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ANALYSIS OF PROCESS PARAMETERS ON SPATTER AND DROSS IN PLASMA ARC CUTTING

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Abstract: Plasma arc cutting (PAC) process has advantages such as the ability to cut all electrically conductive materials and to cut various steel materials with medium and large thicknesses. It is also used in the cutting of high-strength structural steel with lower heat input and has a high cutting speed compared to the conventional machining process. In this present work, the spatter and dross formation on S275JR mild carbon steel with a thickness of 5 mm by plasma arc cutting were experimentally investigated. Cutting speed (1000 - 1500 min/min), arc current (90 - 110 A), and stand-off distance (2.5 – 4.5 mm) were selected as cutting parameters with three levels for each parameter. The gas pressure and nozzle diameter were kept constant at 6 bar and 1.5 mm, respectively. Following the completion of the PAC process, the observation and measurement of the spatter and dross were conducted using a digital microscope. The results showed that spatter formation was more prominent near the cut edge or kerf, especially when using a higher stand-off distance. As for the dross formation, the results show maximum length is 1.741 mm and the minimum height is 1.192 mm. Analysis of variance (ANOVA) method is employed to statistically analyse the results and shows the cutting speed and SOD are the most statistically significant. For minimizing dross formation, low arc current, higher levels of cutting speed and stand-off distance should be utilized.
Key words: plasma arc cutting, carbon steel, cut quality, spatter, dross, ANOVA.

1. INTRODUCTION

Plasma arc cutting (PAC) is a process that was expended as an alternative to traditional machining methods in order to improving or enhance the cut quality of end product. PAC process offers several advantages, such as the ability to cut all electrically conductive materials and various steel materials [1,2] with medium and large thicknesses. However, in order to melt and remove the material, PAC uses a high-velocity jet of ionized gas which has a maximum heat of around 33,000 °C and also known as plasma [3]. Compared to conventional machining processes, PAC also allows for cutting high-strength structural steel with lower heat input and at a higher cutting speed. PAC involves the creation of a plasma arc through the ionization of a gas, typically a mixture of gas, or compressed air. PAC is known for its capability to cut materials ranging from medium to thick [4] and it is the most cost-effective method available, and no cutting tool is required for the machining process [5].
Recent industrial in any manufacturing production is characterized by the need to meet customer and consumer satisfaction in terms of quality, range, availability, costs, as well as on-time delivery of products or services. This is because, most consumers have high expectations on products and services so they are more attracted to a good quality product that can compete on the international market. Furthermore, the current and future industrial systems should adapt to the demands of the markets. Additionally, the cutting process is an initial step of production in the manufacturing industries of a particular component or product are cutting process. One of the major issues that is common in PAC is the formation of dross on the cutting surface [3]. In PAC, the amount of dross formation on the worst side of a cut depends on the parameter setting i.e. cutting speed, arc current, and type of material [3, 6]. Dross in PAC can be characterized in terms of two specific speeds. At cutting on maximum speeds plasma jet does not cut through metal plate. At minimum speeds below the molten metal from the kerf sticks to the bottom of the plate, forming the so-called dross. Some of the molten metal does not leave the metal plate but sticks to the bottom, forming the so-called high-speed dross, which is tightly attached to the plate. In most cases, by reducing the cutting speed, it is possible to get rid of the high-speed dross [7]. However, the melted metal formed by low-speed dross cutting followed by the occurrence concave surface. The appearance of molten metal has the same effect when increasing power or decreasing the distance between the nozzle and cutting

