor and interaction									
	A	**B**	**AxB**	**AxB**	**F**	**AxF**	**AxF**	**C**	**D**	**E**
0	103.15	102.67	138.68	122.96	133.39	80.77	75.78	64.23	56.78	72.496
1	107.31	111.93	99.33	82.47	102.62	152.38	119.31	171.84	135.67	173.031
2	114.69	110.55	87.14	119.72	89.14	92.00	130.06	89.09	132.71	65.986
Sum of sq. of difference (S)	204.83	150.03	4353.34	3037.98	3086.27	8900.77	4957.38	19044.37	11996.45	21608.15
Contribution ratio (%)	0.26	0.19	5.63	3.93	3.99	11.51	6.41	24.62	15.51	27.94
										
Cumulative contribution	27.94	52.56	68.08	79.58	85.99	91.62	95.61	99.54	99.81	100.00
Check on significant interaction			AxB two-way table							
Optimum combination of significant factor level			A2 B1 C1 D0 E1 F0							

Table 8. Summary of optimum levels for input parameters

Dimensional Accuracy Characteristics	**Optimum Levels**					
	A	B	C	D	E	F
Linear dimensional error	1	0	2	2	0	2
Flatness error	0	2	0	0	2	1
Perpendicularity error	2	1	1	0	1	0

V. CONCLUDING REMARKS

From the experimental work conducted and the subsequent analysis, the following conclusions can be drawn:

- The dimensional accuracy achievable in wire-cut electrical discharge machining is not as high as anticipated and its precision level is far less than CNC end milling.
- Of the six input parameters considered, wire tension showed the greatest overall affect on three dimensional accuracy characteristics, therefore, its value should be chosen carefully.
- The problem of erosion of the corner shapes caused by the wire lag phenomenon remains; consequently requires more research and their practical applications.
- Different input parameters are required to be kept at different levels for optimizing each dimensional accuracy characteristic, which highlights the problem of simultaneously optimizing a number of dimensional accuracy characteristics. A hybrid model can be developed to tackle this problem.

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