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Investigation of cutting qualities of AISI304 stainless steel using plasma arc cutting method

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Abstract: Since cutting stainless steels with non-traditional manufacturing processes such as laser beam cutting or water jet cutting is quite costly, machining with the plasma arc cutting (PAC) method, which is generally more economical, has been preferred more frequently in recent years. In this context, the use of PAC method in manufacturing of machine parts, especially in the construction and manufacturing industries, as well as in other industries such as food, automotive and petrochemicals, is increasing day by day. In these sectors, where high corrosion resistance and resistance to acidic environments are required, AISI304 stainless steel is generally preferred as the raw material. In this study, comprehensive literature research on PAC was conducted and the cutting qualities of AISI304 stainless steel plates with 4 and 8 mm thickness were investigated. Nine different types of experiment conditions (E1-E9) were created by the machining parameters (gas pressure: 0.6, 0.7 and 0.8 MPa – cutting speed: 151, 215 and 217 mm/min) determined from other experimental studies in the literature. The lowest average kerf taper value (0.32°) was obtained on the 4 mm thick plate with a gas pressure of 0.6 MPa and a cutting speed of 151 mm/min, whereas the highest average kerf taper value (2.59°) was obtained on the 8 mm thick plate where the gas pressure was 0.8 MPa and the cutting speed was 217 mm/min. The results revealed that for both plates, as the cutting speed increases at constant pressure values, the cutting surface roughness values increase. On the other hand, as the cutting speed is constant, the surface roughness decreases as the gas pressure value increases. The plates were cut into 100 mm long straight lines and the bottom surface burr formations and the top surface spatter formations in the PAC method were also examined.

Keywords: Plasma arc cutting, plasma cutting speed, plasma gas pressure, cutting width taper, kerf taper angle, cutting surface roughness

1. Introduction

Plasma arc cutting (PAC), a non-traditional manufacturing process, begins with the creation of a plasma arc by constricting a high-temperature, partially ionized gas (plasma) through a torch. It involves transferring the high energy released by the plasma arc to the electrically conductive workpiece surface to be processed, melting the material and removing the melted parts from the cutting environment [1]. For the plasma arc to form, the electrode (cathode) and the workpiece (anode) must be polarized with direct current, as seen in ▶**Figure 1**. Therefore, electrically conductive materials such as stainless steels, alloy steels, aluminium and copper can be machined with PAC [2-4]. The consumables and processing parameters (gas pressure, cutting speed, workpiece thickness, torch-to-workpiece distance, arc voltage, arc current, plasma and shielding gas type) used in the method directly affect the cutting quality [5, 6].

Austenitic stainless steels are the most widely used stainless steel class in the world, and the 304-grade stainless steel in this class is a steel quality containing high amounts of Cr and Ni. Due to their properties such as high hardness, corrosion resistance, high melting point and good weldability, AISI304 stainless steels are widely used in food, automotive, petrochemical, painting etc. industries [7]. In these industries, it is very dif-

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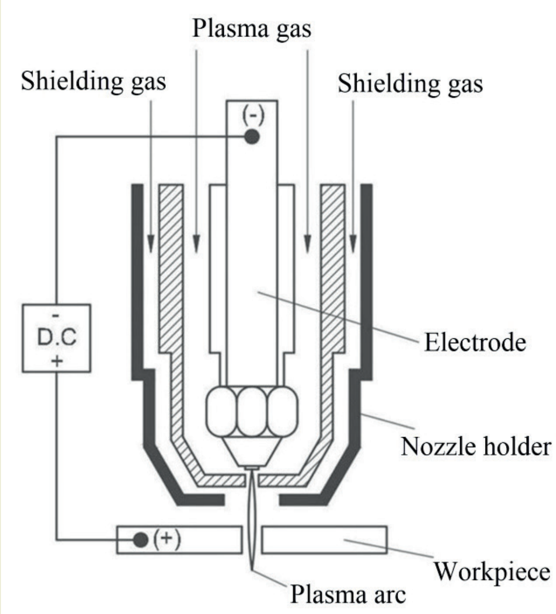

Figure 1. The schematic representation of the PAC process

ficult to cut and drill the hard-to-machine and thick sheet materials with the desired surface properties and geometric tolerances. At this point, the PAC offers more economical and faster production opportunities compared to other non-traditional manufacturing methods.

A considerable amount of literature has been published on the machining of stainless steels with the PAC. Numerous studies have argued that effects of machining parameters on cutting quality of PAC. For example, Bhowmick et al. [8] investigated the workpiece removable rate (WRR) and surface roughness by machining AISI304 stainless steel sheets with thicknesses of 4, 6 and 8 mm in the PAC method at different gas pressures (0.6, 0.7 and 0.8 MPa) and cutting speeds (151, 214 and 217 mm/min). They found that the cutting speed and plate thickness had a greater effect on the WRR value, while the gas pressure had a more significant effect on the surface roughness. They observed that WRR value increased in three different experiments by increasing the plate thickness at 0.6 MPa gas pressure and 151 mm/min cutting speed. They also found that the average surface roughness (R_a) decreased as the gas pressure value increased on the 6 mm thick plate at a cutting speed of 217 mm/min. Çelik and Özek [9] subjected the S235JR plate material to the PAC process to obtain standard tensile samples using different machining parameters. In their experiments for 80 A current, they found that the R_a value decreased with increasing arc voltage, and for 130 A current, the R_a value increased with increasing arc voltage. Likewise, Tsiolikas et al. [10] investigated the surface roughness of St37 steel in the PAC by cutting rectangular samples with dimensions of 30x40 mm at different cutting speeds (2000, 2600 and 3200 mm/min), different torch-to-workpiece distances (3, 3.6 and 4.2 mm) and different arc voltages (145, 150 and 155 V). They determined the best machining parameters in terms of surface roughness as follows: cutting speed 2000 mm/min, torch-to-workpiece distance 3.6 mm and arc voltage 155 V. For the surfaces cutting with these machining parameters, the R_a value was determined as 0.835 µm and the R_z value was determined as 7.7 µm. Similarly, Patel et al. [11] concluded that cutting speed has a significant effect on surface roughness in machining AISI D2 steel by PAC method. Bhuvenesh et al. [12] reported that the relationship between the WRR and R_a values in the PAC is inversely proportional and the lowest R_a value was obtained in the machining that they performed at 6.0 bar gas pressure, 80 A cutting current, 600 mm/min cutting speed and 4.0 mm torch-to-workpiece distance.