objects. Due to this phenomenon, the practical countermeasures are removing part of the heat from the cutting zone which can be achieved by increasing the distance between the nozzle and the workpiece or reducing amperage.
Another major issue that occurred in PAC is spatter formation. On the top edge may appear a slag spatter, which refers to the creation of tiny molten metal droplets that are expelled from the cutting area. These droplets can land on the workpiece or surrounding surfaces, causing surface imperfections, and rough edges, and potentially affecting the quality of the cut. Spatter is undesirable in cutting operations as it can lead to increased post-processing requirements and reduced overall cutting quality. This phenomenon occurs at high speed, the large distance between the nozzle and the workpiece, if the nozzle is worn. Slag spatter may also arise from the whirling motion of plasma gas. Top spatter is caused by fast cutting or by too high a torch height setting. Reducing cut speed or lowering torch cutting height reduces top spatter and it is easy to remove. On the other hand, the penetrated material shows a larger spatter that discharges from the liquid metal when cutting thicker material using PAC [8]. This problem affected the quality and efficiency of the workpiece which requires careful attention to cutting parameters, torch maintenance, and material cleanliness to ensure high-quality cuts and efficient operation.
Key parameters in the PAC process include gas composition, gas flow rate, arc current, stand-off distance (SOD), cutting speed, and electrode configuration. Understanding and controlling these parameters is crucial for achieving the desired cut quality, minimizing material distortion, and maximizing cutting efficiency. The quality of the cut is typically evaluated based on criteria such as kerf width, dross formation, spatter, and surface roughness. It provides an in-depth exploration of PAC, covering various aspects, including the cutting process, principles, process parameters, materials, and cut quality considerations.
In this study, the spatter and dross formation generated in the cutting process of carbon steel using a plasma arc was experimentally carried out and a statistical analysis of variance (ANOVA) is performed to identify and evaluate the process parameters that are statistically significant. The cutting quality is required by obtaining to minimize spatter and dross formation that occurs on the cutting surface of the workpiece.

2. MATERIALS AND METHODS

The experiment was performed using a CNC plasma arc machine (ArcBro: Stinger 4400) as shown in Figure 1 with a maximum arc current and cutting speed of 120 A and 8000 mm/min, respectively. From the Figure 2, the workpiece is connected to the positive terminal of the power source while for the negative terminal of the power supply connected to the tungsten electrode. The gas pressure and nozzle diameter were kept constant at 6 bar and 1.5 mm, respectively.
The S275JR mild carbon steel (equivalent to BS EN10025) with a specimen workpiece of 5 mm thickness with dimension of 50 mm and 10 mm respectively was used in this study. As shown in Table 1, chemical composition of the specimen material has been specified. It contains a very low carbon since used for vast general and structural applications [9]. In addition, these materials are utilized in the manufacturing and structural application industries to create construction equipment. It is also used in the construction of pipelines for transporting liquids and gases. Its high strength and corrosion resistance make it suitable for use in pipeline construction. Its durability and strength make it suitable for use in building bridges, frames, and other structural projects. The unalloyed low carbon mild steel grade S275JR has good machinability despite having a low strength. S275JR also offers excellent high-temperature properties and includes great ductility [10].
The PAC process of the S275JR carbon steel is done by fixing the workpiece on the worktable of the plasma arc machine. The input parameters of PAC were three-levelled cutting speed (v), arc current (I), and stand-off distance (SOD) as tabulated in Table 2. A full factorial design-of-experiment (DOE) that requires 27 cutting conditions was performed with three replications for each condition.

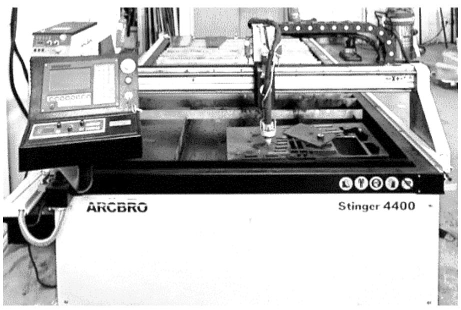


Fig. 1. CNC plasma arc machine

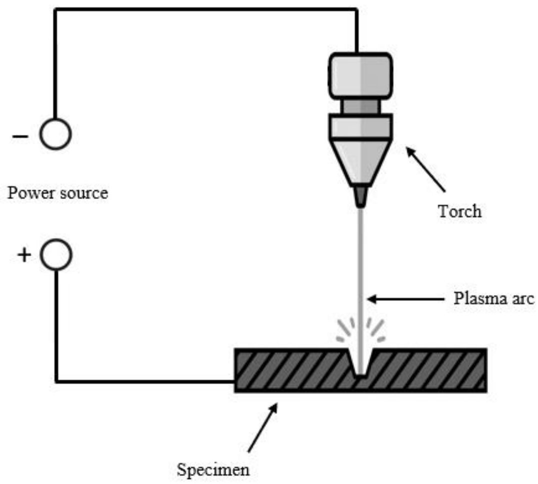


Fig. 2. Schematic diagram of experimental setup

Table 1. Chemical composition of S275JR mild carbon steel (in wt.%)

