JKIE (Journal Knowledge Industrial Engineering) Vol. 12, No. 1, April 2025, pp.19-28

http://jurnal.yudharta.ac.id/v2/index.php/jkie

Journal Knowledge Industrial Engineering

E-ISSN: 2541-4461 | P-ISSN: 2460-0113

Analysis on Effects of Process Parameters CNC Flame Cutting on Dimensional Inaccuracy Using Taguchi Method and ANOVA

Reihan Rafly Prasetya[a)], Tranggono[b)]

[a,b] Department of Industrial Engineering, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Indonesia

Corresponding Autor: reihanraflyprasetya@gmail.com,

Article Info

Article history

Received : January 25, 2025

Revised : January 29, 2025

Accepted : April 12, 2025

Published : April 30, 2025

Keywords: (3-5 words).

CNC Flame Cutting;

Dimensional Inaccuracy;

Taguchi;

ANOVA.

ABSTRACT

Carbon steel is a primary material in various engineering applications that require cutting accuracy to maintain product quality. Advances in flame cutting technology in the manufacturing industry highlight the importance of understanding proper parameter settings. Incorrect parameter adjustments can lead to inaccuracy, material defects, and increased operational costs. In this study, the Taguchi method combined with ANOVA will be used to optimize dimensional inaccuracy in the CNC flame cutting process on SS400 steel plates. The effects of variations in cutting parameters, including cutting speed, gas pressure, and oxygen pressure, on the dimensional inaccuracy of the cut were identified. The analysis results show that gas pressure is the most influential parameter, with a contribution of 86.31%, followed by cutting speed at 6.06% and oxygen pressure at 2.42%. The optimal parameter combination for minimizing dimensional inaccuracy was found at a cutting speed of 319 mm/min, gas pressure of 4 bar, and oxygen pressure of 6 bar. These findings highlight the importance of adjusting gas pressure to improve cutting accuracy and reduce operational costs and time at PT XYZ.

DOI: https://doi.org/10.35891/jkie.v12i1.5892

1. Introduction

Carbon steels are the most commonly used basic material in several engineering applications, with approximately 85% of total world steel production (Ismail & Adan, 2014). Steel is an alloy mainly composed of iron (Fe) and carbon (C), alloying with small amounts of manganese (Mn), silicon (Si), nickel (Ni), chromium (Cr), vanadium (V), and others. Low-carbon steel is defined as steel with a carbon content of fewer than 0.3%, and has relatively low hardness, soft, high ductility (Davis, 1998). One example of low-carbon steel commonly used is SS400 steel. SS400 steel is classified as low carbon steel, with a maximum carbon content of 0.17%. SS400 steel is commonly used in the railway industry, bridges, general construction industry, and others (Rosyadi et al., 2022).

Steel is regularly cut utilizing gas cutting, which is more efficient than using a grinding cutter for metal or steel cutting (Aziizudin et al., 2023). A gas cutting machine is a instrument utilized for cutting steel by utilizing the combustion of a gas blend, regularly oxygen and LPG (Liquefied Petroleum Gas) or oxygen and acetylene (Tauvana & Widodo, 2020). Within the development industry, meterial cutting is an starting arrange where different cutting strategies can be connected depending on particular prerequisites, such as cutting capacity, surface quality, the sort of material being cut, operational capabilities, cost efficiency, and security contemplations (Sunaryo, 2008).

As competition in the market increases and the demand for high precision grows, CNC (Computer Numerical Control) flame machining has become one of the most popular gas cutting methods (Kolhe et al., 2018). The application of CNC technology in this field has significantly improved overall production quality and is the result of the integration of information technology and numerical control technology (Nie et al., 2024).

However, despite the fact that CNC technology has brought unprecedented flexibility and accuracy, process efficiency, cost-effectiveness, and its impact on the material remain some of the main challenges currently faced (Nie et al., 2024). As experienced by PT XYZ, a company engaged in logistics, distribution, and construction that manufactures industrial goods, electrical installations, instruments, and other fabricated components, the company has been using CNC flame cutting technology to improve accuracy and efficiency in the steel plate cutting process. However, failures still frequently occur during the cutting process. These failures can negatively impact production outcomes, including cutting inaccuracies, material defects, and reduced productivity (Kurniawan et al., 2023). The demand for accurate and clean cutting quality is always a priority in the cutting process. By selecting the right processing parameters, dimensional accuracy can be improved, reducing the need for additional cutting. As a result, machining costs and processing time will be significantly reduced (Yousefi & Zohoor, 2019). There is data reveals dimensional inaccuracies in the CNC flame cutting process on SS400 steel plates with a thickness of 16 mm, particularly for products measuring 255 mm x 280 mm at PT XYZ.