Improving the cutting quality of stainless steel by controlling the machining parameters during PAC is a very difficult task. Recent developments in the field of PAC have led to a renewed interest in kerf width and kerf taper. For example, Parthiban et al. [13] determined the top surface kerf width, bottom surface kerf width and kerf taper by cutting 2 mm thickness AISI316L stainless steel with different parameters and determined the best processing parameters as 40 A cutting current, 5000 mm/min cutting speed and 2 mm torch-to-workpiece distance. Guatam and Gupta [14] obtained the lowest R_a value (2.635 µm) in a 30x30 mm square cutting process at 6 bar gas pressure, 150 A cutting current, 400 mm/min cutting speed and 2 mm torch-to-workpiece distance. Ilii et al. [15] detected burr (beard) formation at the bottom of the cut surface depending on the cutting speed and material thickness. The machining parameters that did not cause burr formation in the cutting of a 4 mm thick plate (AISI304) were determined as 130 A cutting current and 1000 mm/min cutting speed. Rana et al. [16] observed that the current value has more than 65% effect on the kerf, the cutting speed has about 34% effect and the gas pressure have less than 1% effect. Hamid et al. [17] conducted research using Taguchi and GRA methods for surface roughness and kerf taper angles by experimenting with different machining parameters in PAC. They discovered that the cutting current primarily affects the surface roughness and taper angle values by 79.42%, while the cutting speed affects the value secondarily by 11.03%. Similarly, Das et al. [18] reported that gas pressure significantly affects WRR and surface roughness as a result of their study. Chamarthi et al. [19] investigated the surface roughness by cutting Hardox-400 material with different machining parameters using a water-cooled torch at PAC. They stated that the cutting speed should be reduced to decreased surface roughness. They also mentioned that the required machining parameters (cutting speed 2100 mm/min, arc voltage 125 V and plasma gas flow rate 70 l/h) must be to obtain the minimum surface roughness. Skoczylas et al. [20] encountered rougher and more curved surfaces with increasing cutting speed and cutting current in their study. However, they reported that the smoothest surface (R_a = 1.27 μm) and less directional curvature were obtained in the machining where the cutting speed was 1200 mm/min, the cutting current was 60 A, and the gas pressure was 10 bar. Hatala et al. [21] determined from their experiments that the most important parameter affecting the surface roughness is the cutting speed and the least affecting parameter is the nozzle diameter. Chiarelli et al. [22] have conducted studies to investigate the fatigue properties of 8 mm thick Fe510D1 steel sheet by cutting it with both PAC and milling methods to obtain 40 mm wide fatigue test specimens. When milled and PAC cut samples were compared, it was observed that the fatigue strengths of PAC cut samples were almost equal to the milled samples.

A theoretical issue that has dominated the field for many years is artificial neural network (ANN). Radovanovic and Madic [23] conducted experimental studies for PAC modelling using ANN. For modelling, cutting operations were performed using different cutting speeds (0.33 and 2.8 m/min), different cutting currents (45 and 130 A) and workpieces of different thicknesses (4 and 15 mm). They determined from experimental studies that the surface roughness increases with the decrease in cutting current and increase in cutting speed and confirmed it with the ANN model. Hoult et al. [24] investigated the cutting performances of aluminium-based metal matrix composite sheet by cutting in the rolling direction. They concluded that the surface roughness increased by 25% in the right region, and the left side of the cut was twice as bad as the right side in terms of heat affected zone (HAZ) width and kerf angle. Similarly, Gostimirović et al. [25] found that the increase in cutting speed resulted in a larger kerf angle, a smaller kerf width, and a HAZ width of approximately 1 mm for all machining conditions. Also, Singh et al. [26] obtained the minimum kerf angle value (2.52 °) by machining 10 mm thick mild steel material with PAC at 1600 mm/min cutting speed and 7 mm torch-to-workpiece distance. Suresh and Diwakar [27] found that arc voltage had the greatest effect on WRR and surface roughness, while cutting speed had the smallest effect. Iida et al. [28] investigated the slag formed after cutting steel material with PAC at 125 A cutting current, 1000 mm/s cutting speed and 1.6 mm diameter nozzle. They used a high-speed video camera to observe the slag that formed during melting and the metal that adhered to the other side of the cutting zone. From video recordings, they determined that cutting speed is a more effective parameter than cutting current in slag formation. Naik and Maity [29] investigated the cutting performances of 10 mm thick Hardox-400 steel by machining it with PAC under the influence of four different plasma gases (air, argon, oxygen and nitrogen). In their experiments conducted at a plasma gas flow rate of 12 g/min, they determined that nitrogen, argon and air created sharper surfaces. Ferreira et al. [30] cut 15 mm thick QstE-380 alloy steel with PAC under different machining conditions to increase productivity and make cost analysis in PAC with response surface methodology. They stated that in order to increase productivity and surface quality, the cutting speed should generally be above 1800 mm/min, and the arc voltage should be kept as low as possible to keep the cost low. Masoudi et al. [31] found that increasing the cutting current increases the HAZ width, while high gas pressure and cutting speed decrease the HAZ width. Sharma et al. [32] determined that with the increase in gas pressure in PAC, the WRR initially decreases but increases after a certain value (68 psi). Sandeep et al. [33] found in their study that the cutting current and torch-to-workpiece distance values in the PAC affect the surface roughness in direct proportion. Muhamedagic et al. [34] stated that cutting speed is a more important parameter than plasma gas pressure for cutting quality and the best machining parameter values is 2500 mm/min for cutting speed - 6 bar for plasma gas pressure.