C	Si	Mg	K	S	Fe
0.25 max	0.05 max	1.6	0.04	0.05	Balance

Table 2. PAC parameters and their levels

Process Parameter	Level		
	1	2	3
Cutting speed, v (mm/min)	1000	1250	1500
Arc current, I (A)	90	100	110
Stand-off distance, SOD (mm)	2.5	3.5	4.5

The output variables were the observation of spatter and measurement of dross formation using a digital microscope, which is measured between the cutting line with the spatter and dross formation that occurred during cutting. In this experiment, the optimal microscope Dino-Lite Edge was utilized to conduct the measurement of the dross and spatter formation that occurred on the cutting line. The measurement involved capturing the dross height readings and collecting corresponding data using Dino Capture 2.0 software with 20x magnification and resolution up to 2560 x 1920 without compression. At the edge of a cut, the re-solidified metal forms dross. The observation of spatter refers to the tiny molten droplets or particles of metal that are expelled from the workpiece during the cutting process. This optimal microscope was able to check the surface quality of the specimen workpiece.

3. RESULTS AND DISCUSSION

Figure 3 shows the cutting line which uses different cutting speeds with the constant arc current which is 90 A and constant 2.5 mm of SOD, respectively. The result shows the higher cutting speed which is 1500 mm/min showing the cutting line without the occurrence of spatter. It also improves the molten metal removal from the kerf, reducing the likelihood of the spatter being ejected from the cut. Besides that, the arc contacts the workpiece for a shorter period when using a higher cutting speed and it also helps to maintain a more stable and controller cutting process. Figure 4 shows the cutting line which uses different arc currents with a constant cutting speed which is 1500 mm/min and a constant 3.5 mm of SOD resulting in all cutting lines without the appearance of a spatter. Arc current plays a crucial role in PAC as the arc current affects the stability of the plasma arc. A stable arc is less likely to produce a spatter compared to an unstable arc. Moreover, the temperature and energy of the arc influence the arc current which helps to maintain a stable arc. However, Figure 5 shows different SOD with a constant cutting speed of 1000 mm/min and a constant 90 A of arc current, respectively. It shows lower SOD that creates more spatter. The cutting line shows the occurrence of spatter and without spatter formation from that captured by the optical microscope during the observation.

The spatter formation is influenced by the parameter setup. When spatter formation is minimal or without spatter occurring, the cutting quality tends to be higher as shown in SOD 3.5 mm most of the samples of the cutting line are without spatter formation graph as shown in Figure 6. Nevertheless, the higher SOD more challenging to maintain a precise focus of the plasma arc on the workpiece specimen. Due to the lack of focus, it tends to result in uneven cutting and increased spatter formation formed. Besides that, with higher SOD, more heat is dissipated before reaching the workpiece specimen which resulted in insufficient heat for clean cutting, leading to increasing spatter formation.

v = 1000 mm/min v = 1250 mm/min v = 1500 mm/min

Fig. 3. Spatter condition (top view) under different cutting speeds (I: 90 A, SOD: 2.5 mm)

I = 90 A I = 100 A I = 110 A

Fig. 4. Spatter condition (top view) under different arc currents (v: 1500 mm/min, SOD: 3.5 mm)

SOD = 2.5 mm SOD = 3.5 mm SOD = 4.5 mm

Fig. 5. Spatter condition (top view) under different stand-off distances (I: 90 A, v: 1000 mm/min)

