PLASMA ARC CUTTING – REVERSED SWIRL RING, ELECTRODE THREAD AND CUT DIRECTION EFFECTS ON KERF GEOMETRY

S. Chabert[a,b,*], J.J. Gonzalez[a], P. Freton[a]

[a] *Laboratoire Plasma et Conversion d'Energie, Université de Toulouse, CNRS, INPT, UPS, 118 route de Narbonne,3106 2 Toulouse CEDEX, France*

[b] *Gys SAS, 1 Rue de la Croix des Landes, 53940 Saint-Berthevin, France*

[*] chabert@laplace.univ-tlse.fr

Abstract. Plasma arc cutting is used to cut any conductive material. It consists in blowing pressurized gas and feed current to an arc, leading to a thin plasma dart able to melt the material down and blow it away, creating a kerf. Its quality depends on its shape. This paper shows, through experimental measurements, how the inner geometry of the torch can affect the cut quality. It appears that one side of the kerf is much more oblique and sensitive to factors variation than the other. A theory based on a computational fluid dynamics model is proposed to investigate the causes of these phenomena.

Keywords: Plasma arc cutting, air plasma, cutting quality.

1. Introduction

The torch under study is an AT-125 torch from the Toparc brand. It can withstand direct currents up to 125 A. It uses compressed air as both the plasma and shielding gas. Its components can be seen in Figure 1. The cathode (which is referred as electrode in this paper as per industrial standards), which has a thread and the swirl ring, which blows air tangentially, break the torch axisymmetrical layout. The tangential air injection is aimed at constricting the plasma jet. There is a backward flow that passes into the electrode thread. In plasma arc cutting, one side of the kerf always displays a side straighter than the other. In previous unpublished work, it has been noticed that changing the electrode rear part with a cylinder drilled with holes spread in a circular manner (instead of the usual thread) led to more symmetric kerfs.
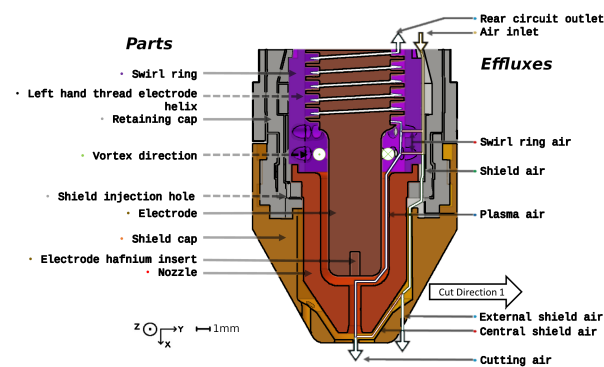

Figure 1. AT-125 torch components

This paper pushes the investigation further with regards to torch geometry's effects on cut quality. Prototypes electrodes with reversed thread and swirl rings with opposite tangential injection have been made (Figure 2).
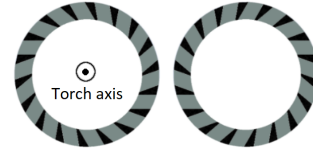

Figure 2. ZY Cut plane of the original and prototype swirl rings

Cut direction has also been investigated. This gives three parameters, namely thread direction, injection angle and cut direction, which effects have been studied comparatively through a Taguchi's [1] design of experiments. This method allows to study the effects of the parameters and their interactions (synergy).

2. Experimental Setup

The cuts were performed on 4 mm thick S355 steel plates (used as anodes). The torch is moved by a Computer Numerical Control (CNC) Autotec cutting table. The used generator is a Gys Neocut105. All over the experiment, cutting voltage is regulated through CNC height control at 160 V, while the cutting speed is set at 1 m/min.

The cut kerfs are parallel lines cut either in one direction or its opposite, later referred as Direction 1 (Figure 1) and Direction 2.

After the plasma kerfs are made, the plate is cut perpendicularly to them with a band saw in order to have a profile observable with a microscope.