Hamood and Najm [35] discovered that although the machining parameters have direct effects on dimensional accuracy and machining time, the most affecting machining parameter is the cutting current. Adalarasan et al. [36] stated that in order to increase the surface quality, the cutting current should be reduced, the distance between the torch-to-workpiece should be reduced and the gas pressure should be increased. Kim and Kim [37] observed that the surface roughness increased with increasing cutting speed, and the surface roughness decreased with increasing cutting current, but the HAZ width increased. Begic et al. [38] observed that the top surface kerf width increased with increasing cutting speed, and the top surface kerf width and surface roughness decreased with increasing plasma gas pressure while the cutting speed was constant. Peko et al. [39] discovered that the cutting current has the most significant effect on the kerf width. Kountouras et al. [40] calculated the kerf angle by drilling 20 mm diameter holes in 6.5 mm thick St37 steel with PAC at variable parameters. They concluded that the kerf angle was affected by cutting speed, arc current and torch-to-workpiece distance by 19%, 59% and 16%, respectively. Zajac and Pfeifer [41] found that the cutting speed affects the surface quality, the cutting speed affects the kerf angle more than the cutting current, and the kerf angle value increases as the cutting speed increases.

Mentioning current applications of the PAC method, many old oil production facilities are currently being decommissioned. Removing underground pipes from abandoned oil wells and shutting down facilities is very important in terms of protecting the environment. In this conjecture, PAC has been preferred in cutting steel structures in oil facilities in recent years due to its low cost and high-speed precision cutting performance. Liu et al. [42] experimentally investigated the cutting of oil pipes by underwater plasma arc method. They used a workpiece composed of a steel plate and a cement block to simulate the oil casing pipe during the cutting process. Their experimental results revealed that optimizing the side air flow at constant cutting speed improved the slag emissions but reduced the kerf depth. They also stated that underwater plasma arc cutting could be a suitable method for extracting oil pipes.

In PAC, the characteristics of the plasma gas flow existing from the nozzle significantly affect the cutting quality. The high-pressure jet in the PAC creates complex shock wave structures as it is incident on the metal surface to be cut. In this area, Tuladhar et al. [43] used a computational fluid dynamics simulation model to analyse the effects of a curved cutting front on the gas flow behaviour during the PAC process. They observed that the curvature of the cutting fronts creates oblique shock wave structures that significantly reduce the flow velocity. Recently, studies on the effects of polarization have also been encountered in the PAC. Sidorov et al. [44] examined the phase compositions on the near-surface layers of Al-Mg, Al-Cu-Mg alloys and commercially pure titanium samples obtained by plasma cutting using direct current forward polarity (DCSP) and direct current reverse polarity (DCRP). They discovered that the "water mist" formed around the plasma jet during cutting of all types of materials with DCRP, results in more intense oxidation of the metal, less thermal impact on the material and reduced roughness of the cutting surface. Similarly, Grinenko et al. [45] investigated the structure and properties of the surface layers of AA5056 and AA2024 aluminium alloy plates with a thickness of 35 to 40 mm after DRCP plasma cutting. They stated that the alloy plate could not be cut to its full thickness under the reduced heat input condition with DCRP.

It is a fact that plasma flows under the workpiece are affected by machining parameters. Various variance analyses are performed to determine the significance of independent variables affecting the kerf geometry in the PAC process. For example, Tuladhar et al. [46] proved that the variables selected for PAC significantly affect the kerf length difference and the upper surface kerf width using the regression model they developed. The existing research fail to explain the magnetic effect on PAC. Especially, studies on magnetic re-limiting of plasma cutting arc particularly remain limited in the literature. To fill this gap in the literature, Liu et al. [47] comprehensively investigated the distribution of longitudinal magnetic field (LMF) for PAC with a combined simulation approach using Maxwell and ANSYS. They stated that the application of LMF can significantly increase the current density, temperature and uniformity of the plasma cutting arc and thus improve the cutting performance. Another research area for PAC is statistical data analysis. Hussain et al [48] used Taguchi orthogonal array design to investigate and optimize the PAC parameters. They stated that their current work can contribute to industrial practitioners by providing high efficiency, minimum material waste and reduction of stubborn resolidified metal buildup. They also reported that it can help them to select, to control and optimize PAC machining parameters to achieve excellent cutting quality.

In this study, comprehensive literature review on PAC was conducted and the cutting qualities of PAC were investigated using nine different types of experiment conditions (E1-E9) created with different cutting speeds (151, 214 and 217 mm/min) and different gas pressures (0.6, 0.7 and 0.8 MPa) on AISI304 stainless steel plates with thicknesses of 4 and 8 mm with the machining parameters determined from the experimental studies in literature. Kerf taper was determined by cutting AISI304 sheets into 30 mm long straight lines and cutting them into 30x50 mm rectangles to determine the cutting surface roughness values. Moreover, the plates were cut into straight lines of 100 mm length and the bottom surface burr formations and the top surface spatter formations were also examined.

