

TAGUCHI-BASED OPTIMIZATION OF PLASMA CUTTING PARAMETERS OF LOW-CARBON STEEL FOR SURFACE ROUGHNESS AND HEAT-AFFECTED ZONE CHARACTERISTICS

M. Demouche^{1*}, F. Bettine¹ and B.M.B. Mertani¹

¹Institute of Optics and Precision Mechanics
Ferhat Abbas University, Sétif, Algeria

*Corresponding Author's Email: demouchemourad@yahoo.fr

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ABSTRACT: Plasma arc cutting is a non-conventional manufacturing process widely used in the mechanical industry. In this process, material removal is achieved through localized melting under the action of the high-temperature plasma jet. The cut quality is primarily influenced by the operating parameters of the cutting process, which necessitates their accurate adjustment. Furthermore, the mechanical and metallurgical properties of the Heat-Affected Zone (HAZ) can also have an effect on the quality of this surface. However, previous research often neglects to study the link between technological parameters, cut quality, and the properties of the Heat-Affected Zone (HAZ). To fill this gap, this study aims to optimize the process parameters of plasma cutting, such as the cutting speed, current intensity, and standoff distance, of a 4 mm thick mild steel sheet in order to minimize the cut surface roughness. We also seek to establish the link between the optimal conditions and the phase transformations generated in the Heat-Affected Zone (HAZ). This provides a global overview of the relationship between the process parameters, the cut quality (particularly surface roughness), and the HAZ characteristics. To achieve this objective, the Taguchi method was employed using the Signal-to-Noise Ratio (S/N). This approach allowed for the determination of the optimal configuration for a minimal surface roughness. Analysis of Variance (ANOVA) revealed that cutting speed is the most influential factor on roughness, contributing to 43.7% of the response variation, followed by current intensity (20%) and the standoff distance (3.3%).

A mathematical prediction model was also developed. Furthermore, a microstructural analysis of the heat-affected zone (HAZ) and hardness measurements were performed to highlight the thermal impact and establish the link between these parameters and the final metallurgical state of the base metal. This analysis revealed a hardness increase of approximately 260% near the cutting edge, confirming the microstructural changes observed in this area. This study not only showed the dominant effect of cutting speed on surface roughness, but also highlighted the correlation between this parameter, surface quality and HAZ properties.

KEYWORDS: *Plasma cutting, Taguchi method, ANOVA, microstructure, hardness.*

1.0 INTRODUCTION

Plasma arc cutting is a thermal cutting process in which material is removed by localized melting. Its principle involves generating an electric arc between the torch and the workpiece [1]. Under the effect of this arc, a pressurized gas is ionized and transformed into plasma [2]. This plasma is then ejected at very high speed through a small-diameter nozzle (Figure 1). This produces a concentrated jet with a temperature that can reach 30,000 °C. This cutting technique is effective for all electrically conductive materials [3, 4].

In general, a plasma cutting system consists of an electrical power supply and a torch, the main component for cutting metal. The torch is composed of three main parts: the cathode, the nozzle, and the torch body. Its primary role is to create a very high-temperature plasma jet [5,6,7]. Various types of gases can be used for cutting, such as oxygen, hydrogen, nitrogen, and argon. To improve cut quality, these gases can be used alone or in combination [8]. Performance and cut quality can be evaluated based on several indicators, such as the surface finish of the cut, the kerf width, the bevel angle, and the level of dross produced during cutting. The fundamental parameters that influence plasma cutting quality are the cutting speed, the arc current intensity, the standoff distance, and the gas pressure [9,10]. To optimize the operating parameters that determine plasma cutting quality and to highlight their influence on the cutting process, numerous studies [11-

14] have been conducted using various methods. Furthermore, much research is dedicated to studying the effects of the plasma cutting process on the resulting mechanical and microstructural properties in the heat-affected zone (HAZ).