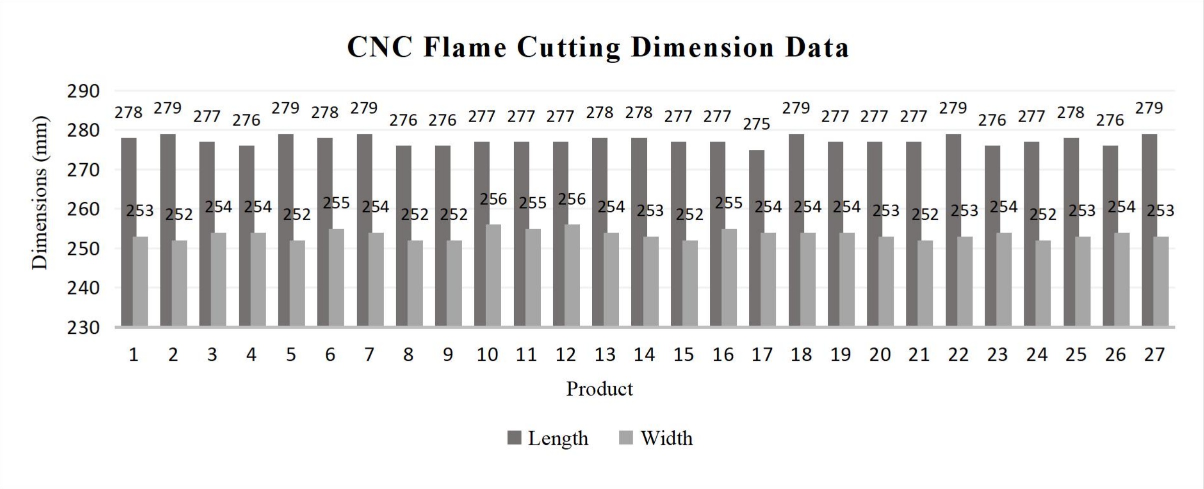

Figure 1. CNC Flame Cutting Dimension Data

According to the JIS standard implemented by PT XYZ, the allowable dimensional tolerance for steel with a thickness of 16 mm is ±2 mm. Inaccuracies in cutting SS400 steel using CNC flame cutting at PT XYZ are caused by inadequate machine parameter settings. CNC flame cutting depends on various parameters, such as the torch distance from the material, the type of fuel used, preheating time, material type, material thickness, nozzle type, cutting speed, oxygen pressure, and gas pressure. Differences in these parameters can impact the quality of the metal cut, and optimal cutting conditions can be achieved through precise adjustments (Ramakrishna et al., 2018). Identifying the optimal combination of parameters can address the company's challenges using the Taguchi method. This method is used to find combinations of factors and levels that are unaffected by noise factors (Park & Antony, 2008). By using an orthogonal matrix in experimental design, this approach provides a low-cost investigation as it reduces the number of experiments required (Rifelino et al., 2021).

In line with this, several previous studies have investigated various factors influencing cutting accuracy. For instance, the research by Cepauskaite, L. & Bendikiene, R. (2024) analyzed the impact of cutting parameters on S355JR steel using fiber-laser, focusing on the effects of laser power, cutting speed, and gas pressure on dimensional accuracy, surface roughness, and cutting slope, across two plate thickness variations. This study involved a total of 24 non-replicated experiments, which provided parameter combinations to achieve optimal cutting quality for 4 mm and 6 mm thick plates. In a similar experiment conducted by Halim et al. (2022) with three test replicates, it was stated that the lower the cutting speed used, the more optimal and accurate the cutting results would be. Aziizudin et al. (2023) stated that in steel cutting using a gas cutting machine, gas and oxygen pressure can affect the cutting results. The higher the pressure, the faster the process and the cleaner the cut, but excessive pressure can damage the material. On the other hand, low gas and oxygen pressure can slow down the cutting process and result in rough cuts. Nisar et al. (2021) optimized the cutting parameters in the pocket milling process of pure copper using the Grey-based Taguchi method and Analysis of Variance (ANOVA) to identify the most influential parameters in minimizing surface roughness and dimensional inaccuracy. The results showed that feed rate had the most significant impact, with optimal conditions at a spindle speed of 3000 rpm, feed rate of 200 mm/min, and cutting depth of 0.1 mm.