3. Measurement protocol

The measurements are performed with a Keyence VHX-6000 microscope and its embedded measurements tools. The precision is 10 μm. Measurements have been made according to standard ISO9013.
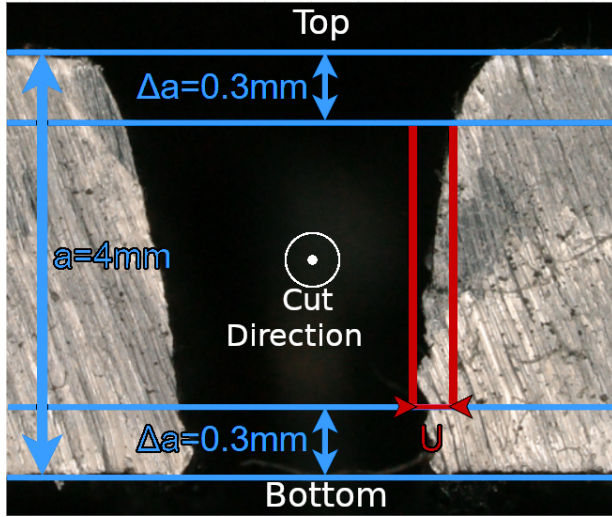
Figure 3. Kerfs bevel measurement as per ISO9013 standard - Only left side measurement shown

Figure 4. Average difference between U on the left and right side of each kerf

Figure 3 shows one side of a kerf and the measured values according to ISO-9013 standard. From the standard, $\Delta a = 0.3$ mm because the plate thickness is $a = 4$ mm. U (taken on each side of the kerf) is the value this paper focuses on and quantifies the oblicity (bevel) of the kerf. With regards to Taguchi's method, this is the studied response.

3.1. Design of Experiments

The experiments were conducted by varying the factors as seen in Table 1. For each line of this table, three kerfs were made, measured as explained previously and the results were averaged (side by side) to limit results scattering.

4. Experimental results

The overall results (for both sides) range from 100 to 700 µm. Standard deviation is 52 µm for the left edges and 65 µm for the right edges. In this paper, references to "right" and "left" reference for the edges of a kerf are taken with respect to the torch's direction 1 (torch direction 1 is forward and the kerf is left behind).

4.1. 5 bar 105 A trials

A full 3 factors - 2 levels design was employed, wherein each combination of factors at all levels was executed, resulting in a total of 8 experiments ($2^3 = 8$). These correspond to the first 8 rows of Table 1.

4.1.1. On the left side of the kerfs

On the left sides, nor the studied parameters nor their interaction has any measurable effect on the bevel angle. These sides remain very straight and display an average U of 151 µm for the 5 bar 105 A trials. They are also very consistent as their standard deviation is 15 µm.
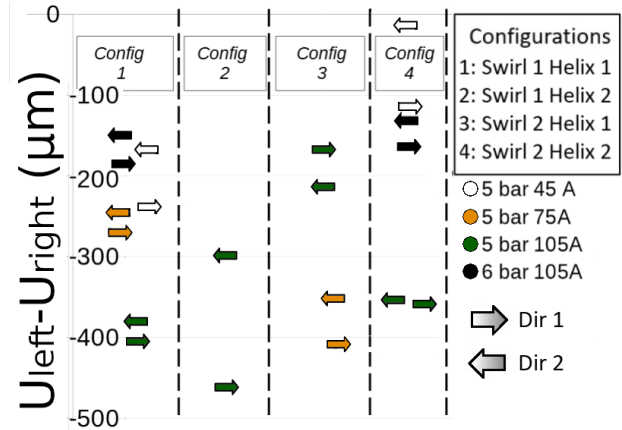
4.1.2. On the right side of the kerfs

The right sides are much more oblique and much more sensitive to the parameters variation and their interactions. For the 5 bar 105 A trials, on the right sides, U spreads from 341 to 591 µm with an average of 481 µm and a 91 µm standard deviation. The calculated effects are given in Table 2.

As per Taguchi, this is the effect that the parameters or their interaction have on the response (U). It can be seen that a left hand thread electrode (electrode 1), a $-30°$ swirl ring (swirl ring 2) and cutting direction 2 lead to straighter right sides of the kerfs (negative effect on U). Also, the effects of the electrode helix and of the swirl ring injection angle interacts together (but the helix-cut direction and swirl-cut direction interactions are negligible and thus not displayed in Table 2). Electrode 2 and swirl ring 1 lead to even straighter right sides when used together.

4.2. Varying pressure and currents trials

More tests were conducted with variable pressure and current. Not all configurations were studied (Table 1).