In this context, Abdulkadir Gullu et al. [15] studied the effects of plasma cutting parameters on the microstructural variations and hardness of AISI 304 stainless steel and St 52 carbon steel. Design of experiments (DOE) is a highly effective statistical method for structuring and organizing scientific experiments. This methodology allows for obtaining reliable results using a reduced number of experimental trials. For this reason, it is widely used in the optimization of industrial processes, particularly plasma cutting processes. A. Gani et al. [16] applied the Taguchi method and analysis of variance (ANOVA) to optimize cutting parameters and highlight the effects of plasma-generated heat on surface deformation and heat-affected zone of 0.6 mm thick DC01 steel sheets. A mathematical model was constructed to predict the output response. K. Salonitis et al. [17] investigated the influence of operating parameters such as current, cutting speed, cutting height, and plasma gas pressure on the plasma cutting quality of mild steel.

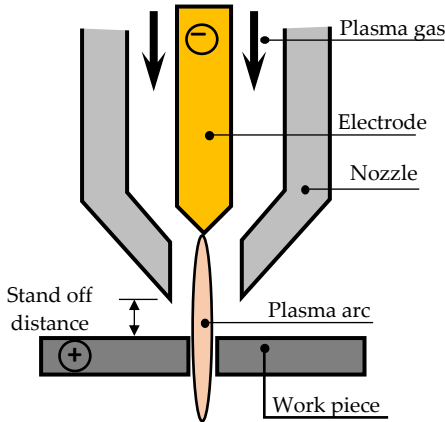


Figure 1: Principle of a plasma cutting torch



Figure 2: Plasma-cut samples

Cutting quality was assessed by measuring surface roughness, kerf taper angle, and the extent of the heat-affected zone (HAZ) during plasma cutting of mild steel. This study was conducted using the response surface methodology (RSM). A statistical analysis (ANOVA) of the results was used to determine the contribution of each parameter to the variations in response. A regression model was constructed to predict the impact of these parameters on cutting quality. D.N. Sharma et al. [18] focused their study on the influence of cutting parameters on the dross formation rate during the cutting of low-carbon steel. They used response surface methodology (RSM) to identify the optimal combination that minimizes the level of dross formation. Another study conducted by A. Suresh et al. [19] also employed the response surface method to determine the optimal conditions for plasma cutting of TWIP steel sheets.

ANOVA analysis was used to quantify the contribution of each input parameter to the variations in the output response. The main effects of process parameters on the material removal rate, surface roughness, and cutting time were also identified. Although design of experiments

(DOE) methods, such as the Taguchi approach, are widely used for optimizing plasma cutting processes, previous research has generally been limited to analyzing isolated responses. The lack of studies investigating the combined effect of optimal parameters on cut quality and the metallurgical properties of the base material represents a significant gap in the literature. To address this gap, we adopted a more comprehensive approach. Our methodology involves studying the influence of parameters optimized by the Taguchi method not only on surface roughness but also on the heat flow generated by the plasma jet and the metallurgical transformations induced in the heat-affected zone (HAZ). This approach provides a more complete understanding of the relationship between operating parameters and the thermal and physical phenomena that occur during cutting, and their influence on the cut surface quality. This represents a significant advancement compared to previous work.

2.0 MATERIALS AND METHODS

2.1 Materials

All cutting operations were carried out on a mild steel workpiece with a thickness of 4 mm, using a CNC plasma cutting system. Eight linear cuts, each measuring 100 mm in length and spaced at 20 mm intervals (Figure 2), were executed under controlled conditions. To prevent cumulative thermal effects from influencing subsequent cuts, sufficient cooling periods were observed between experiments. The detailed chemical composition of the workpiece material is given in Table 1.

