Observation of keyhole in visual plasma welding robot*

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Stable formation of the back bead in joining of thick material is important so as to achieve high quality of welded joint. Since plasma welding employs high current density, it is suitable in the joining of thick material. The quality of plasma welding depends on keyhole which is generated from pilot gas and welding current. As a result, the relationship between welding voltage and keyhole is unclear. It is very difficult to estimate the keyhole by welding voltage and current. Authors have tried to observe the keyhole and weld pool from the top side of base metal directly. For this purpose, a CCD camera is applied with an external trigger. Moreover, the situation of keyhole is taken by high speed camera in order to determine the peak current and base current. Timing of the shutter in CCD camera is set up to take clear images of the weld pool. The formation of keyhole is investigated under two kinds of pilot gas. One is a mixture of Ar 93% and H₂ 7% and the other is Ar 100%. The welding condition and groove shape are found to observe the keyhole from the top side of base metal.

Key Words: Observation of weld pool, Cooperative control, Robotic welding, Plasma welding

1. Introduction

Nowadays, it is commonly required to cut down the production cost in joining of thick material. Automation and high efficiency arc welding have already attracted a lot of attention¹⁾, while skill workers are reducing year by year. Plasma welding is available to make a deeper penetration, so that authors have applied it to the joining of material. During the welding process, plasma arc will become narrower, and as a result, current density is going to be higher²⁾. Hence, it is quite easy to make the keyhole for full penetration³⁾ and the capability of plasma arc welding for full penetration is better than any other gas metal arc welding (GMAW). Moreover, the plasma welding has made a contribution to the improvement of environment in working field by reducing the fume during welding process.

In plasma welding, there are a lot of parameters like travelling speed, pilot gas, welding current and so on. Nevertheless, the effect of welding parameters to penetration is not very clear. The quality of welding depends on the stabilization of keyhole. Therefore, it is necessary to get the state of keyhole during the welding process. According to conventional welding, generator of constant current has been applied, and as a result, it is known that welding voltage depends on the arc length when keyhole is not formed. However, at the moment keyhole once forms, welding voltage is up to keyhole and not related to the shape of weld pool.

Control of the keyhole is proposed by measuring the voltage between electrode and plate, which is set under the base metal⁴⁾. During the welding control process, generation and disappearance of keyhole has been repeated, hence the keyhole is not continuous. In this study, visual sensors have been used here to detect the keyhole from bottom surface entirely because sensing and describing the keyhole shape and geometry with proper methods are of great significance for optimizing the welding process parameters and enhancing the stability of weld quality. Additionally, in the practical field, it is impossible to set up the CCD camera to the rear side of the base metal. The generation and disappearance of keyhole are synchronized with each pulse of welding current. Since the keyhole is discontinuous, travelling speed has become very slow. Additionally, it is difficult to detect the state of keyhole by measuring welding current and voltage.

As a matter of fact, skill workers detect the state of keyhole through their visual sense in practical field during welding process. However, it is available to make an observation by using visual sensor instead of human sense. Authors have applied the pulsed current to plasma welding rather than constant current in this paper. Consequently, keyhole forms during the peak of pulsed current and the size of keyhole shrinks during the base current. In other words, the tolerance of welding conditions will be extended.

Power source of plasma welding is operated by the control of inverter. On that account strong electrical noise has been emitted to the peripheral equipment. There being a CPU, the reset of equipment might probably occur during the welding process. Control of power source is required to synchronize with CCD camera. However, it is quite difficult to connect a personal computer to the power source apart from electrical noise. For this reason, authors have used the dsPIC with a digital signal

*Received: 2014.11.27

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controller of 16-bit. Then, once strong electrical noise comes into being, the dsPIC will operate itself according to the program saved in EPROM. The influence of electrical noise will become smaller than the direct connection to personal computer.

The effect of pilot gas to keyhole has been studied in the paper. Two kinds of pilot gas are adopted as a mixture of Ar 93% and H₂ 7%, and Ar 100%. Back side of base metal is taken by high speed camera. As a result, the relationship between base current and stabilization of keyhole has been investigated. Furthermore, welding condition and the groove shape of base metal have been confirmed to make a clear image of keyhole.

