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Optimization of Dimensional Accuracy in Plasma Arc Cutting for Mild Steel Plate Using Taguchi Method

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ABSTRACT

This paper presents an experimental optimisation of dimensional accuracy in the precision CNC Plasma Arc Cutting (PAC) of 6 mm thick mild steel plates. The machining trials were conducted using the Taguchi methodology, employing an (L9) OA design with three process parameters: current, voltage, and cutting speed, each of which was evaluated across three levels. The experimental specimens were designed to incorporate both linear (x-y axis) and circular cutting paths. The results demonstrate that a combination of 70 A current and 115 V voltage achieved the highest dimensional accuracy for both square and circular-shaped parts. The optimal cutting speeds for square and circular-shaped specimens were 1100 mm/min and 1000 mm/min, respectively. Although the current yielded the highest contribution (PCR = 47.50% for linear and 56.74% for circular dimensions), it lacked statistical significance at the 95% confidence level. This statistical insignificance among the investigated factors is attributed to the narrow response variance across the L9 orthogonal array. It was noted that the cutting of circular-shaped samples is considerably more sensitive to thermal variations than square-shaped parts.

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Keywords: *Plasma arc cutting (PAC), Dimensional accuracy, Mild steel, Linear and circular cutting paths, Design of Experiment (DoE), Taguchi method.*

1. Introduction

Dimensional accuracy is fundamental to determining the efficiency of production processes in modern manufacturing industries. With the continuous development of engineering materials, including high-strength, high-melting-point metals and other difficult-to-machine alloys, manufacturing processes face increasing challenges, including difficulty in achieving dimensional accuracy that matches the design specifications. To achieve high precision and address increasing market competition, tremendous research and development in non-traditional manufacturing processes have taken place over the past few years, making these processes a backbone of modern industry. One of the most important non-traditional manufacturing methods is plasma arc cutting (PAC). PAC is likewise considered a challenging technology compared to similar technologies like oxy-fuel and laser cutting [1]. This type of cutting is characterised by high finishing accuracy and the ability to produce complex geometrical shapes in materials that cannot be processed with comparable accuracy using conventional methods [2]. This technology can be used to cut most electrically conductive metals, including carbon steel, stainless steel, aluminium, copper, brass, titanium alloys, high-strength alloys, high melting points, and other difficult-to-machine alloys [3,4]. Furthermore, it is a perfect solution for thick metal sheets up to 40 mm thick [5]. The PAC system begins with a high-energy electric arc, generated by passing a high-voltage direct current between the electrode (torch) and the conductive workpiece part to complete an electrical circuit, as shown in Figure 1 [6]. Under the influence of this electric arc, the compressed air passing at extremely high speed through a small-diameter nozzle towards the workpiece is ionised, turning into a plasma stream [7]. The high temperatures of the plasma stream, which can reach 30,000 degrees Celsius, melt various electrically conductive materials [8].

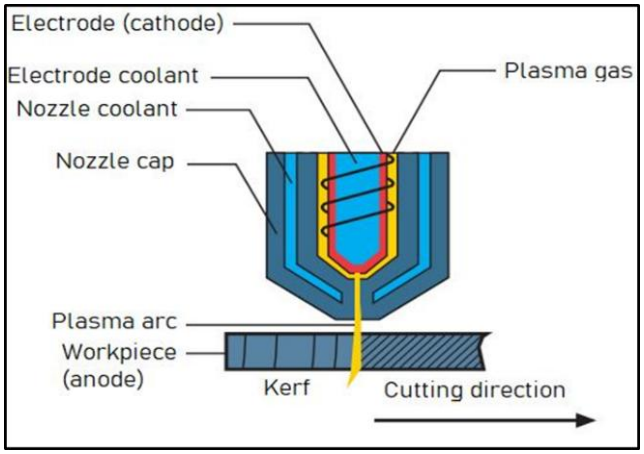


Figure 1: Schematic Diagram of PAC Process [6]