Table 1: Chemical composition of the material used for experiments (wt.%)

C	Si	Mn	P	S	Cr	Mo	Ni	Fe	Co	Cu
0.096	0.143	0.653	0.020	0.028	0.508	0.061	0.181	89.03	0.14	0.199

2.2 Designing of Experiments

This study goes beyond the classical application of the Taguchi method, which consists of optimizing cutting parameters to minimize surface roughness. It also aims to correlate the optimal conditions obtained by this method with the metallurgical state and mechanical

properties of the base material. The Taguchi method was chosen for its ability to optimize industrial processes with a minimal number of trials compared to other methods, such as the Response Surface Methodology [20, 21]. It also enables the design of robust processes, which are less sensitive to noise factors. This robustness can be measured using the Signal-to-Noise Ratio (S/N). To study the effect of three control factors at two levels each (Table 2), an eight-trial Design of Experiments ($L_8(2^3)$) was implemented. This optimization aims to minimize the surface roughness (Ra), following the "smaller is better" criterion.

Table 2: Factors and Levels

Process parameter (Factor)	Level	
	1	2
Current (A)	80	110
Cutting Speed (mm/min)	1000	2000
Standoff distance (mm)	1,5	2,5

3.0 RESULTS AND DISCUSSION

3.1 Experiment design array

According to the orthogonal array L_8 , Table 3 displays the experimental run order and their parameter settings. To evaluate the cut quality, the surface roughness (Ra) of the cutting surface was measured. The average of the three measurements taken on each sample was retained. An additional column, to the right of the table, indicates the signal-to-noise ratio (S/N).

Table 3: Experiment design array with 3-Two Level factors and results

Runs N°	A	B	C	Surface Roughness Ra (μ)	S/N Ratio
	Current (A)	Cutting Speed (mm/min)	Stand-off distance (mm)		
1	80	1000	1,5	1,3808	-2,80262
2	80	1000	2,5	1,7218	-4,71965
3	80	2000	1,5	0,9596	0,358195
4	80	2000	2,5	1,0774	-0,647539
5	110	1000	1,5	2,3396	-7,38283
6	110	1000	2,5	0,7225	2,82324
7	110	2000	1,5	0,4325	7,28028
8	110	2000	2,5	0,4305	7,32054

3.2 Analysis of Signal-to-Noise (S/N) Ratio

In this study, the experimental data were analyzed using the Minitab 19 software. To ensure high cut quality, the cutting surface roughness must be minimal. To achieve this, the “smaller-is-better” criterion was applied to calculate the signal-to-noise (S/N) ratio. This ratio, which serves to measure the variability of experimental results, is expressed by the following formula:

$$S/N = -10\log\left(\frac{1}{n}\sum(Y)^2\right) \tag{1}$$

Where, Y is the surface roughness measurement in column R_a ,
 n is the number of repetitions; in this case, $n = 1$.

Minitab calculates the S/N ratio for each control factor combination (Table 3) and determines the average S/N ratio for each level of the individual factors (Table 4). The effect of each factor on surface roughness (R_a) can be evaluated by referring to the Δ value. This value represents the difference between the maximum and minimum signal-to-noise (S/N) ratio for each factor. Based on the Δ values, the cutting speed is the most influential factor on the S/N ratio, as it has the highest value ($\Delta = 6.5983$; rank = 1), followed by the current ($\Delta = 4.4632$; rank = 2), followed by the Standoff distance factor.

Table 4: Response for signal-to-noise ratios (Smaller is better)

Level	Current	Cutting Speed	Standoff distance
1	-1,9529	-3,0205	-0,6367
2	2,5103	3,5779	1,1941
Δ	4,4632	6,5983	1,8309
Rank	2	1	3

Main effects plots are very useful tools for visualizing the influence of each factor on the surface roughness, allowing for the determination of the most influential factor. In order to determine the optimal response and minimize the effect of noise, these graphs are plotted for the signal-to-noise ratio (S/N), always aiming to maximize this ratio. Graphically, a steeper slope of the plot indicates a greater main effect of the corresponding factor.

