Experimental investigation of magnetic arc blow in plasma arc cutting

10.1007/s40194-014-0177-0

Experimental investigation of magnetic arc blow in plasma arc cutting

Yamaguchi Yoshihiro [1,*]

Email yoshihiro_yamaguchi@komatsu.co.jp

Katada Yusuke [1]

Itou Takeru [1]

Uesugi Yoshihiko [1]

Tanaka Yasunori [1]

Ishijima Tatsuo [1]

[1] Komatsu Industries Corp, Kanazawa University, Kanzawa, Japan

Abstract

Oxygen plasma arc cutting is widely employed in various industrial fields. In the case of cutting magnetized plates, the magnetic field is concentrated around the cutting front as cutting progresses, and the electromagnetic force induced by the leakage of magnetic field deflects the plasma jet. The deflected plasma jet leads to poor cutting quality and sometime causes damage to the electrode and nozzle because of double arc abnormal discharge. This phenomenon is called magnetic arc blow, and it is a critical issue when applying plasma cutting on magnetized plates. In this study, magnetic arc blow behavior is investigated, and a method to prevent it is devised. We examined the relationship between operating conditions and the double arc using external magnetic fields on a plasma jet. We found criteria regarding operation conditions that induce arc blow. In addition, we succeeded in suppressing the double arc caused by the leakage external magnetic field by using a magnetic shield cap composed of ferromagnetic material around the nozzle.

Keywords

Plasma cutting
Arc cutting
Electromagnetic fields
Arc blow

1. Introduction

Oxygen plasma arc cutting (PAC) is employed in many industrial fields such as in shipbuilding, building of bridge or construction machines in production lines for welding structures, and in other cutting applications. PAC is known as a high-efficiency cutting method for mild steel plates of medium thickness. When magnetized plates are cut by PAC, magnetic arc blow (or simply arc blow) occurs. Arc blow leads to poor cutting quality or damage to the nozzle or electrode of the plasma torch, making the application of plasma cutting to magnetized plates impossible. It is known that arc blow easily occurs in high-quality steel such as high-tension steel including nickel and cobalt that exhibit ferromagnetism. The reasons for this occurrence are not yet clear.

A magnetic lifter for transporting a steel sheet or magnetic field induced by the electric current created by PAC may cause this phenomenon.

If arc blow leads to poor cutting quality, extra costs may be incurred because of grinding or welding repairs of the defective sections. Further, it is not possible to predict the time and occurrence of arc blow. Several researches [1 , 2] for arc blow were conducted regarding arc welding, but hardly carried out on PAC. The lack of knowledge regarding arc blow hinders the use of PAC on magnetized plates.

Several methods for suppressing arc blow have been proposed according to Japanese patients [3 – 5]. However, these methods do not completely succeed in the suppression of arc blow primarily because the mechanisms that cause arc blow are not clear. It is necessary to understand the mechanism involved in arc blow to produce efficient countermeasures. We aim to obtain knowledge of this physical phenomenon known as arc blow.

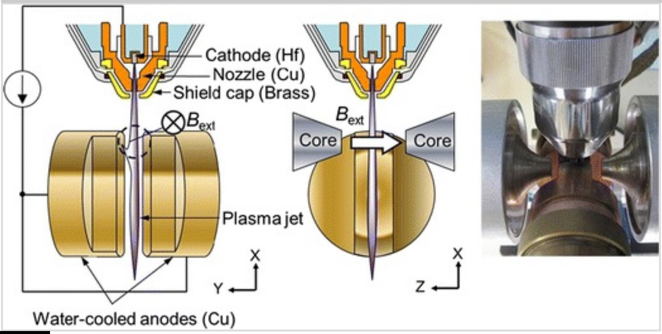
2. Experimental set up and results

2.1. Experimental study of magnetic arc blow with water-cooled anodes

Figure 1 shows the experimental setup. Two water-cooled anodes are located under the plasma torch. The gap between the anodes simulates a cutting kerf. Two electromagnets are placed between the torch and anodes. The magnets induce a magnetic field perpendicular to the plasma arc. The magnetic field induced by the magnets is altered from 0 to 140 mT (1,400 G) at the plasma arc. On hundred forty metric ton is a maximum value by the magnets. The plasma torch system is produced by Komatsu Industries Corporation. Oxygen is used as plasma gas, and the maximum arc current is 150 A. The nozzle orifice size is 1.6 mm in diameter.