Based on the issues mentioned above, this study aims to optimize the process parameters in CNC flame cutting to improve the cutting quality of products at PT XYZ. The research focuses on analyzing three main parameters: cutting speed, oxygen pressure, and gas pressure. The Taguchi method is used to analyze the impact of parameter combinations on dimensional inaccuracy, while analysis of variance (ANOVA) is applied to identify the parameters that significantly affect the CNC flame cutting process. This analysis uses Minitab 18 software to obtain the most optimal formulation. The expected result is to find the optimal parameter combination to achieve the smallest dimensional inaccuracy of the product cuts that meet the design specifications.

2. Literature Review

2.1 CNC Flame Cutting

As market competition intensifies and the demand for high precision increases, non-conventional machining methods have become a key solution in the industry. One of the most significant non-conventional machining techniques is CNC flame machining (Kolhe et al., 2018). CNC flame cutting depends greatly on parameter settings, including torch distance from the material, type of fuel, preheating time, type of material being cut, material thickness, nozzle type, cutting speed, oxygen pressure, and gas pressure. Changes in these parameters can impact the quality of metal cutting, with optimal cutting conditions achieved through accurate parameter adjustments (Ramakrishna et al., 2018). Flame or gas cutting machines are used to cut iron or steel by relying on the combustion of a gas mixture, such as oxygen and LPG or oxygen and acetylene. The cutting process involves heating the steel to a bright red (around 875°C), after which cutting gas is blown at high pressure to penetrate the steel. The oxygen flow is directed to the area to be heated, triggering a rapid oxidation process (blast) between the oxygen and the metal, which leads to the metal being expelled and the cutting process occurring (Tauvana & Widodo, 2020).

2.2 SS400 Steel

Steel is an alloy primarily composed of iron (Fe) and carbon (C), along with trace amounts of other elements such as manganese (Mn), silicon (Si), nickel (Ni), chromium (Cr), vanadium (V), and others, which influence its overall quality. Low-carbon steel contains less than 0.3% carbon. It is characterized by relatively low hardness, softness, and high ductility. This type of steel is commonly used in the form of plates, profiles, scrapers, threads, and bolts (Davis, 1998). Low carbon steel is generally more economical to process than other metals and is widely used (ASM, 1990). One example of low-carbon steel commonly used is SS400 steel. SS400 steel is classified as low-carbon steel with a maximum carbon content of 0.17%. The application of SS400 steel is widely found in the railway industry, bridge construction, general construction industries, and others (Rosyadi et al., 2022).

2.3 Dimensional Accuracy

A steel cutting machine is a crucial component in industrial systems, requiring high standards of accuracy, productivity, and efficiency. According to the State Standard GOST R ISO 5725-1–2002, accuracy is defined as the closeness of the measurement results to a reference value. In the context of multiple measurement results, accuracy encompasses both random variations and systematic errors. The reference value may be a theoretical value based on scientific principles, an experimentally derived value, a certified value from a combination of experimental outcomes, or, in the absence of these, an agreed-upon mathematical value.

Accuracy represents the degree of alignment between the properties of an object, system, or process and the desired, defined, or ideal value or behavior. In the context of information, accuracy refers to the difference between the representation of an object's information and its true value. From a mathematical perspective, accuracy is the deviation of the determinant vector or the status field deviation of an object's properties from its theoretical value. In terms of structure, accuracy pertains to the variation in the relationships between elements within a structure.

The progress of machining accuracy, especially in steel cutting machines, has been driven by industrial needs and societal demands. Advancements in supporting technology have created new requirements for components, mechanisms, and manufacturing systems, while also encouraging the use of innovative physical principles and phenomena. The strict accuracy demands for machine components have led to ongoing improvements in the precision of steel cutting machines. Over the years, engineers and specialists have worked on refining designs, production methods, and industrial applications for steel cutting machines to achieve greater machining accuracy (Kuznetsov, 2017).