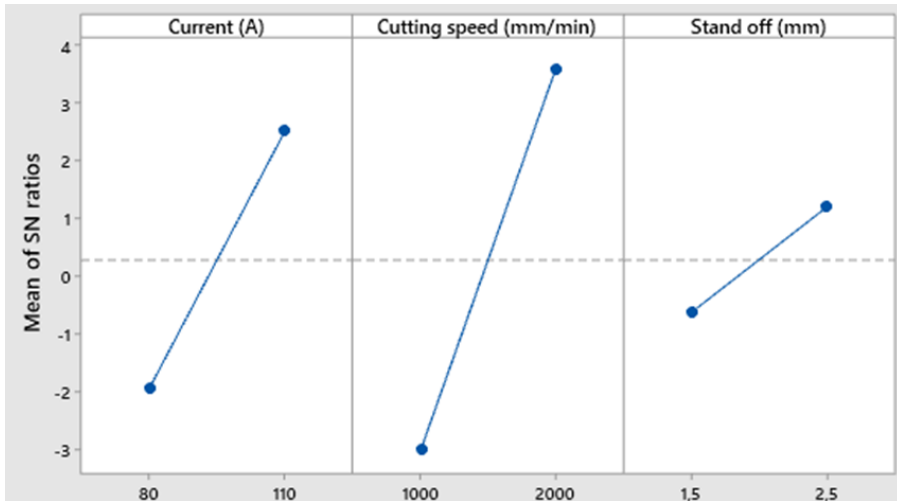


Figure 3: Main effects graph for SN ratios for surface roughness

According to the graphs in Figure 3, cutting speed is the most influential factor (steeper slope), while standoff distance has the weakest effect (slightest slope). The main effects graphs clearly show that the optimal levels of the three factors are obtained with the A2-B2-C2 configuration. This combination corresponds to a cutting speed of 2000 mm/min, a current of 110 A, and a standoff distance of 2.5 mm. This configuration corresponds to experiment 8.

3.3 ANOVA Analysis for S/N ratios

To evaluate the contribution ratio of each cutting parameter (speed, current, and standoff distance) to the variations in surface roughness (R_a), an analysis of variance (ANOVA) was performed. The results are presented in Table 5.

Table 5: ANOVA table for S/N ratios

Source	DF	Seq SS	F	P
Current (A)	1	39,840	2,43	0,194
Cutting speed (mm/min)	1	87,076	5,32	0,082
Stand-off (mm)	1	6,704	0,41	0,557
Residual Error	4	65,505		
Total	7	199,126		

The results of the ANOVA analysis confirm that cutting speed is the most influential parameter on surface roughness (Ra) variability, with a predominant contribution rate of 43.7%. Current intensity is the second most influential factor, contributing 20%. In contrast, standoff distance has only a minor contribution of 3.3%. It is important to note that the residual error contributes significantly at 32.9%. A relatively high residual error rate reflects the complexity of the phenomena involved (thermal, electrical, mechanical) during the cutting process. This error also indicates the presence of other uncontrolled factors, such as arc instability, variations in cutting gas pressure or flow rate, nozzle and electrode wear, and variations in the chemical composition or hardness of the base material. Unmodeled interactions between cutting parameters (speed, current, and standoff distance) can also be a source of variation.

3.4 Mathematical model

A mathematical model has been developed to predict surface roughness Ra as a function of cutting parameters.

$$Ra = 3,90 - 0,0101 \textit{ Current} - 0,000816 \textit{ Cutting speed} - 0,290 \textit{ Standoff} \quad (2)$$

• Predicted Results at Optimal Settings

The optimal roughness value Ra is predicted using the optimal values of the cutting parameters. This value represents the process performance when each parameter is adjusted to its optimal level. The predicted value of Ra calculated from the mathematical model is:

$$Ra = 0.428 \quad \text{and} \quad S/N \text{ Ratio} = 6.725$$

This indicates that when the cutting process is carried out under the identified optimum conditions (current = 110 A, speed = 2000 mm/min and standoff distance = 2.5 mm), the surface roughness should be equal to the expected value (Ra = 0.42 μm).