Let us recall that more vertical edges on the left were consistently observed over the experiment. Therefore, representing only the difference between the U values of the left and right edges for each case provides interesting information about these results, as is seen in Figure 4. A value close to zero indicates a rather symmetrical kerf, while a highly negative value corresponds to a strongly asymmetrical kerf.

First, the cutting direction effect is low but steady except for configuration 3: the kerfs are a bit more symmetrical with cutting direction 2. It can be seen easily on Figure 4 because the left pointing arrows are above the corresponding right pointing arrows.

About the configuration 1 and 4, for which the most data are available:

1. Decreasing current from 105 to 45 A at steady pressure makes kerfs more symmetrical

2. Increasing pressure from 5 to 6 bar (at 105 A) also tends to make kerf more symmetrical

Set number	Swirl (°)	Electrode thread	Pressure (bar)	Current (A)	Cut direction
1	30 (level 1)	Left (level 1)	5	105	1 (level 1)
1	30 (level 1)	Left (level 1)	5	105	2 (level 2)
2	30 (level 1)	Right (level 2)	5	105	1 (level 1)
2	30 (level 1)	Right (level 2)	5	105	2 (level 2)
3	-30 (level 2)	Left (level 1)	5	105	1(level 1)
3	-30 (level 2)	Left (level 1)	5	105	2 (level 2)
4	-30 (level 2)	Right (level 2)	5	105	1(level 1)
4	-30 (level 2)	Right (level 2)	5	105	2 (level 2)
5	30	Left	6	105	1
5	30	Left	6	105	2
6	-30	2	6	105	1
6	-30	2	6	105	2
7	30	Left	5	75	1
7	30	Left	5	75	2
8	-30	2	5	75	1
8	-30	2	5	75	2
9	30	Left	5	45	1
9	30	Left	5	45	2
10	-30	2	5	45	1
10	-30	2	5	45	2

Table 1. Design of experiment

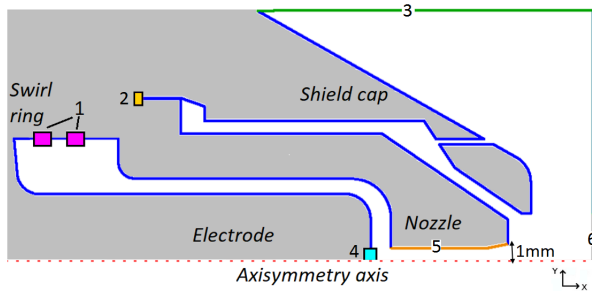| Simple effect	Level 1	Level 2	Helix-Swirl Interaction		
				Swirl 30°	Swirl -30°
Helix	-29	29			
Swirl	49	-49	**Left hand helix**	48.3	-48.3
Cut direction	18	-18	**Right hand helix**	-48.3	48.3

Table 2. Effects of the parameters on the right side given in µm

Figure 5. 2D model domain and boundary limits - non indexed walls all share the same settings

These phenomena led us to a theory that is exposed in section 7 (Discussion) and that is supported by the use of a numerical model that is presented in the following sections.

5. The numerical model

The numerical model, we used runs on Fluent represents the torch in a limited domain meshed with 17k cells and represented in Figure 5 along with the boundaries. The model is described as follows:

1. Mathematical method: Finite Volume Method solved with user defined function to take the electromagnetic values into account and to calculate the source terms of the energy and momentum equations (Joule effect, Laplace forces).

2. Geometry: The model is 2D axisymmetrical (with swirl) and as a consequence, cannot consider the helix of the electrode nor the torch movement. The injections hole of the swirl ring have been replaced by an equivalent section full ring. The backwards flow is not represented but the effluxes in the other circuits met experimental accordance. No solid is meshed and only the fluid zone is resolved.

3. Hypothesis: The model is time-steady (no arc fluctuations), the flow is laminar, the radiation is taken into account through the Net Emission Coefficient method, no matter is ablated from the solid parts. A porous anode is used that cannot describe electric current flowing to the anode workpiece. Current is injected at the electrode head with a uniform profile over the surface of the boundary. No slip condition (speed = 0) on every wall.

4. Initialization: The current is fed into the simulation after the plasma zone has been patched to 10k°C to bring sufficient level of conductivity.