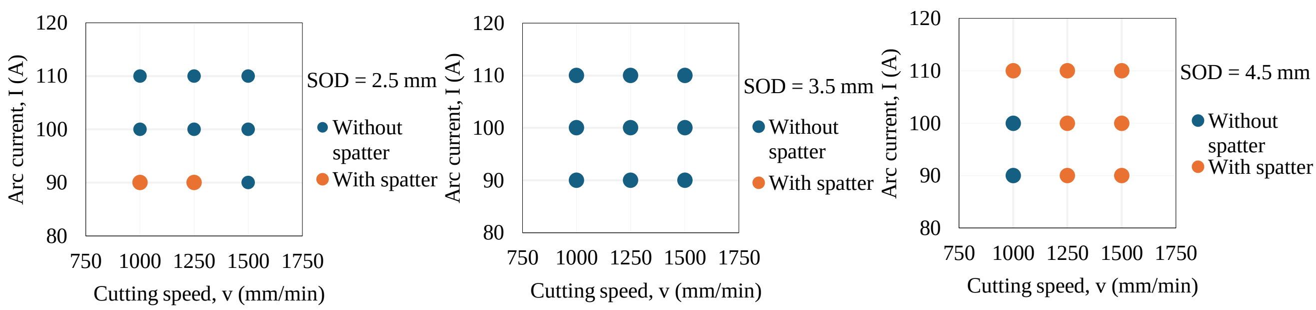
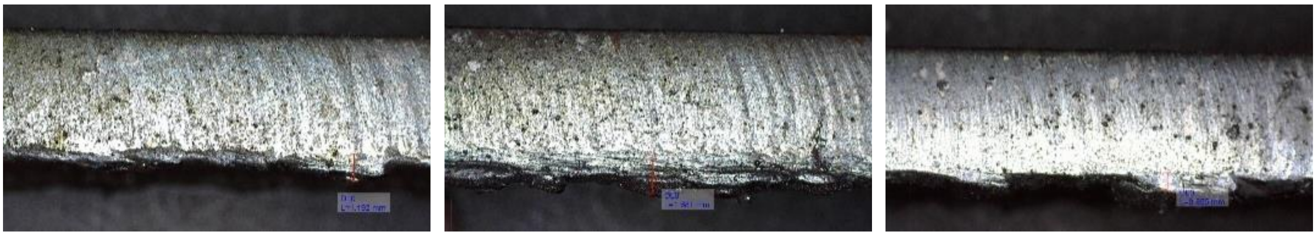


Fig. 6. Spatter formation under different cutting parameters

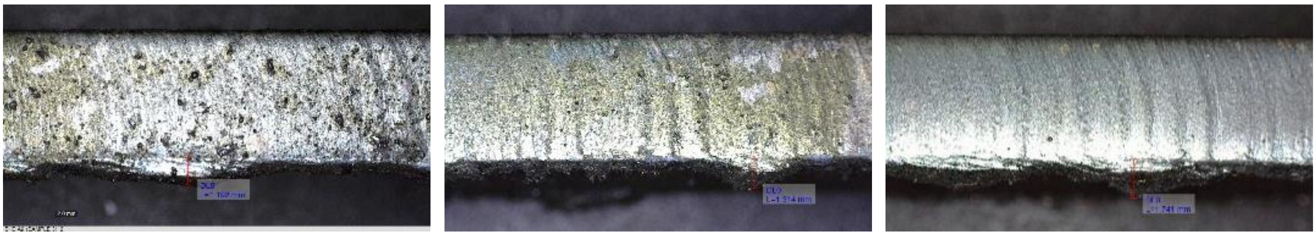
The result of dross as shown in Figure 7 the different cutting speeds of 1000 mm/min, 1250 mm/min, and 1500 mm/min of cutting speed with the constant arc current which is 90 A and constant 4.5 mm of SOD. The average dross has been measured and resulted in the higher cutting speed reducing dross formation while the lower cutting