• Confirmation test

To verify the reliability of the established model, an experimental validation test was performed under optimal conditions: (a speed of 2000 mm/min, a current of 110 A, and a standoff of 2.5 mm). The average

measured roughness was $0.67 \mu\text{m}$. The significant difference between the value predicted by the model and the experimental value may be due to the considerable influence of uncontrolled factors on the cutting process. This affected the final cut quality and the model's predictive accuracy.

3.5 Microstructure and hardness analysis

In this section, the aim is to analyze the impact of the plasma cutting process on the mechanical and microstructural properties of the HAZ (Heat-Affected Zone). To achieve this objective, an experimental characterization of this zone is necessary. Sample N°1 was prepared by performing a cut as illustrated in Figure 4. Subsequently, a metallographic preparation was carried out, which involved polishing until a mirror surface was obtained, followed by a chemical etching with a 3% Nital solution. Finally, the etched surface was subjected to optical microscopy examination in order to visualize and analyze its microstructure. To complement this analysis, a hardness test was performed within the HAZ by applying a 100g load.

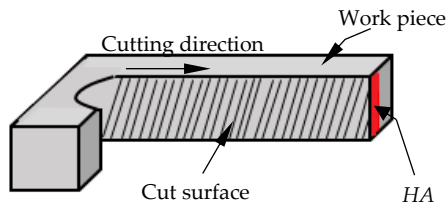


Figure 4: Schematic view of the Cutting surface and HAZ

Vickers hardness (H_v) measurements were taken in three distinct zones: Zone 1 (heat-affected zone, very close to the cutting surface), Zone 2 (transition zone), and the unaffected zone (Zone 3). The average hardness values are presented in Table 6.

Table 6: Hardness of steel cut by plasma arc

Hv (mean)	Zone 1	Zone 2	Zone 3
	357	250	173

The base material studied is a low carbon steel with an average hardness of 173 HV. Its microstructure consists of a predominant ferrite matrix in which pearlitic grains are dispersed (figure 5). Analysis of the microstructure and hardness in the HAZ shows that this critical zone has undergone significant phase transformations. The localized heat flux generated by the plasma jet causes intense heating of the area adjacent to the cutting surface. This heating, followed by rapid cooling, has led to a change in the microstructure in this region. Figure 6 presents a global micrograph of the heat-affected zone after cutting, showing the evolution of the microstructure from the region near the cut surface to the unaffected base metal. Examination of this micrograph reveals the presence of three zones with different microstructures. The analysis of the micrograph of zone 1 (Figure 7) reveals the presence of an acicular microstructure with a high hardness value reaching 357 HV, representing an increase of about 260% compared to the base metal.

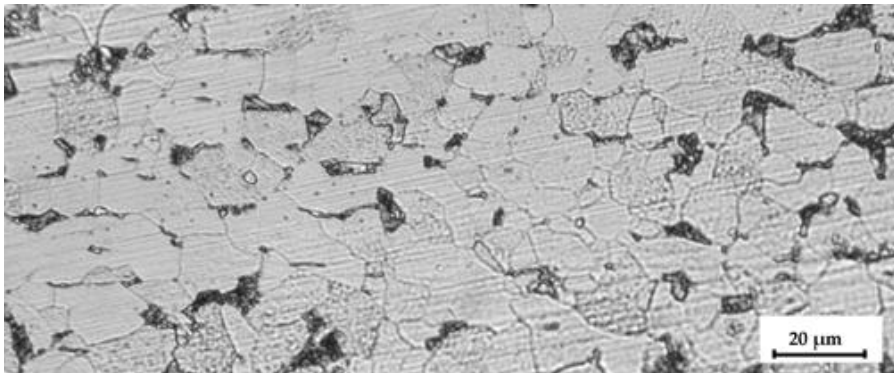


Figure 5: Microstructure of the investigated steel (as received)

This significant increase in hardness leads to embrittlement of this region. The appearance of this acicular microstructure confirms that this zone was heated beyond the critical temperature, followed by rapid cooling. The intermediate zone (zone 2) exhibits a ferrite–pearlite microstructure (Figure 8), with a hardness of 250 HV. This suggests that

this zone underwent moderate heating below the critical temperature. The thermal cycle therefore caused a partial transformation of the initial phase. The base metal zone (zone 3) was not affected by the heat and retained its initial structure with a hardness of 173 HV.