I	P	Q nozzle	Z momentum
105 A	4.3 bar	0.64 g/s	13 kg.m²/s
75 A	4.3 bar	0.75 g/s	16 kg.m²/s
105 A	6 bar	1.15 g/s	25 kg.m²/s

Table 3. Simulation cases and results

5. Equations: Navier Stokes equations, scalar potential (with porous anode) and vector potential (closed by Biot & Savart [2]) are solved.

The boundary conditions (Figure 5) are:

1. Swirl ring injection (pressure inlet): fed air under 4.3 bar at 25°C with a 30° angle of swirl injection. Experimental and numerical accordance with regards to the flow rates is reached for 4.3 bar simulated at the swirl ring injection (5 bar experimentally set but pressure drops in the hose).

2. Shield air injection (pressure inlet): 4.3 bar, 25°C

3. Ambient (pressure outlet): 1 bar, 25°C

4. Electrode head (wall): Uniform current profile, 2220°C (melt of the hafnium)

5. Nozzle channel (wall): Resolving Biot and Savart

6. Kerf (pressure outlet): Scalar potential value is 0 V. This the porous anode.

7. Unindexed walls temperature is set at 25°C.

6. Model results

Three simulations have been run with the same parameters except for the current and the swirl injection pressure. These parameters and results of interest are displayed in Table 3, where P is the input pressure, Q_{nozzle} the mass flow rate and Z momentum is azimuthal. Figure 6 shows the swirl (Z) momentum field. Its shape remains the same in every case, but not its range. Z momentum (Table 3) is taken at point A.

Decreasing the current reduces the (viscous) arc width, allowing more air to flow around the plasma jet. Increasing the injected pressure also forces more air into the plasma jet fringes. In both cases this leads to higher mass flow rates.

The swirl component of the flow could lead to assymetrical results, because the kerfs are open behind (with regards to torch movement) the torch and closed before the torch. As a result, air hitting the kerf might leave it immediately if the swirl effect bring it outwards. However, on the opposite side, the swirl effect shall bring the flow inward onto the molten metal: the air flow encounters different conditions depending on the angular position around the plasma jet where it its the plate. As a consequence, the swirl momentum might be held responsible for (part of) the assymetry.
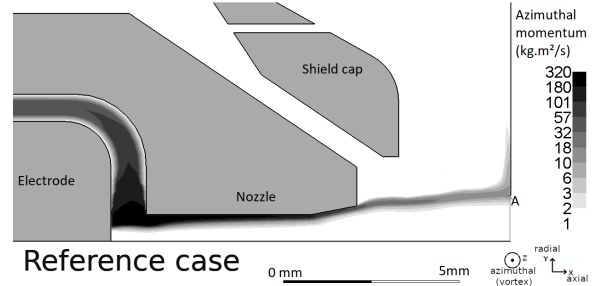

Figure 6. Azimuthal momentum field - Reference case

7. Discussion

1. Experimentally : Decreasing current or increasing pressure makes kerfs more symmetrical

2. From the model : Decreasing current or increasing pressure leads to higher flow rates and noticeably swirl momentum in the plasma jet

As a result, it might be suggested that:

1. Higher flow rates make kerfs more symmetrical. This could be because of a lack of momentum axial symetry in the plasma that gets overriden at higher global flow rates (high flow rate lead to straighter kerfs).

2. Higher swirl momentum make kerfs more symmetrical. This sounds conflicting with the phenomena given as conclusion of previous section. However this could also be explained by some flow angular assymetry in the plasma flow that would get smoothed by higher swirl momenta.

8. Conclusion

The reasons for the kerfs assymetry in plasma arc cutting are not yet explained. This paper suggests the shape of the inner torch parts has an impact on the kerfs. Besides, the electrode helix and swirl ring angle interact with each other. However, the model presented in this paper is 2D axisymmetrical and thus cannot represent this. Cut direction also shows some noticeable yet not predominant effect on kerfs. However, every kerf in this paper showed much straighter left sides regardless of the set of parameters, so other factors that remain yet to discover may be provoking this phenomenon. Especially any assymetry in air efflux even upstream the plasma jet and its relation to swirl ring and helix should be investigated.

Acknowledgements

References

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[2] P. Freton et al. Magnetic field approaches in dc thermal plasma modelling. *J. Phy. D: Appl. Phys.*, 44(34):345202, 2011. doi:10.1088/0022-3727/44/34/345202.