2.4 Taguchi Method

The Taguchi method, developed by Dr. Genichi Taguchi, is a quality control technique applied before a process begins, often called offline quality control. It is highly effective in enhancing quality and minimizing costs. The goal of Taguchi's quality engineering is to make product or process performance resilient to factors that are challenging to control (Roy, 2010).

This method is reliable for implementation in various manufacturing processes. By utilizing orthogonal matrices in experimental design, this approach enables cost-effective investigations by minimizing the number of required experiments (Rifelino et al., 2021). The Orthogonal Array (OA) matrix is used to determine the minimum number of experiments that can yield the most information about all the factors influencing the experimental results. It is called orthogonal because each factor's levels are balanced and independent of the effects of other factors in the experiment. An orthogonal array is a matrix that arranges factors and levels in a way that prevents their influences from blending with one another. The most important aspect of an orthogonal array is the selection of level combinations for the input variables in each experiment. The notation for an Orthogonal Array is $L_n(\ l^f\ )$, where f represents the number of factors, l is the number of levels, n is the number of experiments, and L is the symbol for the orthogonal array (Roy, 2001).

A comprehensive quality strategy maintains the strength of the process outcomes during the design phase. This method is also known as robust design, which means that the system's performance can withstand or overcome unfavorable conditions. Furthermore, this method allows for the detection of the appropriate control factor levels in experimental design to ensure the system is not sensitive to noise factors (Rifelino et al., 2021). In the Taguchi method, Signal to Noise Ratio (SNR) is used to identify factors that affect the variation of a response. A product or process design that is consistent with a high SNR value will always result in production with optimal quality and minimal variation.

According to Taguchi, there are three types of SNR characteristics: Nominal is the best, Bigger is better, and Smaller is better. "Smaller is better" is a characteristic measured by values where the target is to achieve the smallest value. The SNR value for the "Smaller is better" quality characteristic as shown in Equation 1 (Roy, 2010):

$$SNR =-10\,Log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i{}^2\right) \tag{1}$$

2.5 Analysis Of Variance (ANOVA)

Analysis of Variance (ANOVA) is a calculation technique used to quantitatively assess the impact of each factor on all response measurements. ANOVA in parameter design helps identify the contribution of each factor affecting the test, allowing for precise determination of the model estimation's accuracy (Nugraha et al., 2023). The formulas used in ANOVA calculations are shown in Table 1.

Table 1. Formulas Analysis Of Variance (ANOVA)

Description	Equation
Total degrees of freedom for variable factors	$f_T = N - 1$
Factor for each variable	$f_A = k_A - 1$
Error factor	$f_E = f_T - (f_A + f_B + f_N)$
Sum of squares for all variables	$S_T = (T_{S_1}^2 + T_{S_2}^2 + T_{S_3}^2 + T_{S_N}^2) - \left(\frac{\left(T_{S_1}+T_{S_2}+T_{S_3}+T_{S_N}\right)^2}{N}\right)$
Sum of squares for each variable	$S_T = \left(\frac{(\Sigma A_1)^2}{k_{A_1}} + \frac{(\Sigma A_2)^2}{k_{A_2}} + \frac{(\Sigma A_N)^2}{k_{A_N}}\right) - \frac{\left(T_{s_1}+T_{S_2}+T_{S_3}+T_{S_N}\right)^2}{N}$
Sum of squares for error factors	$S_E = S_T - (S_A + S_B + S_N)$
Variation value for each variable	$V_A = \frac{S_A}{f_A}$
F-ratio for all variables	$F_A = \frac{V_A}{V_E}$
Percentage contribution of each variable	$P_A = \left(\frac{S_A}{S_T}\right) \times 100$

Source: Nugraha et al., 2023

3. Methodology

3.1 Research Tools

This research was conducted using the CNC Flame Cutting Machine Hugong GSI1-4500GD located in the Construction Department of PT XYZ, as shown in Figure 2. The measurement of specimens to determine the dimensional accuracy of the cutting results was carried out using a Vernier Caliper Mitutoyo 530-118, with the unit in millimeters (mm). This tool has an accuracy level of up to 0.05 mm and is capable of measuring up to a maximum length of 200 mm, as shown in Figure 3.