2. Materials and Methods

Experimental studies were carried out on the AJAN brand CNC Plasma Arc Cutting machine, which is capable of cutting materials with a maximum size of 2000x12000 mm and a thickness of 40 mm, as shown in ▶**Figure 2**, at a maximum current of 260 A and an arc voltage of 171 V. AISI304 stainless steel sheets with dimensions of 950x730 mm and thicknesses of 4 and 8 mm were used as workpieces. Air was chosen as the plasma gas and nitrogen was chosen as the shielding gas. The torch was held in a perpendicular position relative to the workpiece and the distance between the two was set as 1 mm for each experiment. The nozzle diameter used is 1.2 mm. The equipment used in the torch is selected as follows: electrode E1, swirl ring SW2, nozzle N5, gas ring G1 and shield cup S3, depending on the type of material to be cut, the plasma gas used and the current at which the cutting process will be performed (▶**Figure 3**) [49].

Figure 2. AJAN brand PAC machine (during cutting of AISI304 sheets with thicknesses of 4 and 8 mm) [49]

In literature, because AISI304 steel plates were cut by the PAC method in the study of Bhowmick et al. [8], it was preferred the same machining parameters for our study. Three gas pressures (0.6, 0.7 and 0.8 MPa) were directly taken as reference from the study of Bhowmick et al. However, instead of the maximum cutting speed value (417 mm/min) used in Bhowmick et al. study's, the cutting speed value of 217 mm/min, which is closer to the cutting speed value of 214 mm/min, was preferred for our study. It can be said that the reason for this preference is to investigate the possible cutting quality results in cutting speed ranges closer to each other in our study. Because it is also known that surface quality will be negatively affected in thick plates at high cutting speeds. In addition, it is very difficult to observe the change in the kerf angle at very high cutting speed values. For each experiment, the current value was kept constant at 80 A and the arc voltage was kept constant at 120 V. As seen in ▶**Table 1**, nine different experiment conditions (E1-E9) created from machining parameters, 18 experiments were applied to 4- and 8-mm thick plates, and a total of 54 cuts were performed, with each experiment being repeated 3 times. ▶**Figure 4** shows the geometries and machined forms of the test samples prepared for experimental studies. As seen in ▶**Figure 4**.b, circles cut with a diameter of 40 mm were used in another study conducted by the authors of this study on circularity tolerance in PAC [49].

Table 1. Nine different experiment conditions created with machining parameters [8, 49]

Experiment No.	Cutting speed (mm/min)	Gas pressure (MPa)
E1	151	0.6
E2	214	0.6
E3	217	0.6
E4	151	0.7
E5	214	0.7
E6	217	0.7
E7	151	0.8
E8	214	0.8
E9	217	0.8

Figure 3. The equipment used inside the torch [49]

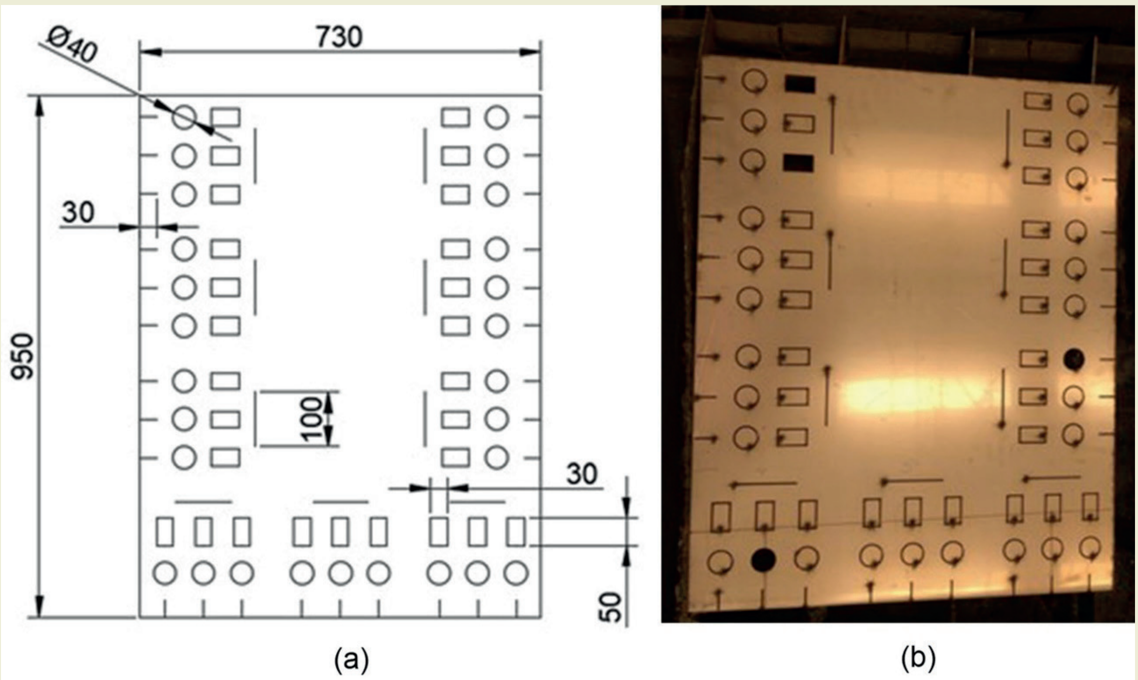

Figure 4. Geometries of the test samples: a) technical drawing and b) processed state with PAC [49]