Plasma cutting technology appeared in the 1950s [9, 10], as a specialised thermal method for metal material removal. Initially, processes relied heavily on hand-guided torches with simple physical markings to identify direction. This manual approach was highly dependent on the operator's skill and reaction speed, resulting in significant variations in cut quality, wide dimensional tolerances, and excessive material waste. Recently, this technology has been integrated with computer numerical control (CNC) systems to control main process parameters for efficiency, quality and high dimensional accuracy. When CNC is integrated with a cutting machine, the optimisation of process parameters becomes the key to achieving the best dimensional accuracy and machining efficiency [11]. Like other machining processes, accuracy is the most important performance of plasma arc cutting. Thus, it is very important to have a good knowledge of the parameters of the PAC process to achieve the best dimensional accuracy. Basic parameters of the PAC are plasma current, cutting voltage, cutting speed, torch-to-workpiece distance, nozzle diameter, gas type, gas pressure, and the type of metal and thickness [12]. Adjusting these parameters is crucial to ensuring that the cut dimensions remain as close as possible to the target specifications. The Taguchi method is an engineering framework designed for improving the quality of products and industrial processes while minimising cost and time by reducing the number of experiments [13]. It was developed by Dr. Genichi Taguchi as an off-line quality control technique for robust products that are insensitive to interference factors [14]. Taguchi systematically categorised the factors influencing process stability into two main distinct classes: controllable and uncontrollable factors (Noise factors) [15]. In industrial engineering and experimental design, a combination of analysis of means (ANOM) and variance (ANOVA) with the Taguchi method is used as a powerful tool to determine the proportion of influence of each factor on the process, as well as to estimate the error rate in the process, which is the influence of uncontrollable factors (noise) [16].

2. Systematic Literature Review and Methodology

In fact, researchers have not paid much attention to dimensional accuracy as one of the important machining responses for the optimisation of cutting parameters when cutting metal plates using plasma arc cutting (PAC) technology. In the same vein, Panchal and Mungla [17] confirmed this deficiency in their studies, which included much research on improving plasma cutting parameters using the Taguchi method, revealing a complete absence of the topic of improving cutting parameters and their impact on dimensional accuracy. The dimensional accuracy of the PAC process is

heavily contingent upon the identification of optimal operating parameters. Generally, the PAC process is governed by a combination of control factors: current, voltage, cutting speed, torch-to-work piece distance (standoff distance), and gas pressure, as well as material type and plate thickness. Naik and Maity [18] investigated the effects of cutting parameters on the X-axis dimensional accuracy of 10 mm thick 304L stainless steel rectangular plates. The Taguchi L16 orthogonal array was utilised and four parameters were evaluated: current, voltage, standoff distance (SoD), and cutting speed. Three levels were selected for each process parameter. A rectangular cut of 40×50 mm was performed for all 16 tests. The experimental results indicated that the optimal cutting conditions for linear dimensions along the X-axis were a current of 80 A, a voltage of 140 V, a SoD of 4 mm, and a cutting speed of 2500 mm/min. ANOVA demonstrated that the linear dimensional accuracy along the X-axis was significantly influenced by the SoD, with the percentage contribution ratio (PCR) of 67.74%. Additionally, Kechagias et al. [19] conducted an experimental study on the effect of plasma arc cutting parameters on X-axis dimensional accuracy of 16 mm-thick AISI 1037 mild steel sheets. The cutting parameters tested included cutting speed, flame spacing (standoff distance), and voltage, which were evaluated using a full factorial experimental design (L27). The average of five X-axis measurements of the linear dimensions was calculated. The optimal values for the determined parameters were a cutting speed of 3200 mm/min, a flame spacing of 3 mm, and a voltage of 145 V. Analysis of variance (ANOVA) showed that the X-axis linear dimensional accuracy was primarily affected by the cutting speed, with PCRs of 76%. In addition, Hamood and Najm [20] evaluated the effect of PAC parameters such as current, cutting speed, and cutting time on both dimensional accuracy and machining time of 4 mm thick AISI 1010 mild steel. Twelve experiments were performed; in each experiment, one parameter was varied across four different levels while keeping the other parameters constant. Y-axis dimension was added, where dimensional evaluation was performed by recording three measurements along the X-axis and three along the Y-axis on the top surface, and the average of these six measurements was calculated for each cut section. The results showed that the optimal setting of cutting parameters for better dimensional accuracy was current of 110 A, cutting speed of 4000 m/min, and arc distance of 2 mm. In the same vein, the optimal combination setting for obtaining better dimensional accuracy with less machining time was current of 110 A, cutting speed of 4000 m/min and arc distance of 5 mm. The study also concluded that the accuracy of the top surface dimension increases with increasing cutting speeds and current. Although the previous three studies [18,19,20] presented significant results for