Figure 2. CNC Flame Cutting Machine Hugong Type GSI1-4500GD

Figure 3. Vernier Caliper Mitutoyo 530-118

3.2 Research Materials

The specimens used in this study are made of SS400 steel plates with a thickness of 16 mm, as shown in Figure 4. The research specimens are designed with dimensions of 60 mm x 60 mm, as illustrated in Figure 5.

Figure 4. SS400 steel material with a thickness of 16 mm

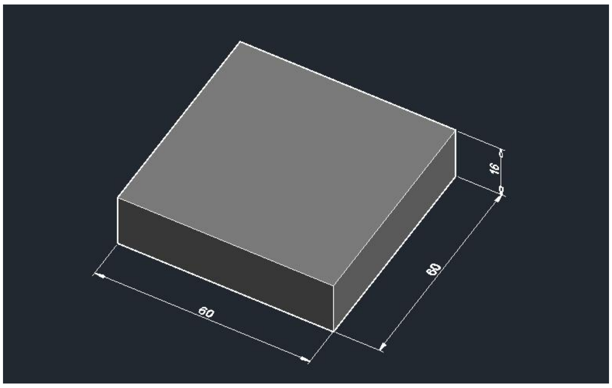

Figure 5. Specimen dimension size 60 mm x 60 mm

3.3 Factors and Levels of Process Parameters

This study focuses on optimizing three process parameters: cutting speed, gas pressure, and oxygen pressure. Each parameter has three levels, which are used to form a factorial design or Orthogonal Array (OA). This design will be used to determine the optimal variation of the process parameters, as shown in Table 2.

Table 2. Control factors and process parameter levels

Process Parameters	Factors	Level		
		1	2	3
Cutting Speed (mm/menit)	A	312	379	431
Gas Pressure (bar)	B	4	5	6
Oxygen Pressure (bar)	C	4	5	6

3.4 Orthogonal Array (OA) Factorial Design

The selection of the Orthogonal Array (OA) was made as a fundamental reference in the specimen manufacturing and testing process. This study uses the Taguchi L9 (3^3) OA design, as it involves three factors, each with three levels. The L9 design represents the study with nine experimental conditions, where each condition will be tested to optimize the cutting process using a CNC flame cutting machine, as presented in Table 3.

Table 3. Orthogonal Array Factorial Design L9

Experiment	**Cutting Speed (mm/menit)**	**Gas Pressure (bar)**	**Oksigen Pressure (bar)**
1	312	4	4
2	312	5	5
3	312	6	6
4	379	4	5
5	379	5	6
6	379	6	4
7	431	4	6
8	431	5	4
9	431	6	5

4. Results and Discussion

4.1 Signal to Noise Ratio (SNR) Analysis

The determination of SNR values was conducted by processing the average data obtained from the tests without replication. In this study, the formula for SNR Smaller is Better (Equation 1) was used to identify the factor levels affecting the dimensional inaccuracy response. This formula was selected based on the premise that the smallest factor level indicates the minimum dimensional inaccuracy in the cutting results of 60 mm x 60 mm (square) specimens using CNC flame cutting. Data processing from the experimental tests was performed using Minitab 18. The results of the dimensional accuracy tests and SNR values are presented in Table 4.

Table 4. Calculation Results of SNR for Dimensional Inaccuracy

Exp.	**Parameters Control**			**Dimensional Inaccuracy on Each Side of The Square (mm)**					**SNR**
	Cutting Speed (mm/menit)	**Gas Pressure (bar)**	**Oxygen Pressure (bar)**	**1**	**2**	**3**	**4**	**Averege**	
1	312	4	4	62,083	61,433	61,917	61,600	61,758	-35,814
2	312	5	5	62,633	61,817	62,650	61,883	62,246	-35,882
3	312	6	6	61,933	61,517	61,867	61,367	61,671	-35,802
4	379	4	5	61,667	61,900	61,400	62,167	61,783	-35,817
5	379	5	6	62,433	62,167	62,300	62,300	62,300	-35,890
6	379	6	4	61,317	61,867	61,217	62,250	61,663	-35,800
7	431	4	6	61,683	61,667	61,667	61,733	61,688	-35,804
8	431	5	4	62,883	61,750	62,800	62,017	62,363	-35,898
9	431	6	5	61,967	62,083	62,000	62,300	62,088	-35,860

Table 4 above shows the results of the SNR analysis for the dimensional inaccuracy measurement experiment. The cutting specimen with the minimum dimensional inaccuracy was found in the 6th experimental trial, with an average value of 61.663 and an SNR value of 35.800.