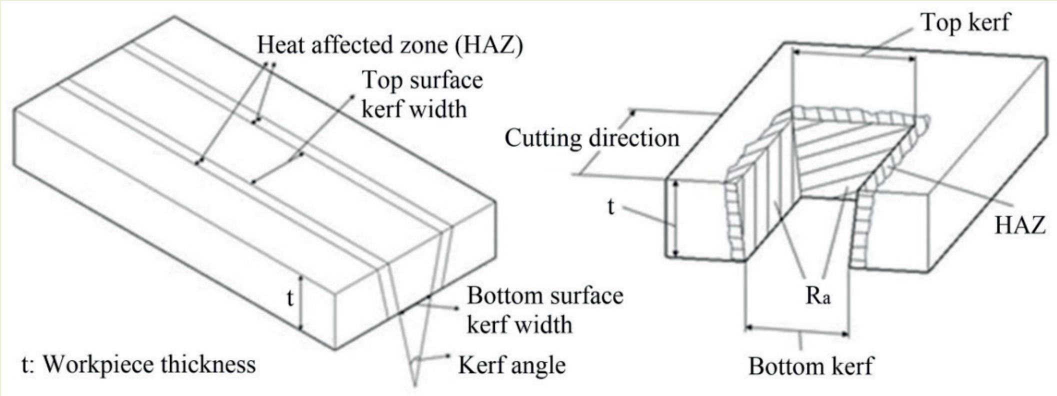

Figure 5. The schematic representation of the kerf taper angle

2.1. Calculation of Average Cutting Width (Kerf) Taper Angle

After cutting AISI304 sheets with thicknesses of 4 and 8 mm with PAC to create 54 straight lines of 30 mm length (▶**Figure 5**) using different experiment conditions (E1-E9), measurements were taken from 3 different areas (start-middle-end) of the lower and upper edges of the straight lines with the help of a digital calliper (GFB brand, 1/100 precision). The average cutting width taper angles were calculated by taking the arithmetic averages of the measurements with the help of E.1 [11].

$$The\ avg.kerf\ taper\ angle = \frac{(Avg.top\ margin - Avg.bottom\ margin) \times 180}{Workpiece\ thickness \times 2\pi} \quad (E.1)$$

2.2. Cutting Surface Roughness Measurements

AISI304 sheets with thicknesses of 4 and 8 mm were cut into rectangular shapes of 30x50 mm dimensions with PAC with different experiment conditions (E1-E9). Then, with the help of the MarSurf PS1 surface roughness measuring device shown in ▶**Figure 6**, measurements were taken from three different points from the 4 side cutting surfaces of each sample (a total of 12 different measurements for each sample) and the average R_a values were found by calculating the arithmetic mean. The measuring needle of the device used has a diameter of 2 µm, the pressure force is 0.7 mN and the measurement scan length is 5.6 mm. In surface roughness measurements, the sampling length was selected as 0.8 mm and the measurement length as 2.5 mm, taking Bozdemir's work [50] as reference.

2.3. Investigation of the Bottom Surface Burr Formation and the Top Surface Spatter Formation

100 mm length cutting was performed on 4 and 8 mm thick AISI304 sheets using experiment conditions (E1-E9) created with different machining parameters. During the cutting process (18 lines in total), burr and spatter formations on the bottom and top surfaces of the lines were visually examined and interpreted.

3. Results and Discussions

3.1. Kerf Taper Angle Measurement Results

It was observed that the upper and lower edges of the 30 mm long lines cut with different experiment conditions had different widths compared to each other. This situation is an inevitable result of the PAC method. In the PAC method, if the cutting speed is not adjusted to the appropriate value according to the material thickness, the desired tolerance for the kerf taper cannot be achieved. A total of 54 lines of 30 mm length cut from the plate of both thicknesses were used to calculate the average kerf taper angles using Equation 1. As seen in the graph in ▶**Figure 7**, the kerf taper angle increases as the cutting speed increases at constant pressure values in the machining of both 4 mm and 8 mm plates. When the cutting speed is constant, as the gas pressure value increases, the kerf taper angle value increases similarly. When the processes carried out under the same experimental conditions (E1-E9) were compared, it was determined that the kerf taper was greater in the 8 mm thick plate. Considering Equation 1, under normal

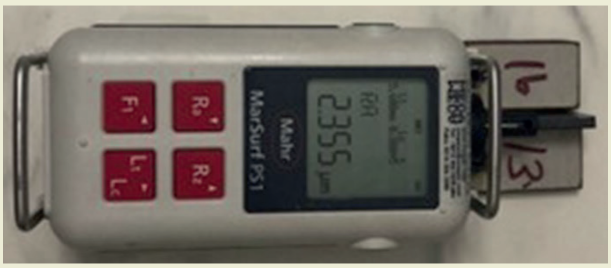

Figure 6. MarSurf PS1 surface roughness measuring device

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conditions, the kerf taper angles in 8 mm thick plates should be smaller due to the thicker material, but larger values were obtained. This finding was unexpected, and it was concluded that the reason for this situation was the fixed torch-to-workpiece distance (1 mm). Also, this constant parameter was thought to be insufficient for cutting an 8 mm plate. With this determination, it was concluded that the amount of thermal energy generated with the initially determined machining parameters was insufficient for the 8 mm plate and therefore the taper tolerance control could not be provided during cutting. In the cutting process (E1) performed with a gas pressure of 0.6 MPa and a cutting speed of 151 mm/min, the lowest average kerf taper value (0.32 °) was obtained on the 4 mm thick plate. In the E9 experiment condition where the gas pressure was 0.8 MPa and the cutting speed was 217 mm/min, the highest average kerf taper value (2.59 °) was obtained on the 8 mm thick plate. When the PAC experiments carried out with the experiment conditions of E1-E4-E7, E2-E5-E8 and E3-E6-E9 in both thicknesses were compared, it was concluded that the cutting speed is a more effective machining parameter than the gas pressure for the average kerf taper.

In the study of Gostimirovic et al. [25], a larger kerf angle and a smaller kerf width were obtained by increasing the cutting speed while the gas pressure was constant. This determination obtained for the cutting speed when the gas pressure is constant from the study of Gostimirovic et al. is parallel to our experimental study. When ▶Figure 7 is examined again, the kerf angle values increase when the cutting speed increases at constant gas pressure in both thicknesses of the plate. In the study of Begic et al. [38], it was concluded that the kerf angle decreased in experiments where the cutting speed was constant, and the gas pressure increased. In this context, the result of the kerf angle decreasing with the increase in gas pressure when the cutting speed is constant in the study of Begic et al. contrasts with this study. Also, as seen in ▶Figure 7, kerf taper angles increase with increasing gas pressure while the cutting speed is constant.