2. Plasma welding system

Plasma welding system with dsPIC of 16-bit Digital Signal Controller is shown in the Fig.1. After pilot gas is supplied, the pilot arc between tungsten electrode and electrode tip will be ignored. In the meantime, by ionizing pilot gas, plasma has come into being. After main current flows to the base metal, a plasma arc with high current density will be generated. Then, due to plasma gas and the nozzle of small caliber, plasma arc will become narrower. As a result, base metal is partially heated, and at the same time, the plasma gas makes a strong depress on the molten metal. Besides, keyhole keeps almost a constant shape. Meanwhile, during the welding process, plasma arc melts the base metal in the front of keyhole. Otherwise, the metal melted has fallen into the keyhole in the rear. On that account, it is very important to maintain the keyhole in an appropriate shape and shut the keyhole with weld pool by force. Additionally, according to pulsed current, it is available to make a control of the plasma pressure. Cooling and coagulating of the weld pool can also be carried out by adjusting the base current. Anyway, the range of proper welding condition has been expanded.

Fig. 1 Visual robotic plasma system.

CCD camera fixed to the plasma torch is used to make a clear observation of the keyhole and weld pool. Authors have taken the image of weld pool with CCD camera during the base current duration. Typical image is shown in Fig.2. A dimming filter is necessary with CCD camera used, so as to reduce the influence of strong arc light. During the experiment, instead of normal dimming filter, a filter of IR 950nm has been used to make an observation of weld pool. Clearer images will be acquired with all the visible light intercepted, and only pass infrared ray by using IR 950nm dimming filter. However, the image is still not clear enough for image processing. Control of welding current is required in order to take clear image without bad influence of arc light. On the other hand, power source has emitted strong electrical noise, which will be transmitted to PC equipment, once it is directly connected. In that case, the current program of PC will probably be stopped and computer may even restart. In other words, welding current will be out of control. In order to eliminate the influence from electrical noise, authors have applied dsPIC to the control of power source with inverter. Besides, the dsPIC is operated according to several programs saved in its EPROM, where welding conditions have already been stored, and if connected to the power source, it may receive strong electrical noise. At that time, the program of dsPIC will automatically restart. Moreover, PC has controlled the welding robot by Ethernet and sent welding conditions to dsPIC with RS-232C. As a result, the welding process will run smoothly without influence of electrical noise.

3. Fundamental experiments

Fundamental experiments have been carried out in Y groove shape welding, which the thickness of base metal is 12mm and root face is 5mm. Welding condition have been listed in Table 1. As below, two kinds of pilot gas have been investigated. Furthermore, the frequency of pulsed current is 20Hz.

Fig. 2 Typical image of weld pool under plasma arc of 150A under Ar 93% and H₂ 7%.

Table 1 Welding parameters used in the plasma welding.

Pilot Gas	Peak Current [A]	Base Current [A]	Peak Width [s]	Welding Speed [mm/s]
Ar 93% and H ₂ 7%	350	150	0.025	3
Ar 100%	350	250	0.025	2.5

Through high speed video camera, it is available to make an observation of keyhole on back side so as to determine the appropriate base current. Relationship between the waveform and images of keyhole has been also investigated. Generally speaking, the keyhole is wide in pulsed peak duration. Yet, after changing the base current, keyhole is going to become narrower than the peak. Welding conditions are determined from the result of high speed video image. Consequently, the peak and base current are determined to maintain the keyhole during welding process.

In order to make a clear observation of the keyhole and weld pool at the same time, shutter of CCD camera opens at 30A to reduce the arc light. Opening of shutter is desired for the base current duration to inhibit the influence of 30A. For this purpose, dsPIC will send out trigger signal, which is synchronized with the pulsed current, to CCD camera. Timing chart of the signal is shown in Fig.3, which keyhole is observed every 50ms once welding current changes from the base current to 30A. Output signal of dsPIC becomes high level after 1ms, and corresponding to the shutter speed, duration will be another 1ms. Moreover, the welding current will change to 30A for 3ms at the moment shutter of CCD camera opens.