optimising plasma arc cutting (PAC) parameters, a fundamental methodological deficiency remains in the investigation of dimensional accuracy. These studies relied almost exclusively on uniaxial (X-axis) linear measurements, except the study by Hammoud [20], which used measurements from both the X and Y axes. This one-way approach fails to investigate the true kinematic behaviour of a machine moving along multiple axes, nor does it analyse the dynamic and thermal responses during changes in orientation during complex and curved forming operations. When executing multi-directional paths, the inherent dynamics of CNC plasma cutting introduce severe geometric and metallurgical challenges. During sharp angular transitions with acute or obtuse corners, the abrupt change in direction forces the axes to decelerate momentarily before rapidly accelerating. This transient velocity fluctuation induces inertial vibrations, resulting in rounded corners and distorted adjacent edges while simultaneously concentrating the plasma arc at a single localised point. This momentary dwelling amplifies the thermal input, causing excessive localised melting, kerf widening, and dense dross accumulation beneath the workpiece corner. Similarly, curvilinear and circular interpolation demand precise, synchronised sinusoidal harmonic motion between the X- and Y-axis motors. Because the plasma arc is a flexible column of ionised gas rather than a rigid cutting tool, any real-time synchronisation delay or tracking error directly induces radial deviations, transforming intended circular paths into elliptical profiles. Furthermore, during continuous curved paths, the base of the plasma arc lags behind the torch tip. This hydrodynamic and thermal lag skews the heat distribution between the upper and lower surfaces of the workpiece, resulting in severe taper defects and non-right edges. In summary, the majority of existing plasma arc cutting (PAC) research heavily prioritises surface quality, material removal rates, and heat-affected zones as key responses, it largely overlooks dimensional accuracy. Specifically, current literature lacks to address how PAC cutting parameters influence dimensional accuracy across varied geometric paths. This study fills this gap by directly comparing the cutting quality during linear (multi-directional X-Y axis) and circular cutting path motions. This work aims to optimise plasma arc cutting (PAC) parameters to achieve maximum dimensional accuracy when cutting 6 mm thick mild carbon steel plates along linear (X-Y axis) and circular cutting paths. The Taguchi optimisation methodology (L_9 OA), alongside analysis of mean (ANOM) and analysis of variance (ANOVA) is utilised in this study. The study is beneficial to the manufacturing industry, as it provides manufacturers with the best parameter settings when cutting steel plates using plasma arc cutting (PAC) technology.

3. Experimental work

3.1 Materials and Tools

Mild steel plates with a nominal thickness of 6 mm were used as workpiece material. This material was selected based on its widespread use in the sheet metal industry in the local market. The experimental specimens were designed with nominal dimensions of 100 mm × 100 mm for the square-shaped parts and a nominal diameter of 100 mm for the circular-profile parts, as illustrated in Figure 2.

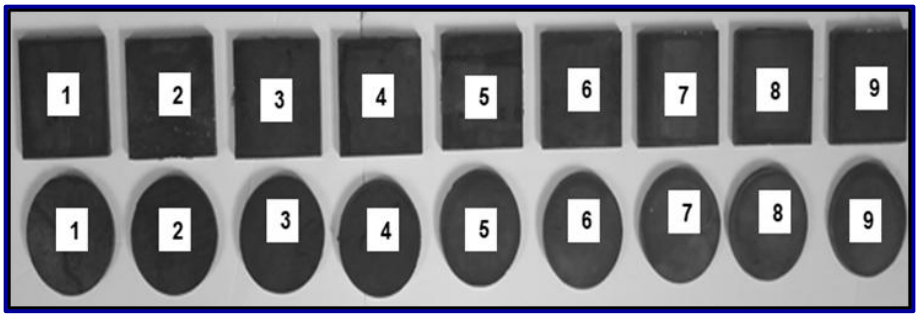


Figure 2: Specimens shapes after plasma arc cutting process

All tests were conducted using a STARFIRE CNC plasma arc cutting machine equipped with a controller manufactured by Shenzhen HYD CNC Technology Co., as shown in Figure 3. All cutting trials were performed at the Al-Nawahi Al-Arba'a Company for Industrial Services and Steelworks, Tripoli, Libya.



Figure 3: Image of a STARFIRE CNC Plasma Cutting Machine used in the study

The dimensional accuracy of the machined parts was measured using a digital Mitutoyo vernier calliper. This metrological tool features a resolution of 0.01 mm, and a maximum measuring capacity of 150 mm. Figure 4 shows the measurement tool used in the study.