speed tends to produce large dross formation. Moreover, to achieved high-quality cut is possible within the range of cutting speed that can be observed during the experiment that has been conducted. On the other hand, a higher dross formation occurred when the uses of a higher arc current which possibility generates more heat as shown in Figure 8 with increasing heights of 1.192 mm, 1.314 mm, and 1.741 mm, respectively. This is because the high arc current can lead to increased melting of the workpiece specimen. This excessive heat can cause the molten metal to flow freely then leading to the formation of dross on the bottom edge of the cut. Moreover, higher arc currents can sometimes lead to instabilities in the arc, such as arc wandering or fluctuations in arc length. These instabilities can cause uneven heating of the workpiece, which can contribute to uneven dross formation. It is different with the increase of SOD in PAC as shown in Figure 9. Higher SOD helps to maintain the stability and controlled arc which led to more consistent heat distribution. It also helps to prevent excessive melting and dross formation on the bottom edge of the cut. Besides that, the plasma arc has to travel longer distances to reach the workpiece when using higher SOD. This can lead to some dissipation of heat before the arc reaches the material, reducing the overall heat input. Lower heat input can result in less melting and reduced dross formation.
Figure 10, the graph typically shows the impact of different cutting parameters on dross formation, and the trends observed. As the increasing of the cutting speed and the higher 4.5 mm SOD, the graph initially shows a decrease in dross formation which the average dross measurement has been taken from the multiple experiments using same parameters. The increasing of both parameters tends to prevent prolonged exposure to the molten material. As a consequence, it is also preventing the formation of dross. Hence by increasing the cutting speed toward optimum value, dross formation decreases continuously. Moreover, it can be observed from the other graph that using different SOD parameters which are from 2.5 mm, 3.5 mm, and 4.5 mm. The graph shows lower SOD tends to spread out which helps increase the formation of dross even using the higher cutting speed.



v = 1000 mm/min | v = 1250 mm/min | v = 1500 mm/min

Fig. 7. Dross height (side view) under different cutting speeds (I: 90 A, SOD: 4.5 mm)



I = 90 A | I = 100 A | I = 110 A

Fig. 8. Dross height (side view) under different arc currents (v: 1500 mm/min, SOD: 4.5 mm)

SOD = 2.5 mm | SOD = 3.5 mm | SOD = 4.5 mm

Fig. 9. Dross height (side view) under different stand-off distances (I: 90 A, v: 1500 mm/min)

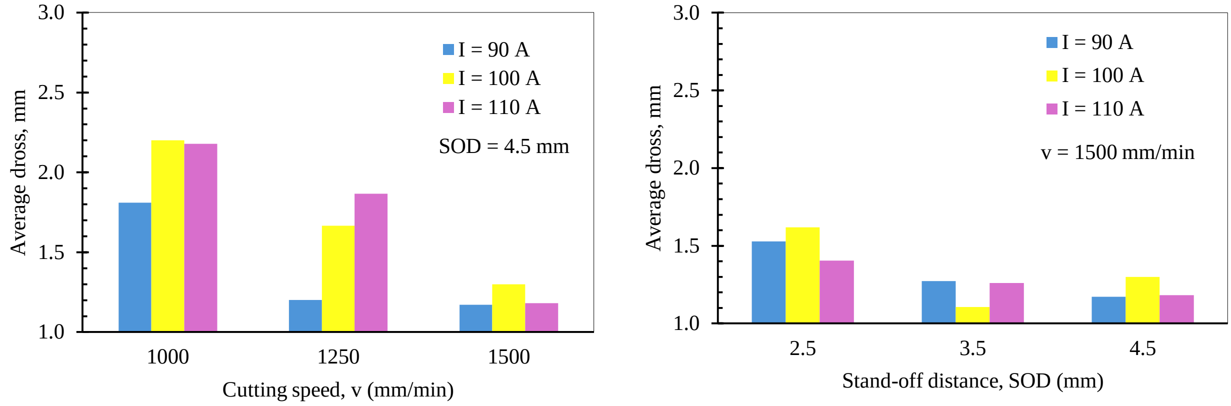


Fig. 10. Effect of cutting parameters on dross

On the other hand, ANOVA was performed for which to evaluate the statistical significance of the selected independent variables that affect the appearance during cutting processes for dross formation. The ANOVA result for average dross formation at 95% confidence level as shown in Table 3. It is observed that the cutting speed has the most influencing parameter on dross formation with a P-value 0.000 with the highest contribution 68.32% follows by P-value for SOD which is 0.036 with 7.58% contribution and it is statistically significant for both parameters since it is below 0.05. While the arc current shows P-value 0.102 which is statistically insignificant.