By reducing the welding current, it will be available to take clear images of the keyhole, which has been shown in Fig.4. Since shutter time is only 1ms, the decrease of current will not affect the quality of welding.

In order to carry out welding experiment on the thick material,

it should properly refrain from the hydrogen embrittlement. However, once hydrogen is used as pilot gas, the hydrogen embrittlement would be so hard to avoid. Pilot gas has been changed from Ar 93% and H₂ 7% to Ar 100%. Anyway, authors have investigated the welding condition, listed in Table 1, to get the most suitable back bead. On the other hand, it is available to raise the base current so as to get the similar back bead as Ar 93% and H₂ 7%. As known to us, when there is a big specific heat, in order to reduce the thermal diffusion to arc outskirts, electricity course of arc current has been limited near the center of plasma of a high temperature. Therefore, growing with electromagnetic pinch effect, evoked plasma currents of air will increase, and due to the heat loss with the convection, the cooling of arc plasma has been promoted. As a result, the shrinkage of arc pillar occurs,

Fig. 3 Welding current waveform and trigger timing of CCD camera **Fig. 4** Typical image of keyhole under plasma arc of 30A under Ar 93% and H₂ 7% (a) Pilot gas is the mixture of Ar 93% and H₂ 7%. (b) Pilot gas is Ar 100%.**Fig.5** Typical image of plasma arc.

Fig.6 A schematic diagram of keyhole and bead height.

which is essence of thermal pinch effect⁵⁾. That is to say, higher the specific heat is, more remarkably the arc pillar will retrench. Moreover, the fact that hydrogen has a bigger specific heat owing to the smaller molecular mass, and during the welding process, hydrogen in pilot gas has been dissociated, on that account plasma arc of Ar 93% and H₂ 7% has a higher concentration than Ar 100%.

By taking advantage of high speed camera, plasma welding phenomena has been investigated according to the difference between Ar 93% and H₂ 7%, and Ar 100 %. Typical image of top surface is shown in the Fig.5. Just as it is seen, the width W_2 of plasma arc, under the pilot gas of Ar 100%, becomes wider than the width W_1 , which is under Ar 93% and H₂ 7%. Plasma arc in Ar 100 % spreads through the groove surface, and at the same time, the discharged area of arc has been melted. Besides, the melted area of groove surface under Ar 100% is wider than that of Ar 93% and H₂ 7%, which the amount of molten pool becomes bigger. Additionally, in accordance with the amount of molten metal, bead height R_2 is going to be higher than height R_1 of Ar 93% and H₂ 7%.

A schematic diagram of the relationship among a field of view in CCD camera, the keyhole and bead height on the welding line has been shown in the Fig.6. Since CCD camera is fixed to the plasma torch, it is possible to make an observation of keyhole at

the angle with respect to the vertical axis. Nevertheless, keyhole will be hidden by the bead height R_2 , if the amount of molten metal becomes larger. Meanwhile, in order to get clear image of the keyhole, it is really needed to reduce bead height R_2 , depending on the root face. Hence, root face has been shortened from 5mm to 4mm. Fundamental experiments have been carried out under the same welding condition. Eventually, as a result that bead height becomes lower, the keyhole under Ar 100% can be well observed with CCD camera, which is shown in Fig.7.

4. Conclusions

Plasma welding, as an important technology, is used to get a high working efficiency and make an improvement of welding environment. The quality of welding results is almost decided by the situation of keyhole. Authors have made an observation of keyhole from the top of base metal. The results of this research are shown as below:

1. Visual robotic welding system for plasma welding is developed by using dsPIC, which is available to deal with the electrical noise of inverter power source effectively.
2. Image of the keyhole can be well obtained under the pilot gas of Ar 100% and a mixture of Ar 93% and H₂ 7%.
3. The system is valid to make a clear observation of keyhole in real-time, since image has been taken every 50ms with CCD camera.

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Fig.7 Typical image of keyhole under plasma arc of 30A and Ar 100%