Fig. 1

Plasma torch system and water-cooled anodes



AQ2

We investigated the criteria regarding the minimum magnetic field ($B_{W.A}$) that causes double arc. We altered the arc current *I* and plasma gas flow rate *Q* as parameters for $B_{W.A}$. Figure 2 shows the induced double arc. The $B_{W.A.}$ is thresholds of minimum magnetic field where arc blow is induced at certain *I* and *Q*. The results are shown in Fig. 3 . $B_{W.A.}$ decreases with increasing *I* and decreasing *Q*. Therefore, arc blow easily occurs under either a high arc current condition or low gas flow condition.

Fig. 2

Photograph of double arc by magnetic blow. **a** Normal and **b** double arc

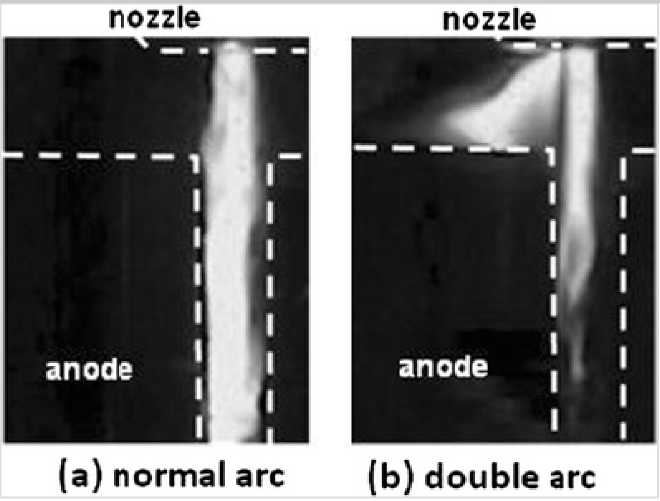
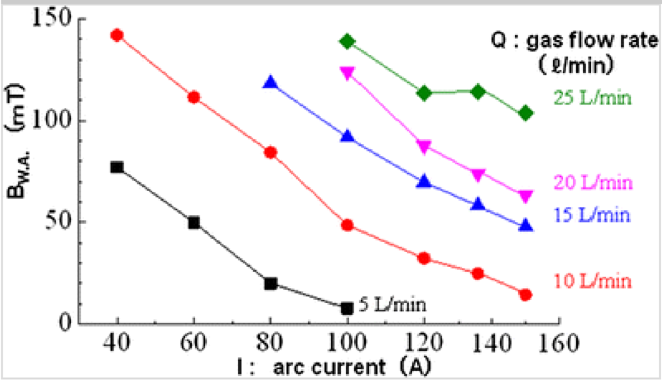