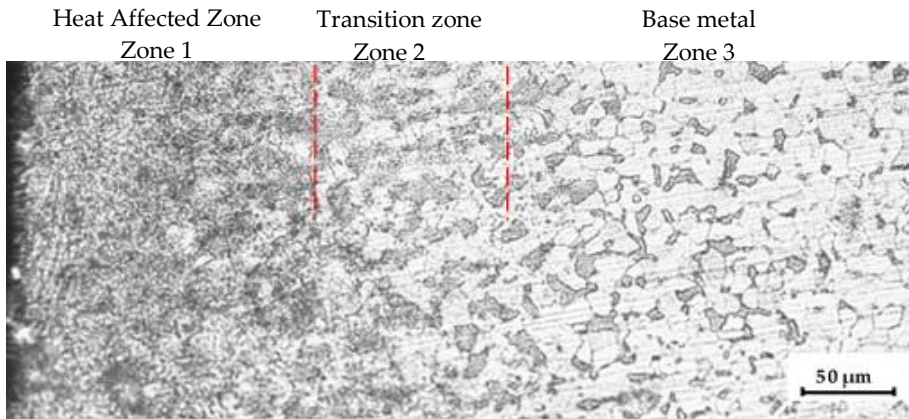


Figure 6: Microstructural overview of the HAZ after plasma arc cutting – Sample No. 1.

These microstructural and mechanical (hardness) changes highlight the need for precise control of process parameters in order to improve the properties of the heat-affected zone and minimize the risk of brittle regions forming. The changes in microstructure and hardness observed in the HAZ confirm the presence of a significant metallurgical gradient. This gradient is a direct consequence of the thermal cycle generated by the plasma jet. In turn, this thermal cycle is strongly dependent on the cutting parameters. The metallurgical characterization carried out made it possible to highlight the nature of the transformations induced in the HAZ (Heat-Affected Zone). It also provided a physical basis that confirms and complements the results of the statistical analysis.