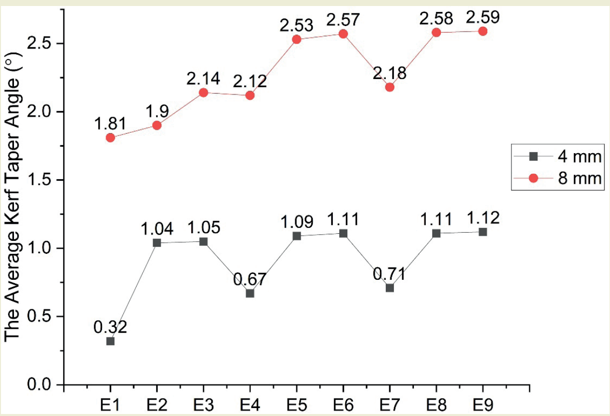

Figure 7. The average kerf taper angle values of lines cut on 4- and 8-mm thick plates

3.2. Roughness Measurement Results of Cutting Surfaces

In the machining of both plates, as the cutting speed increases at constant pressure values, the cutting surface roughness values increase (▶Figure 8). When the cutting speed is constant, R_a decreases as the gas pressure value increases. As the experiments carried out under the same experiment conditions on 4- and 8-mm thick plates were compared, rougher surfaces were observed on the 8 mm thick plate. As clearly seen in ▶Figure 8, the lowest surface roughness value (R_a = 24.12 µm) was obtained on the 4 mm thick plate in the cutting operation (E7) performed at a gas pressure of 0.8 MPa and a cutting speed of 217 mm/min. Moreover, in the E3 experiment condition where the gas pressure was 0.6 MPa and the cutting speed was 217 mm/min, the roughest surface was encountered on the 8 mm thick plate and the surface roughness value was obtained as (R_a = 31.65µm). As the PAC tests performed on the plates of both thicknesses in the E1-E4-E7, E2-E5-E8 and E3-E6-E9 experiment conditions were compared, it was concluded that gas pressure is a more effective parameter for R_a than cutting speed.

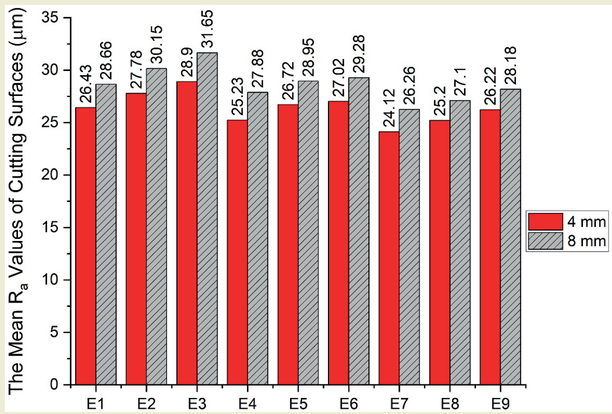

Figure 8. The mean R_a values of cutting surfaces of samples cut from 4 and 8 mm thick plates

With this study, many studies in the literature were identified in which similar results were obtained in terms of surface roughness values. For example, Bhowmick et al [8]. reported that gas pressure is the most effective parameter in terms of surface roughness. They concluded that with the increase of gas pressure, less roughness is encountered on the cutting surface. So, this finding is parallel to our experimental study. While the nozzle diameter used in the study conducted by Bhowmick et al. was 1.4 mm, the nozzle diameter used in our study was preferred as 1.2 mm. Since the nozzle diameter is narrower, the plasma arc is focused in a smaller area, which causes the melting process to occur relatively less. For this reason, although the same workpiece and the same machining parameters were used in both studies, larger surface roughness values were obtained in our study. In addition, it was concluded that another effect causing the difference between these two studies in terms of surface