Fig. 3

Relationship between B_{wa} and *I*, *Q* with nozzle ϕ 1.6 mm



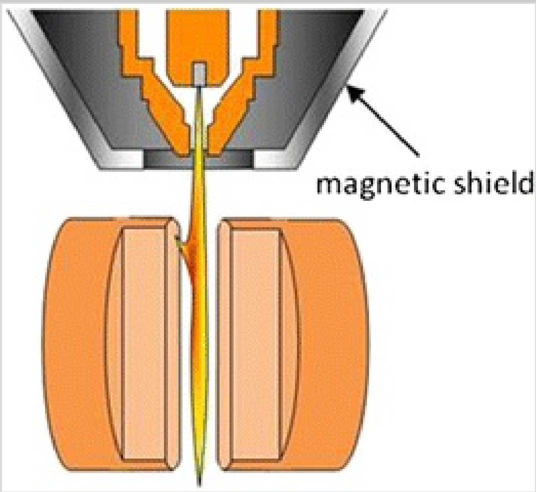
AQ1

2.2. Suppression of magnetic arc blow by a magnetic shield cup

We found that arc blow is prevented by decreasing *I* or increasing *Q*. However, either prevention technique leads to the deterioration of PAC performance. We aimed to develop countermeasures for arc blow without compromising on the performance of PAC. We designed a magnetic shield to prevent arc blow. It is composed of a shield cap made from ferromagnetic material and covers the torch nozzle, where it is supposed to interrupt any leakage magnetic field that arrives at the nozzle, as shown in Fig. 4 .

Fig. 4

Plasma torch with magnetic shield



We made several shield caps with thicknesses of 1, 3, and 5 mm, and we constructed a shield cap of paramagnetic brass for comparison tests. We investigated $B_{W.A.}$ using the experimental equipment indicated in Fig. 1 with the shield caps. The investigation was conducted with following conditions, where the nozzle orifice size is 1.3 mm and arc current is 135 A. The results are shown in Table 1 . Without shield cap, $B_{W.A}$ is same as the result indicated in Fig. 3 . $B_{W.A}$ increases in the case of the mild steel shield caps. With the shield 1 mm cap, $B_{W.A}$ increases than with no shield cap. And $B_{W.A}$ increases with the use of a 3 mm cap or 5 mm than 1 mm. On the other hand, $B_{W.A}$ remains unchanged in case of the brass cap. These results indicate that a magnetic shield cap made of ferromagnetic material is suitable for suppressing magnetic arc blow.

Magnetic shield	Material (μ / μ_0)	Thickness	Magnetic flux density: $B_{W.A.}$ Main gass flow rate 7 L/min	8 L/min	10 L/min
Not applied			20 mT	20 mT	40 mT
Applied	Brass Paramagnetic (≒1)	5 mm 	20 mT	20 mT	40 mT
	Mild steel Ferromagnetic (= 4000)	1 mm 	30 mT	110 mT	
		3 mm 	$B_{W.A.}$ > 140 mT (No double arc)		
		5 mm 			

Table 1

Threshold magnetic flux density of double arc occurs with or without magnetic shield cap

2.3. Verification of magnetic shield by cutting tests

We conducted actual cutting tests to confirm the effect of the proposed magnetic shield. A mild steel plate of 16 mm thickness was cut, and the schematic diagram of the cutting test is shown in Fig. 5 . Strong permanent magnets were fixed on both sides of the plate. A yoke board was connected to both sides of the magnets to produce a strong magnetic field in the plate. As cutting progresses, the magnetic flux at the cutting front becomes concentrated, leading to the increase in the leakage magnetic flux at the nozzle. The intensity of the leakage magnetic flux is shown in Fig. 6 . The intensity was measured at the middle of the plate and at the torch position located 3 mm above the plate surface. The leakage flux increases from 10 to 100 mT as cutting progresses. Mild steel plates of 16 mm thickness were cut by oxygen plasma. The arc current was 150 A. The cutting speed was 2,000 mm/min. We conducted four test cuts designated (a)–(d), as shown in Table 2 . (a) is a normal cutting condition with no magnet and no shield cap. The remaining three conditions include the magnets. Condition (b) has no shield cap, while conditions (c) and (d) include a 3-mm ferromagnetic shield cap. The difference between (c) and (d) is the direction of the applied magnetic field. In condition (c), the electromagnetic force, the Lorenz force, deflects the plasma arc opposite to the cutting direction. On the other hand, in (d), the force pushes the plasma arc forward. Figure 7 shows sections of the left side of the cuts. For all sections, the left side is the start of the cut and the right side is the end of the cut. At the end of each cut, the plasma arc was turned off while moving the torch to measure the delay of the cutting front.