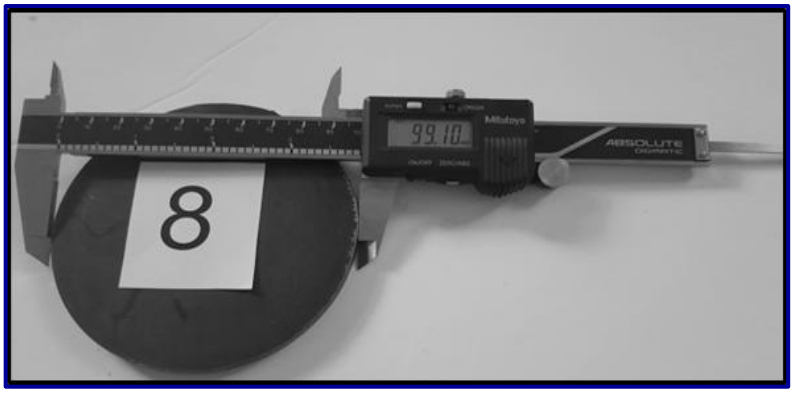


Figure 4: Image of the measurement tool used in the study

3.2 Experimental plan

The values of the factors (inputs) were determined based on the current literature review of plasma arc cutting (PAC) parameters optimisation process, and the practical experience of the machine's operator. In this research, three input parameters with three levels each were examined: cutting speed, current and cutting voltage. The dimensional accuracy was chosen as the output (response) of the cutting process. The compressed air pressure was kept constant at 3.5 bar, the torch spacing was controlled at 3 mm, and the plasma cutting torch path was performed in a clockwise direction only. Table 1 presents the input parameters and their values.

Table 1: Input Parameters and their values

Input parameters/ Factors	Units	Level 1	Level 2	Level 3
Current	(A)	70	80	90
Voltage	(V)	115	120	125
Cutting speed	(mm/min)	1000	1100	1200

3.3 Design of experiment (DoE)

The Taguchi L9 orthogonal array, ANOM and ANOVA statistical tools were employed using Minitab software to generate the experimental plan, develop the relationship between the input and output parameters, identify the most significant parameters, and find the optimal setting of those parameters to achieve the intended objective of the study. Table 2 presents the suggested DoE in this study.

Table 2: Design of experiment (L9 OA)

Run	Current ARC (A)	Voltage (V)	Cutting Speed (mm/min)
1	70	115	1000
2	70	120	1100
3	70	125	1200
4	80	115	1100
5	80	120	1200
6	80	125	1000
7	90	115	1200
8	90	120	1000
9	90	125	1100

3.4 Measurements plan

Figure 5 illustrates the linear and circular measurement technique used. All dimensions were measured on the upper surface. For linear dimensions, five measurements were taken along the X-axis and five along the Y-axis for each specimen. For circular dimensions, four measurements were taken around the circumference of each workpiece. To ensure statistical accuracy, the average of the ten linear and four circular measurements was calculated for each workpiece. It is worth mentioning that dimensional accuracy in this work refers to the measured dimension; the closer it is to the nominal dimensional values, the better.

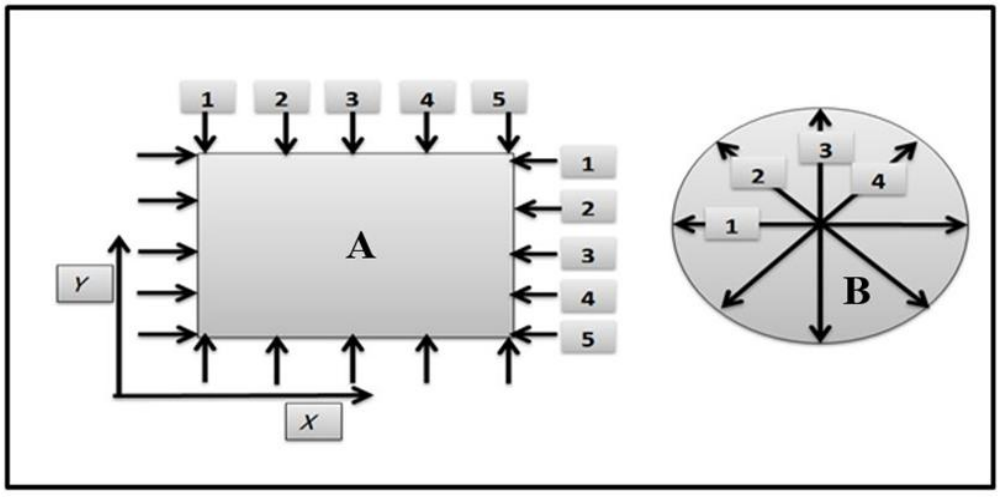


Figure 5: Direction and positions of dimensional measurements for square-shaped (A) and circular-shaped (B) specimens.