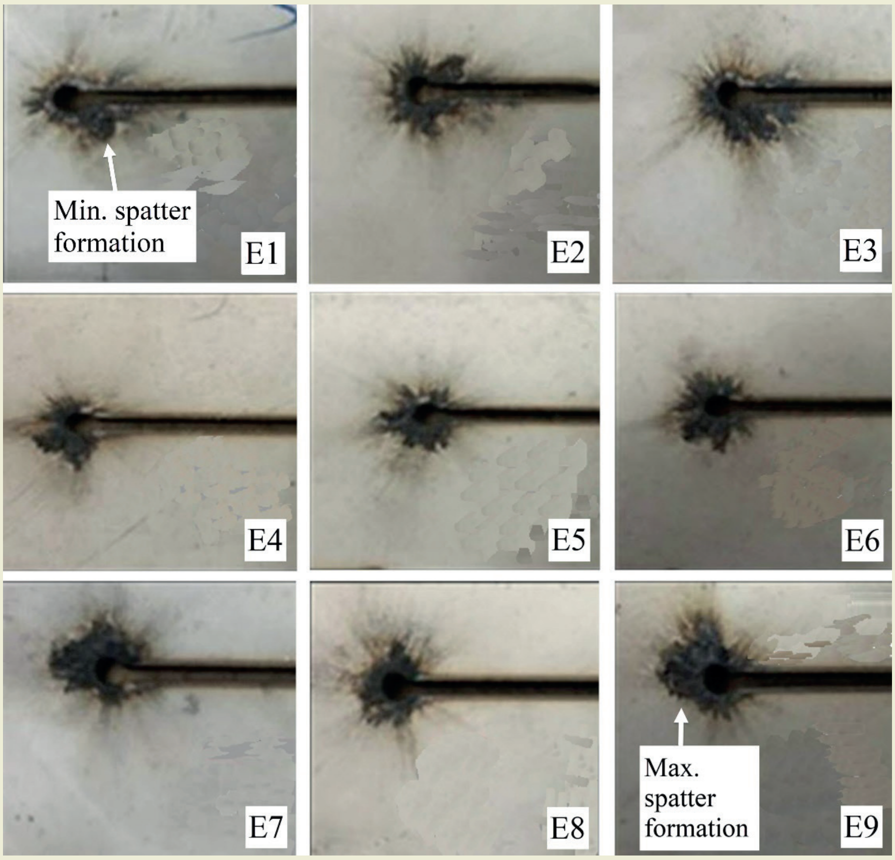

Figure 9. Top surface spatter formation after cutting on a 4 mm thick plate

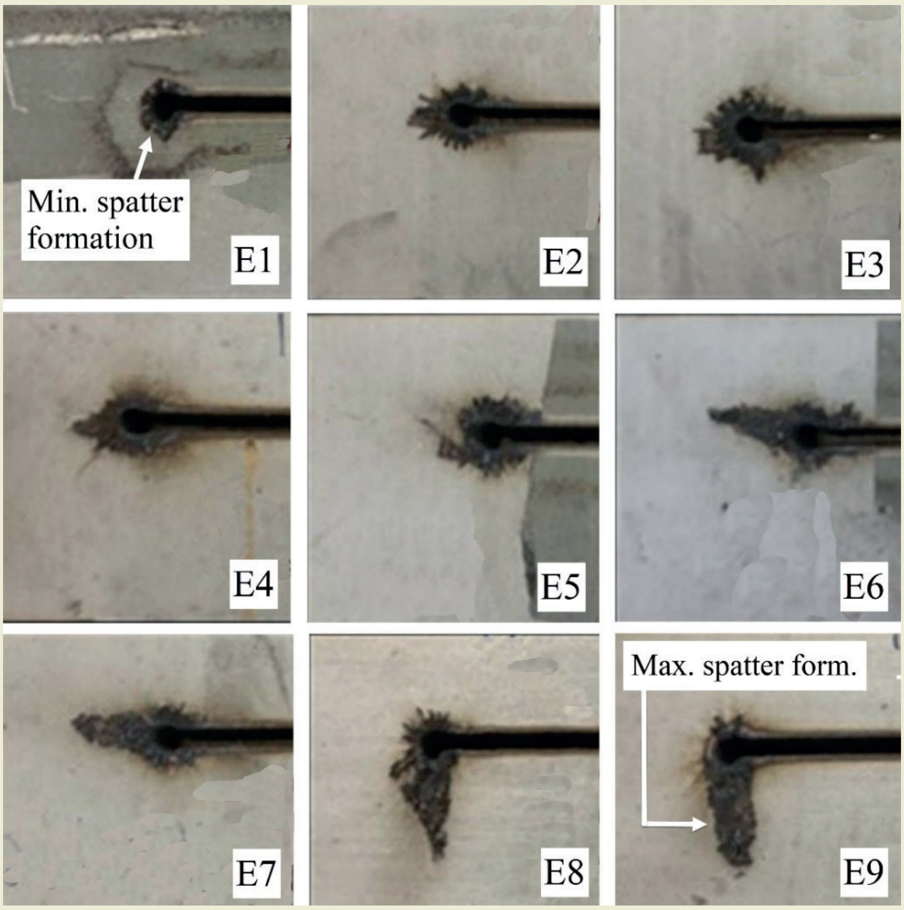

Figure 10. Top surface spatter formation after cutting on 8 mm thick plate

roughness was the electrical parameters. In our study, 80 A cutting current and 120 V open circuit voltage were used, while in the study of Bhowmick et al., 100 A cutting current and 300 V voltage were used. As can be understood from this point, Bhowmicks et al. obtained cutting surfaces with relatively lower rough surfaces than our surfaces by using high energy input (100 A and 300 V) at high cutting speed (417 mm/min). Because, with high energy input at high cutting speed, the molten metal was not allowed to solidify on the surface again. Thus, it is thought that by this mechanism they obtain lower surface roughness values.

Guatam et al. [14] reported that they obtained fewer rough surfaces at high gas pressure and low cutting speed. However, our study is fundamentally in contrast to the results of Das et al.'s study [18], which showed that a smoother and less rough surface was obtained in the experiment conducted at low gas pressure. Chamarthi et al. [19] also reported that they obtained smoother surfaces by reducing the cutting speed. Skoczylas et al. [20] observed that the roughness would increase with increasing cutting speed and decrease with increasing gas pressure. Both of their findings are clearly parallel to this study. Hatala et al. [21] stated that gas pressure has the greatest effect on surface roughness, considering this result, it can be said that their study is parallel to this study. Similarly, Gostimirovic et al. [25] reported that surface roughness increased with increasing cutting speed. Masoudi et al. [31] reported that they encountered the smoothest surface at low cutting speed and average gas pressure. In common, Adalarsan et al. [36] concluded that surface roughness decreases with increasing gas pressure. Likewise, Kim et al. [37] observed that surface roughness increased with increasing cutting speed.

Our study and the vast majority of studies in the literature show that surface roughness decreases as gas pressure increases and also that surface roughness increases as cutting speed increases. It is evaluated that when the plasma gas pressure increases at a constant cutting speed, shock waves will be formed due to the increase in the amount of gas transferred to the cutting zone per unit time, and the surface roughness will decrease because the resulting shock waves increase the molten metal flow rate and move away from the machining zone rapidly without allowing it to resolidify on the surface. Surface roughness increases when the cutting speed increases at constant plasma gas pressure. It is thought that the reason for this situation is the molten metal cools rapidly and resolidifies irregularly on the surface before the spraying operation is completed due to the fast movement of the torch.