Fig. 5

Schematic diagram and photograph of cutting test with neodymium magnet

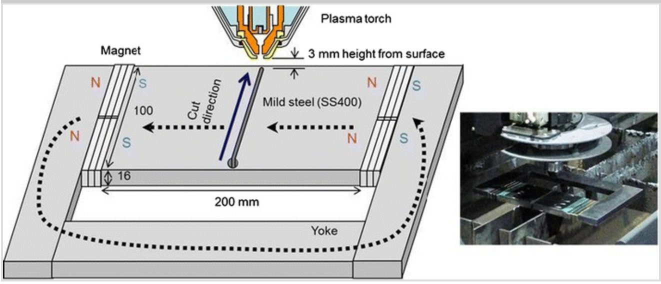


Fig. 6

Magnetic flux density of middle of plate and at torch position with neodymium magnet

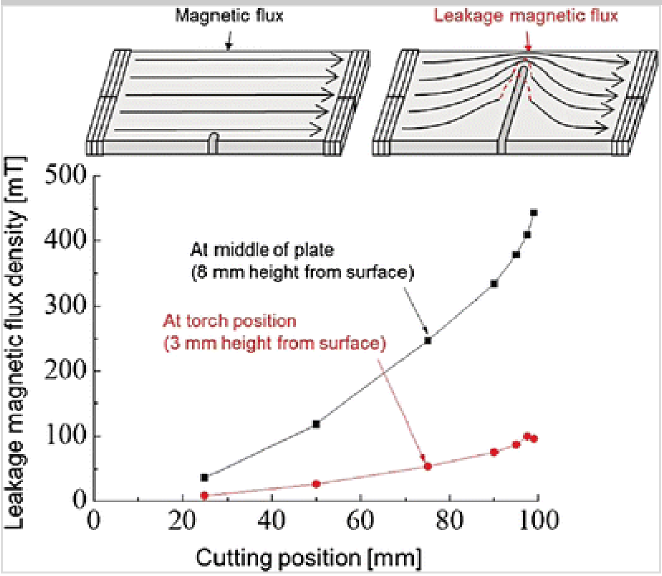


Table 2

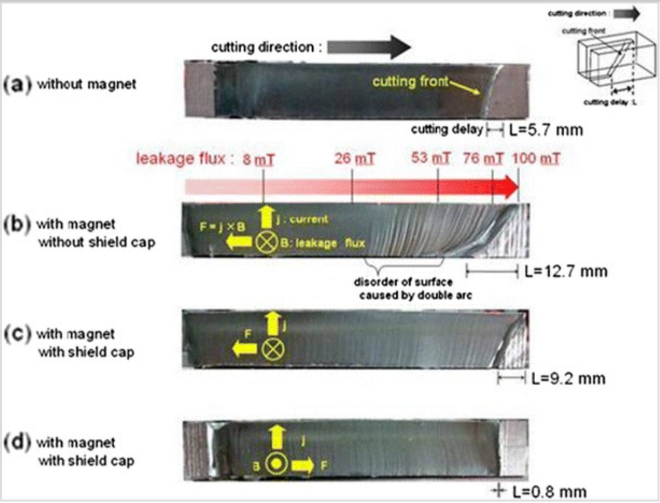
Cutting test condition

Torch	Arc current	150 A	Cutting test			
	Nozzle	1.6 mm		Magnet	Shield cap	Direction of $j \times B$
	Plasma gas	oxygen	(a)	without	without	–
	Plasma gas flow	12 L/min	(b)	with	without	backward
Plate	material	mild steel	(c)	with	with	backward
	Thickness	16 mm	(d)	with	with	forward
Cutting speed		2,000 mm/min				