4. Results and Discussion

The results obtained for each experimental test are presented in Table 3.

Table 3: Experimental results

Run	Current Arc (A)	Voltage (V)	Cutting Speed (mm/min)	*Measured linear dimension	*Measured circular dimension
				Average value (mm)	Average value (mm)
1	70	115	1000	99.946	99.812
2	70	120	1100	99.724	99.325
3	70	125	1200	99.291	99.637
4	80	115	1100	99.568	99.537
5	80	120	1200	99.373	99.300
6	80	125	1000	98.940	99.025
7	90	115	1200	99.199	99.037
8	90	120	1000	98.823	99.177
9	90	125	1100	99.252	99.137

* *Measured dimension refers to the dimensional accuracy; the closer it is to the nominal dimensional values, the better.*

4.1 Analysis of Mean (ANOM)

As shown in Table 4 and Table 5 respectively, the analysis of mean (ANOM) results indicate that the current arc is the dominant factor in the cutting process and primarily controls the dimensional accuracy of both linear and circular plasma-cut dimensions.

Table 4: Response Table for Means (Linear dimensional Accuracy)

Level	Current Arc	Voltage	Cutting Speed
1	99.65	99.57	99.24
2	99.29	99.31	99.51
3	99.09	99.16	99.29
Δ max - min	0.56	0.41	0.28
Rank	1	2	3

Table 5: Response Table for Means (Circular dimensional Accuracy)

Level	Current Arc	Voltage	Cutting Speed
1	99.59	99.46	99.34
2	99.29	99.27	99.33
3	99.12	99.27	99.33
Δ max - min	0.47	0.20	0.01
Rank	1	2	3

Additionally, the ANOM results indicate that the optimal settings for achieving better dimensional accuracy in square-shaped machined parts are 70 A, 115 V, and 1100 mm/min for current, voltage, and cutting speed, respectively, as shown in Figure 6. Similarly, the best dimensional accuracy in the parts with circular profiles was obtained at 70 A, 115 V, and 1000 mm/min for current, voltage and cutting speed, respectively, as presented in Figure 7.