Table 3. Analysis of variance (ANOVA)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting Speed	2	2.6135	68.23%	2.6135	1.30674	35.44	0.000
Arc Current	2	0.1892	4.94%	0.1892	0.09460	2.57	0.102
Stand-off Distance	2	0.2903	7.58%	0.2903	0.14517	3.94	0.036
Error	20	0.7374	19.25%	0.7374	0.03687		
Total	26	3.8304	100.00%				

Figure 11 shows the main effects of PAC process parameters on dross formation which cutting speed, arc current, and SOD. By increasing the cutting speed from 1000 mm/min to 1500 mm/min significantly reduces dross, help minimize molten metal accumulation as shown in the first graph. The second graph that increasing arc current from 90 A to 110 A results in slightly higher dross formation as the higher currents contributes to more dross. While for the third graph, optimal SOD needed for reducing dross formation during cutting process.

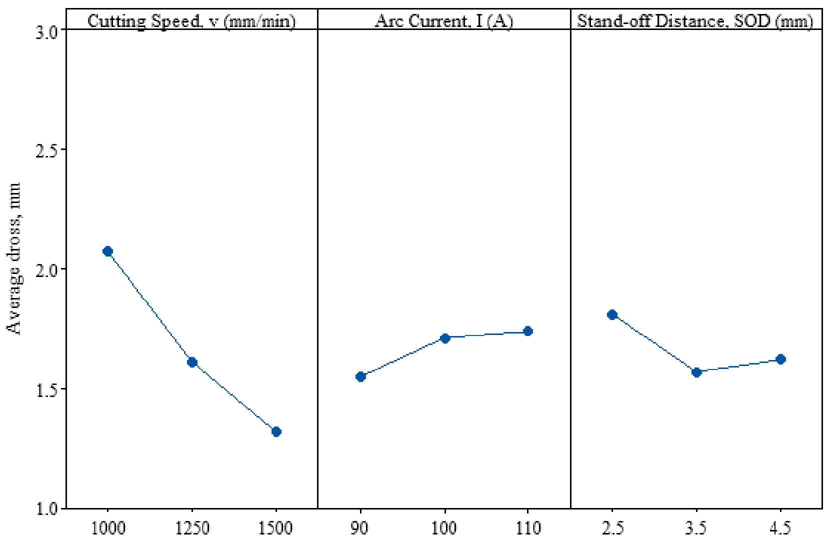


Fig. 11. Plots of main effect of PAC process parameters on dross

4. CONCLUSION

The PAC methods on S275JR mild carbon steel successfully minimized the spatter formation with minimum cutting speed, arc current, and SOD of 1500 mm/min, 100 A, and 3.5 mm, respectively. The minimum cutting speed is required to achieve the desired cut quality while minimizing spatter formation. The arc current is sufficient to maintain a stable and effective plasma arc. For SOD, maintaining the optimal plasma arc length is crucial in ensuring effective cutting without excessive spatter occurred. Dross formation in cutting line could be effective under higher cutting speed, arc current, and SOD with 1500 mm/min, 90 A and 4.5, respectively which small or minimizing dross can be obtained. From the ANOVA, it confirms that cutting speed and SOD is the most statistically significant factor with P-value <0.05 which influence dross formation, while arc current, though influential, are not statistically significant within the studied parameters. For spatter formation, ANOVA not been used in this study as there is no numerical value. Overall, achieving a balance between cutting speed, arc current, and SOD is key to optimizing cutting quality and minimizing defects like spatter and dross. The experiment successfully revealed the effectiveness of various parameters in minimizing dross and spatter formation during plasma arc cutting. Significant reductions in dross and spatter were accomplished by making systematic modifications to cutting speed, SOD, and arc current. These findings underscore the importance of parameter optimization in enhancing the efficiency and quality of plasma arc cutting processes, offering valuable insights for further improving industrial cutting operations.

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