By comparing (a) and (b) in Fig. 7 , the existence of leakage flux leads to poor cutting quality. When the leakage flux increases above 30 mT in (b), a notch appears. Notches were induced by the double arc phenomenon. As the leakage flux increases, the frequency of appearance of notches also increases. In Fig. 7b , the cutting front leans backward, causing an increase in the delay of the cut. It is thought that this occurs, because plasma was pulled backwards by the Lorentz force, and the heat input from plasma to the cutting front was reduced [7]. The cutting surface in (c) and (d) is smooth, same as that in (a), despite the existence of leakage flux. These results prove the effectiveness of the magnetic shield cap for PAC. The cap effectively prevents the double arc induced by arc blow. Furthermore, the delay of the cutting front in (c) is less than that in (b). This improvement is attributed to the shield cap. Note also that the delay of the cutting front in (d) is shorter than that in (a), and the reason for this is possibly because the plasma arc was pushed towards the cutting front by the Lorentz force.

Fig. 7

Influence on cutting front caused by magnetic arc blow. **a** With magnet, **b** with magnet without shield cap, **c** with magnet with shield cap, and **d** with magnet with shield cap



3. Discussion

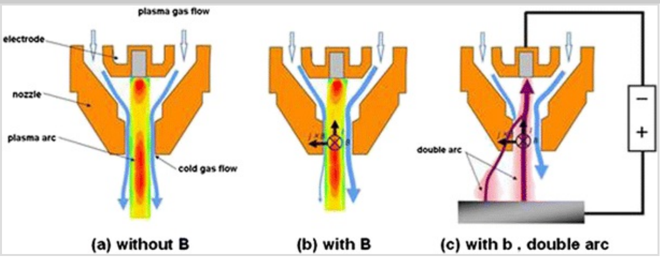
3.1. Mechanism of double arc and its suppression by a magnetic shield cap

We considered the mechanism of the double arc induced by arc blow and the suppression of the double arc by the shield cap.

Figure 8 shows the mechanism involved in the double arc. A plasma arc is a discharge between an electrode and a work plate to be cut. The electrode is the cathode, and the work plate is the anode. A nozzle is located between the electrode and the work surface, and it covers the electrode. The nozzle has an orifice to constrict the plasma arc. The electric current density is approximately 100 A/mm^2. Both the electrode and nozzle are cooled by water. Between the plasma arc and the wall of the nozzle orifice, there is a cool gas flow that isolates the nozzle wall from electricity and heat flux produced by the plasma jet, as shown in Fig. 8a . In the case, where there is an external magnetic field B_{ext} crossing the arc current, the plasma arc is pushed towards the wall by the Lorenz force f. [6]

Fig. 8

Double arc caused by electric magnetic force: j × B. **a** Without B, **b** with B, and **c** with B, double arc



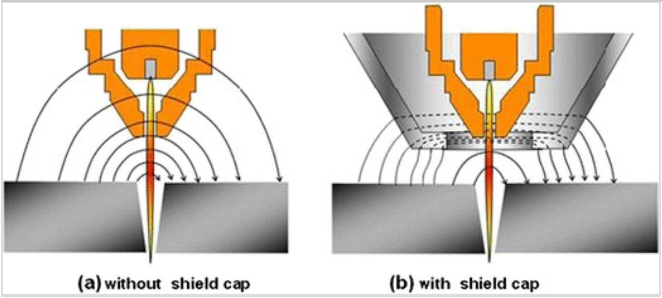
$$f = j \times Bext \quad (1)$$

The cold gas flow is thinned because the plasma arc pushed by the Lorenz force pushes the cold gas flow, as shown in Fig. 8b , and the isolation of electricity and heat is weakened. When isolation is broken, the plasma arc comes in direct contact with the wall, causing the double arc, as shown in Fig. 8c .