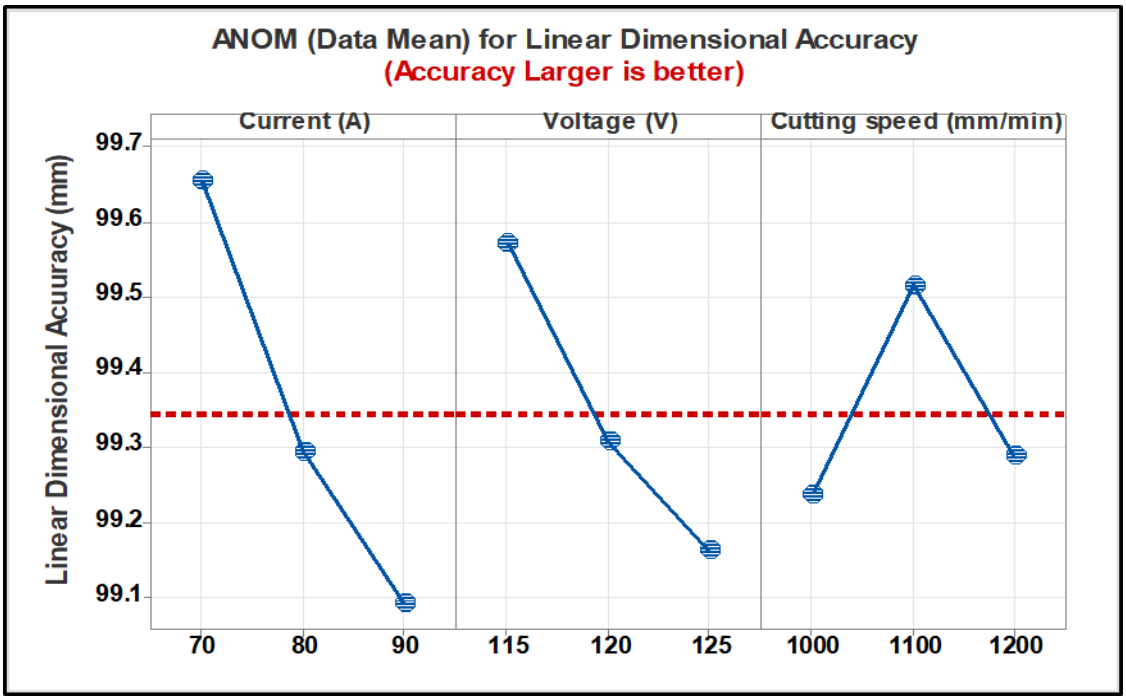


Figure 6. ANOM for linear dimensional accuracy

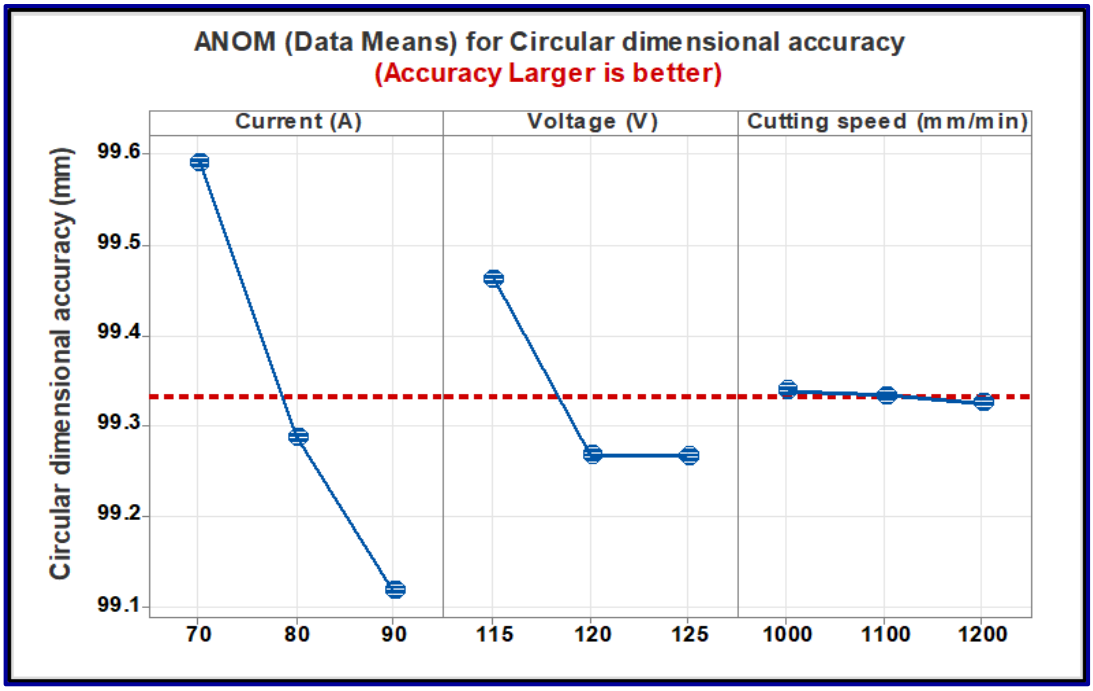


Figure 7. ANOM for circular dimensional accuracy

According to the results detailed above, it can be seen that the low current level of 70 A provided sufficient heats for both linear and circular cuts to remove the material completely and minimise undesirable thermal effects, resulting in dimensions closer to the target value. On the contrary, increasing the current raises thermal energy delivered to the workpiece, resulting in a wider and highly distorted heat zone. This leads to greater dimensional deviations from the target geometry and increased cutting torch wear. Additionally, the low voltage level of 115 V ensures stable energy transfer for both linear and circular cuts, while excessive voltage can cause an increase in plasma column width, causing an increase in cut kerf and cut path irregularity. Cutting speed ranked last; its effect depends strongly on the cutting path geometry. The linear path achieved the highest dimensional accuracy at the medium speed of 1100 mm/min, as the cutting torch followed a constant path, which was sufficient to produce better dimensional accuracy. On the other hand, circular- shape machined parts seem require a lower speed of 1000 mm/min to maintain accurate curve tracking and ensure balance in the cutting process between the X-axis and the Y-axis. It was revealed that any acceleration in the cutting process causes a change in the cutting balance, leading to distortion of the curved path in circular-shaped parts, thus slower movement speeds seem more beneficial for maintaining accurate circular geometry. Figures 8 and 9 show the contour plots of current versus voltage and current versus cutting speed for linear and circular dimensional accuracy, respectively.