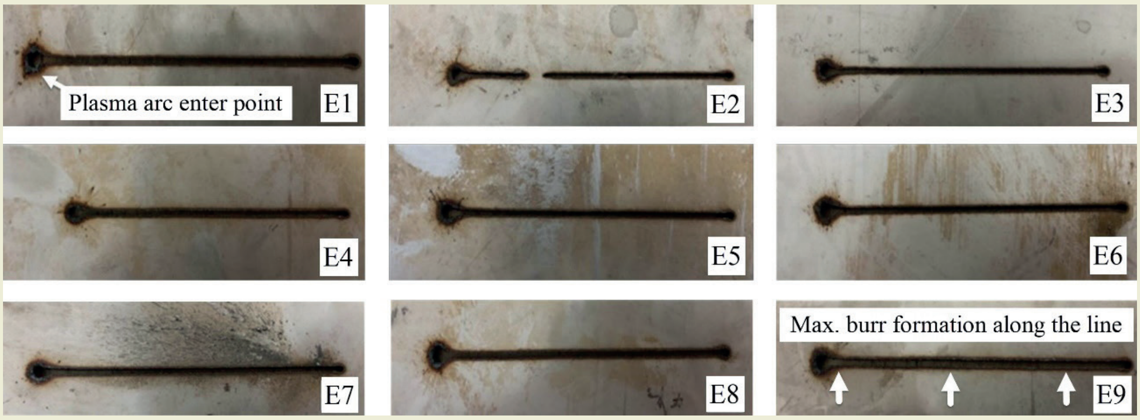

Figure 11. Bottom surface burr formation after cutting on a 4 mm thick plate

Figure 12. Bottom surface burr formation after cutting on a 8 mm thick plate

3.3. Results of Investigation of Bottom Surface Burr Formation and Top Surface Spatter Formation

When ▶Figure 9 and ▶Figure 10 are examined separately for both plate thicknesses, it is seen that top surface spatter formation relatively increases as the gas pressure is kept constant and the cutting speed increases (E1-E2-E3), (E4-E5-E6), (E7-E8-E9) and as the cutting speed is kept constant and the gas pressure increases (E1-E4-E7), (E2-E5-E8), (E3-E6-E9). The highest surface spatter formation in both plates was observed in the E9 processing type, which has the highest cutting speed and highest gas pressure. When the plates were compared with each other for the same experiment conditions, it was determined that the top surface spatter formation in the plates with 8 mm thickness was more and thicker.

When ▶Figure 11 and ▶Figure 12 are examined, it can be said that the bottom surface burr formation increases relatively as the gas pressure is kept constant and the cutting speed increases in 4 mm thick plates. It was found that when the cutting speed was kept constant and the gas pressure was increased, the bottom surface burr formation increased similarly to the top surface spatter formation. As the plates with both thicknesses were compared in the same experiment conditions, very small and less bottom surface burr formation was observed in the plate with 8 mm thickness compared to the plate with 4 mm thickness (▶Figure 12). According to the visual inspection for burr and spatter formations, it was concluded that the cutting lines in PAC processes were at an acceptable level in terms of burr and spatter formations. In this context, it was determined that lines along the cutting line were generally smooth in each experiment condition, except for the first entry and exit points of the plasma in the PAC process.

In the study of Ilii et al. [15], like our study, it was found that more intense burr and spatter formation occurred when the cutting speed was increased in the machining of plates of the same thickness with PAC. In addition, in the study of Ilii et al., it was determined that burr and spatter formations increased with increasing workpiece thickness in experiments carried out on workpieces with different thickness values at the same cutting speed. The increase in burr and spatter formation with increasing material thickness is not consistent with the results of our study.

4. Conclusions

This study has the feature of shedding light on industrial applications with the experimental data obtained. As a result of comprehensive research on key parameters (gas pressure and cutting speed), it can provide a reference for cutting austenitic steels used in industry with PAC. As a general result, it was found that machining parameters such as cutting speed, gas pressure, torch-to-workpiece distance and electrical parameters (voltage and current) directly affect output performances such as kerf taper and cutting surface roughness.

According to our experimental results, in the machining of both 4- and 8-mm AISI304 plates, the kerf taper increases as the cutting speed increases at constant pressure values. When the cutting speed is constant, as the gas pressure value increases, the cutting gap taper value increases similarly. In the machining of both plates, as the cutting speed increases at constant pressure values, the cutting surface roughness values increase. While the cutting speed is constant, the surface roughness decreases as the gas pressure value increases. For both plate thicknesses, it was observed that top surface spatter formation increased relatively as the gas pressure was kept constant and the cutting speed increased, and the cutting speed was kept constant and the gas pressure increased. As the plates with both thicknesses were compared in the same experiment conditions, very small and less bottom surface burr formation was observed in the plate with 8 mm thickness compared to the plate with 4 mm thickness. These findings emphasize the importance of considering the machining parameters before PAC operation and the appropriate machining parameters should be considered together according to the desired output performance.

Research Ethics

Ethical approval not required.

Author Contributions

Conceptualization: [Şerafettin Hırtıslı and Oğuz Erdem], Methodology: [Şerafettin Hırtıslı and Oğuz Erdem], Formal Analysis: [Şerafettin Hırtıslı and Oğuz Erdem], Investigation: [Şerafettin Hırtıslı and Oğuz Erdem], Resources: [Şerafettin Hırtıslı and Oğuz Erdem], Data Curation: [Şerafettin Hırtıslı and Oğuz Erdem], Writing – Original Draft Preparation: [Şerafettin Hırtıslı and Oğuz Erdem], Writing – Review & Editing: [Oğuz Erdem], Visualization: [Oğuz Erdem], Supervision: [Oğuz Erdem].

Competing Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Not applicable.

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