In the case in which we reduce the current or increase the gas flow, the former produces a weak Lorentz force, while the latter produces a strong cold gas flow. These results are in agreement with the experimental results discussed in section 2.1 . Figure 9 shows the working of the magnetic shield. The magnetic flux density B is determined by the intensity of magnetic field o and the magnetic permeability μ. The magnetic permeability is a product of the magnetic permeability of vacuum μ_0 and the relative permeability μ_s.

Fig. 9

Difference of leakage magnetic flux between w.t. shield and w.o. shield. **a** Without shield cap, **b** with shield cap



$$B = \mu \times H \tag{2}$$

$$\mu = \mu \times \mu_1 \tag{3}$$

The magnetic shield cap is composed of mild steel. Its relative permeability μ_s is 4,000. This value is much higher than that of air or copper when considering a nozzle. Therefore, magnetic flux around the nozzle protected by a shield cap selectively penetrates the shield. As a result, the nozzle is shielded from the external magnetic field, and the double arc induced by arc blow is suppressed.

3.2. Influence on arc blow by the relationship between cutting and residual magnetic field directions

To obtain information about leakage flux from the cutting kerf, we conducted numerical simulations of a two-dimensional static magnetic field. The model for the simulation is shown in Fig. 10 . The regions are distinguished by different colors as follows: the work plate composed of mild steel to be cut is denoted by gray; the magnet is denoted by green; the yoke composed of mild steel is denoted by blue, and air is denoted by white. The intensity of the magnets is selected such that the intensity of the magnetic field is 20 mT in the plate. For this simulation of a static magnetic field, we used Maxwell as a solver. We calculated four types of kerf on the plate designated (a), (b), (c), and (d) in Fig. 10 . The difference between these is the direction of the kerf to magnetic field. The simulation results are shown in Fig. 11 . In the case of (a), where the kerf is parallel to the magnetic field, the magnetic flux does not leak out to the kerf. In the case of (b), (c), or (d), where the kerf is crossing the field, the magnetic flux leaks out to the kerf. The leakage flux crosses the kerf in the shortest distance possible. Therefore, the leakage flux is perpendicular to the kerf except at the corner of (d). As the above results suggest, the direction of the Lorenz force is mostly parallel to the cutting direction because of perpendicularity between the kerf and leakage flux.

Fig. 10

Model for stimulation of static magnetic field. **a** Parallel, **b** right angle, **c** diagonal, **d** corner

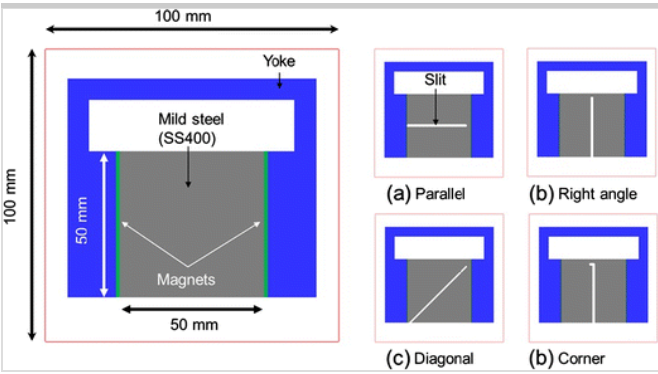
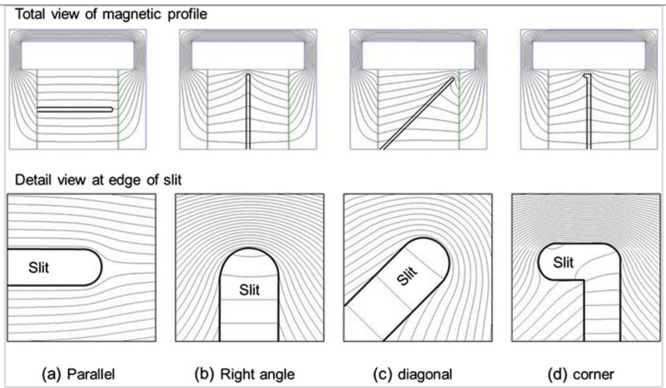