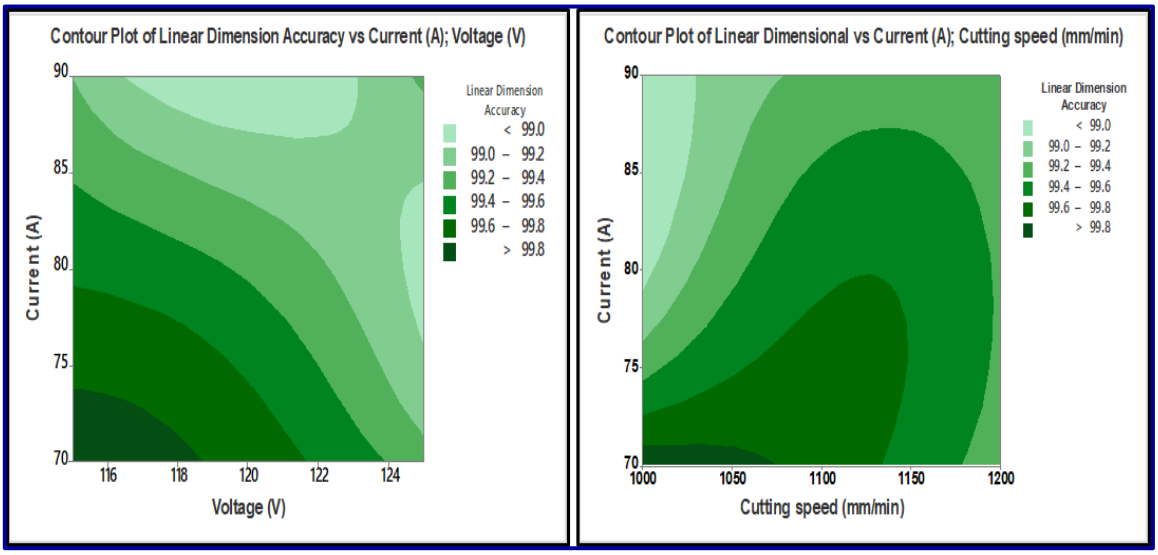


Figure 8. Contour plot for the current vs voltage and current vs cutting speed for linear dimensional accuracy

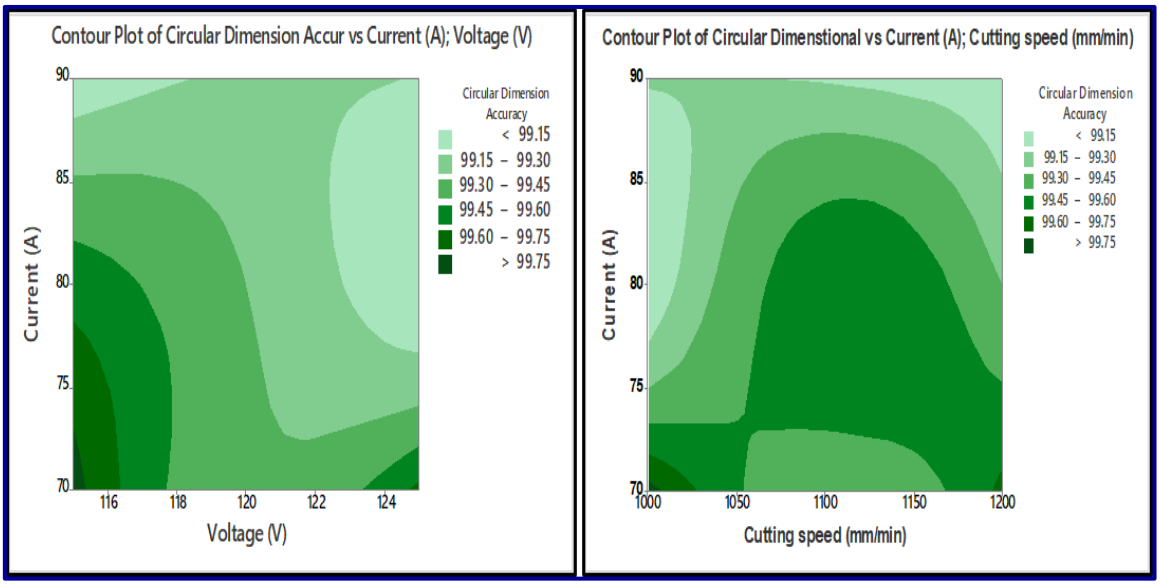


Figure 9. Contour plot for the current vs voltage and current vs cutting speed for circular dimensional accuracy