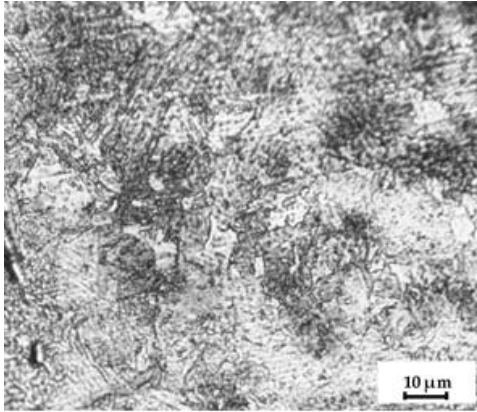


Figure 7: Microstructure of Heat Affected zone (zone 1) - Sample N°1

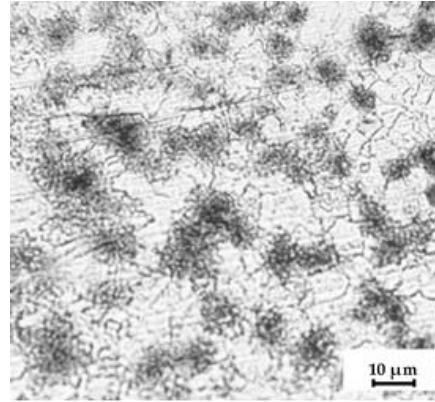


Figure 8 : Microstructure of transition zone (zone 2) – Sample N°1

The application of the Taguchi method, combined with analysis of variance (ANOVA), confirmed the fundamental effect of cutting speed on surface quality. This gives it a key role in controlling the generated thermal cycle. Consequently, it's a major influence on the metallurgical transformations observed. The analysis of the effect of cutting speed on the thermal cycle helps explain its predominant role in the plasma cutting process. A low cutting speed prolongs the interaction time between the material and the plasma arc, resulting in excessive heat input and an extended melting duration. This causes instabilities in the plasma arc, leading to disordered solidification. These factors result in a high surface roughness. Conversely, a properly adjusted cutting speed maintains a balance between melting time, torch travel, and metal removal. This balance reduces the extent of the heat-affected zone (HAZ). The cutting speed governs the phase transformation mechanisms by controlling the material's exposure time to the heat flow. This determines the final microstructural characteristics that influence surface quality.

4.0 CONCLUSION

In this work, an optimization study of cutting parameters was carried out for plasma arc cutting of low-carbon steel. The main objective was to highlight the relationship between the optimal parameters for

obtaining a low surface roughness and the metallurgical characteristics of the Heat Affected Zone of the cutting material. To minimize surface roughness, the Taguchi method was used, based on the signal-to-noise ratio (S/N). The application of this robust optimization method revealed that cutting speed is the most influential factor on surface roughness. The optimal combination for minimizing surface roughness is 2000 mm/min for the cutting speed, 110 A for the current, and a standoff distance of 2.5 mm. The Analysis of Variance (ANOVA) confirmed these results. The contribution rate attributed to the cutting speed is 43.7% of the roughness variability, 20% for the current, and a low contribution (3.3%) for the standoff distance. These results are consistent with previous work carried out by A. Suresh et al. [19]. The authors also emphasized the predominance of cutting speed in optimizing plasma cutting parameters. However, some studies have obtained different results. K. Salonitis et al. [17] showed that standoff distance has the most pronounced effect on roughness compared to speed or current. This discrepancy may be due to variations in experimental conditions, such as the type and thickness of the material. These factors, if not considered, can modify the thermal response of the process. The results of the present study confirm the major effect of the cutting speed on the process's thermal cycle. A low or poorly adjusted speed prolongs the heating time of the cut material. This affects the material's melting process and can lead to irregular solidification. Consequently, these factors can alter the surface quality and lead to an increase in roughness. Therefore, the cutting speed is not a simple setting parameter, but a regulator of the thermal cycle. The direct impact of this parameter on the HAZ microstructure allows it to control the final quality of the material. The central role of this parameter on thermal kinetics and the resulting microstructural changes is confirmed by microstructural analyses and hardness tests within the HAZ. From the base metal to the cut surface, three zones of different metallurgical nature were identified. The zone immediately adjacent to the cutting edge corresponds to the heat-affected zone. This critical zone is characterized by an acicular structure and very high hardness. The zone adjacent to the HAZ corresponds to the transition zone, exhibiting a ferrite-pearlite structure and moderate hardness. Finally, the unaffected zone corresponds to the base metal zone. These

observations, which are consistent with the results of j. Górka [14] and A. Gullu et al. [15], confirm the described thermal phenomena and validate the direct and significant impact of the cutting speed on the HAZ microstructure and surface quality.

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AUTHOR CONTRIBUTIONS

The individual contributions of the authors are detailed as follows:

- M. Demouche: Conceptualization, methodology, validation, supervision, project administration, data and results analysis, and writing of the original draft.
- F. Bettine: Performed the statistical data analysis using Minitab software.
- B.M.B. Mertani: Conducted all experimental work, including plasma cutting, metallographic sample preparation for microscopic observation, and hardness testing. He also contributed to the manuscript's review and editing.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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*Taguchi-Based Optimization of Plasma Cutting Parameters of Low-Carbon Steel
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