Fig. 11

Results of stimulation of static magnetic field. **a** Parallel, **b** right angle, **c** diagonal, **d** corner

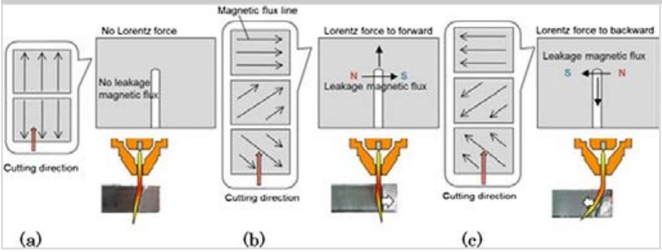
10.1007/s40194-014-0177-0



A summary of the relationship between the cutting direction and magnetic field is shown in Fig. 12 .

Fig. 12

Direction of leakage flux



In the case of (a), where the kerf is parallel to the field, there is no leakage flux; hence, arc blow does not occur.

In the case of (b), where the north pole of the field is left of the cutting direction, the plasma arc is pushed to the cutting front, as previously shown in Fig. 7d .

In the case of (c), the field's north pole is to the right of the cutting direction; hence, the plasma arc is deflected backwards, in opposition to the cutting direction, and the cutting delay is increased as previously shown in Fig. 7c .

4. Conclusion

In this study, we experimentally investigated the magnetic arc blow phenomenon. We clarified the mechanism that leads to the double arc, which causes poor cutting quality in PAC applications. In addition, we determined the criteria that lead to arc blow under operating conditions. Furthermore, we devised a magnetic shield cap composed of ferromagnetic material and succeeded in suppressing arc blow. The knowledge gained from this study is summarized as follows.

1. We investigated the criteria of the minimum magnetic field for causing the double arc $B_{\text{W.A.}}$. $B_{\text{W.A.}}$ increases with decreasing I or increasing Q. Therefore, arc blow is suppressed by decreasing arc current or increasing gas flow.

2. The leakage flux is perpendicular to the kerf except at the corner. The direction of the Lorenz force is mostly parallel to the cutting direction.

3. Arc blow is categorized by the intensity and direction of the leakage magnetic field as follows.

    i. Leakage flux < $B_{\text{W.A}}$, and the field's north pole is to the right of the cutting direction.

       The plasma arc is deflected in opposition to the cutting direction, and cutting delay is increased.

    ii. Leakage flux < $B_{\text{W.A}}$, and the field's north pole is to the left of the cutting direction.

       The plasma arc is pushed towards the cutting front. Cutting quality is not influenced, and cutting delay is minimized.

    iii. Leakage flux ≥ $B_{\text{W.A.}}$

The double arc occurs, leading to poor cutting quality.

4. A magnetic shield cap composed of ferromagnetic material has been shown to suppress magnetic arc blow, even in cases with high induced magnetic fields.

References

1. P.J. Blakeley, Magnetic arc blow – causes and remedies, Welding & Metal Fabrication, Aug/Sept 1991

2. P.R. Reis, D. Souza and a. Scotti, MODELS to describe PLASMA JET, ARC TRAJECTORY and arc blow formation in arc welding, Welding in the world, vol. 55 3–4, p 24–32

3. Koike, Sakai and Tadokoro, Arc process method and apparatus, Japanese published unexamined patent application P2006-247733A

4. Koike, Fulujyo and Hirai, Arc process method, Japanese published unexamined patent application P2008-294263A

5. Koike, Fulujyo and Hirai, Plasma cutting method and apparatus, Japanese published unexamined patent application P2009-214165A

6. Lancaster JF (1986) The physics of welding

7. K. Matsuyama, Study of cutting mechanism and controlling of cutting quality, Doctoral dissertation of Osaka University, Nov. 1992