4.2 *Analysis of Variance (ANOVA)*

As shown in Tables 6 and 7, the ANOVA results revealed that current had the highest percentage contributions (PCRs) of 47.50% and 56.74% for linear and circular dimensions, respectively. However, it did not reach statistical significance at the 95% confidence level in both dimensional accuracies. The lack of statistical significance for the investigated factors can be scientifically justified by the narrow range of the experimental responses across the L_9 OA. For instance, in linear dimensional accuracy, the maximum difference between the highest and lowest values of current

arc, voltage and cutting speed were only 0.56 mm/min, 0.41 mm/min and 0.28 mm/min respectively, as shown above in Table 4. This minimal variation across the trials indicates that the response values were very close to each other, leading to a small variance between groups relative to the experimental error. Consequently, the ANOVA yielded higher p-values despite the high percentage contribution of some factors. In the same vein, the findings indicate that the influence percentage of the current in the circular cutting process is higher compared to linear cutting. Seemingly, cutting circular geometry parts is considerably more sensitive to thermal changes than linear ones. This can be attributed to the change in thermal energy, which has a greater impact on the dimensional accuracy when cutting circular geometries. This is due to the heat distribution and the output of the molten material. The Percentage Contribution Ratio (PCR) was computed based on the following equation:

$$Percentage\ Contribuation\ Ratio\ (PCR) = \frac{AdjSS\ \ of\ Independent\ factros}{AdjSS_{total}} \qquad (1)$$

Table 6: ANOVA Analysis - Linear dimensional Accuracy

Analysis of Variance (ANOVA)						
Source	**df**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**PCR**
Current Arc	2	0.4868	0.24338	3.31	0.232	47.50%
Voltage	2	0.2592	0.1296	1.76	0.362	25.29%
Cutting Speed	2	0.1316	0.06582	0.89	0.528	12.84%
Error	2	0.1471	0.07357			
Total	8	1.0247				
df = Degree of freedom				*P = Probability*		
SS = Sum of squares				*PCR = Percentage contribution ratio*		
F= F- test value						

Table 7: ANOVA Analysis - Circular dimensional Accuracy

Analysis of Variance (ANOVA)						
Source	**df**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**PCR**
Current Arc	2	0.34625	0.173126	1.85	0.351	56.74%
Voltage	2	0.07637	0.038188	0.41	0.71	12.51%
Cutting Speed	2	0.00027	0.000136	0	0.999	0.044%
Error	2	0.18729	0.093647			
Total	8	0.61019				

df = Degree of freedom *P = Probability*
SS = Sum of squares *PCR = Percentage contribution ratio*
F= F- test value

5. Conclusion

This study optimises plasma arc cutting (PAC) parameters to maximise dimensional accuracy. Based on experimental data and statistical analysis obtained from cutting of 6 mm mild steel sheets, combining the Taguchi method with ANOM and ANOVA successfully determined the optimal parameter settings. This integration effectively minimised dimensional errors in the CNC plasma cutting process, the following conclusions were drawn:

- Taguchi L_9 Orthogonal array indicated that the optimal machining condition for cutting square-shaped parts were current of 70 A, voltage of 115 V, and cutting speed of 1100 mm/min.
- The optimum combination of cutting parameters required to maximise dimensional accuracy when cutting circular-shaped parts is a current of 70 A, voltage of 115 V and cutting speed of 1000 mm/min.
- Although current Produced the highest contribution (PCR = 47.50% for linear and 56.74% for circular dimensions), it lacked statistical significance at the 95% confidence level. This insignificance among the investigated factors is attributed to the narrow response variance across the L9 OA.
- It was observed that the cutting of circular or curved geometry-based parts is considerably more sensitive to thermal variations than linear geometry-based components. This is because of the changes in thermal energy, which has a greater impact on the cutting process and subsequently on the dimensional accuracy.

Abbreviation and Terminology

PAC Plasma Arc Cutting
ANOM Analysis of Mean
ANOVA Analysis of Variance
PCR Percentage of Contribution Ratio
CNC Computer Numerical Control
Square-shaped specimens refer to parts produced via a linear cutting path
Circular-shaped specimens refer to parts produced via a circular cutting path

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