The variability level of each control parameter applied is determined by calculating the SNR values for the dimensional inaccuracy measurement using the Smaller Is Better technique. The relationship between the levels that generate the most or least noise and the control parameters can be identified from the variability values. The variability data of each control parameter helps in finding the optimal parameter variations and determining the ranking of each control parameter's influence on the test results. Table 5 shows the variability values of the control parameters related to the dimensional inaccuracy test.

Table 5. Variability Values of Control Parameters for Dimensional Inaccuracy

Level Control Parameters	**SNR Smaller is better Inaccuracy Dimension**		
	Cutting Speed (mm/menit)	**Gas Pressure (bar)**	**Oxygen Pressure (bar)**
1	-35,83	-35,81	-35,84
2	-35,84	-35,89	-35,85
3	-35,85	-35,82	-35,83
Delta	0,02	0,08	0,02
Rank	2	1	3

Based on the variability values with the smallest noise in the data from Table 5, the order of control parameters affecting dimensional inaccuracy is cutting speed, gas pressure, and oxygen pressure. The optimal parameter combination for achieving the lowest dimensional inaccuracy was found at cutting speed level 1 with a speed of 319 mm/min, gas pressure level 1 at 4 bar, and oxygen pressure level 3 at 6 bar.

4.2 Analysis of Variance Method

The Analysis of Variance method was applied using Minitab 18 software to optimize CNC flame cutting parameters with the aim of achieving the minimum dimensional inaccuracy. After the data was processed using the ANOVA approach, it was grouped based on each test and further analyzed. The analysis results, showing the percentage contribution of each parameter in the dimensional inaccuracy measurement experiment, can be seen in Table 6.

Table 6. ANOVA Method Contribution Percentage Calculation Results

Source	**Degree of Freedom (DF)**	**Sum of Squares (SS)**	**Contribution Percentage (%)**	**F-ratio Value (F-value)**	**Probability Value (P-value)**
Cutting Speed (mm/minute)	2	0,05340	6,06%	1,17	0,462
Gas Pressure (Bar)	2	0,76034	86,31%	16,60	0,057
Oxygen Pressure (Bar)	2	0,02135	2,42%	0,47	0,682
Error	2	0,04580	5,20%		
Total	8	0,88089	100,00%		

Table 6 above presents the results of the ANOVA calculation regarding the percentage contribution of each process parameter in the dimensional inaccuracy test. Based on the calculation, it is found that the parameter with the greatest influence on dimensional inaccuracy is gas pressure, with a contribution of 86.31%, followed by cutting speed at 6.06%, and oxygen pressure at 2.42%. Therefore, gas pressure is the parameter with the largest impact. These results indicate that gas pressure is the key parameter that needs to be optimized in order to minimize dimensional inaccuracy in CNC flame cutting..

5. Conclusion

Based on the experiments and analysis conducted, the optimization of parameters using a combination of the Taguchi method and ANOVA successfully determined the cutting results with the minimum dimensional inaccuracy on the CNC Flame Cutting machine, as well as the contribution percentage of each parameter affecting the dimensional inaccuracy in the cutting of SS400 material. The optimal parameter combination that produced the lowest dimensional inaccuracy was found at a cutting speed of 319 mm/min, gas pressure of 4 bar, and oxygen pressure of 6 bar. The contribution percentage of each parameter was 86.31% for gas pressure, followed by 6.06% for cutting speed, 2.42% for oxygen pressure, and 5.20% for the error factor. Therefore, the parameter that most influences the accuracy of CNC Flame Cutting is gas pressure. The level of dimensional inaccuracy that deviates from the standard can lead to additional material cutting, resulting in increased operational costs and time.

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