Observation of hole formation process in plasma arc drilling†

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1. Introduction

Recent thermal processes for drilling, such as laser drilling and plasma arc drilling, are challenging the traditional drilling methods. Laser drilling has high speed and high precision for thin plates of almost all materials, while plasma arc drilling has high speed and a high material removal rate for thick plates of almost all metals.

The mechanisms of thermal drilling differ from those of traditional drilling methods. Laser drilling as a representative thermal process has been widely investigated. Melt ejection during laser drilling of metals has been observed and analyzed by high-speed photography, showing a significant mechanism of material removal [1]. When melt ejection occurs, spatter or dross readily forms at the entrance and exit sides of the hole. The characteristics of spatter formation and its prevention have been investigated in detail [2, 3]. Furthermore, phenomena accompanying hole formation, such as the flow velocity of molten material and heat flow models, have also been discussed [4, 5].

The geometrical characteristics and drilling performance of the plasma arc drilling method were investigated in our previous studies [6, 7]. However, the mechanism of hole formation during plasma arc drilling has not yet been fully elucidated. We therefore used a high-speed video camera to observe and analyze the process of drilling under different conditions. The results obtained confirm the mechanisms of the hole formation process, ejection of molten metal, and dross formation.

2. Experimental procedure

The setup for our plasma arc drilling experiments consisted of a power supply device, gas supply device, water-cooled tool, work-piece fixture, and time control switch, as shown in **Fig. 1**. A high-speed video camera was employed to observe the process of plasma arc drilling from different positions (upside, horizontal, and downside). The photographic conditions of the camera were fixed at a frame rate of 2000 f/s and a shutter speed of 1/272,000 s. A number of observational experiments were conducted by varying the arc current (100, 120, 140 A) and torch height (6, 8, 10 mm). Sequences of photographs with the passage of time were obtained to analyze the drilling process.

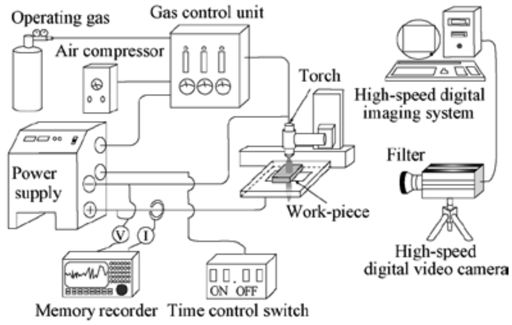

Fig. 1 Experimental setup.

3. Results and discussion

Hole formation in plasma arc drilling is dependent on the removal of molten metal. Observations were carried out at the upside and downside positions of the hole. Representative photographs are shown in **Fig. 2**. The observation results show that the quantity of residual molten metal around the entrance hole increases with the passage of processing time before the penetration time of 0.7 s. Subsequently, the quantity of residual molten metal remains almost unchanged and its temperature falls with the passage of processing time, as shown by the brightness of the white region. The process of ejection at the exit side differs from that at the entrance side. Initially, the molten metal inside the hole is entirely blown away in the form of a cloud without residue immediately after penetration occurs. This is because of the large internal pressure of the hole. Then, with the increase in the exit hole diameter, the internal pressure decreases, leading to a reduction in the

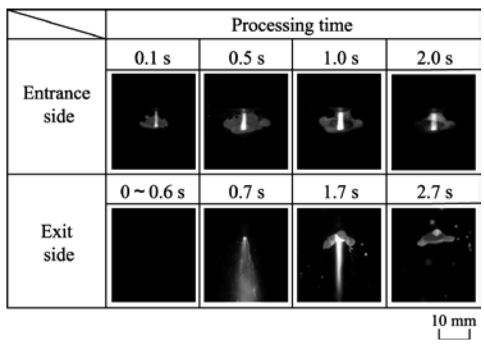

Fig. 2 Ejection of molten metal at an arc current of 140 A and torch height of 6 mm.

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ejection of molten metal. As a consequence, molten metal begins to remain at some specific positions around the exit side.In order to clearly observe the evolution of hole formation, we conducted a series of drilling experiments at the end surface. Representative photographs, which reveal the processes of metal melting and hole formation, are shown in **Fig. 3**. The situation of metal removal and the development of the hole shape with the passage of processing time can be clearly observed. The hole shape changes from a blind taper hole to a taper hole, then a cylinder hole, and finally a reverse taper hole. When the drilling processes under different conditions are compared, the evolution of the hole is seen to be faster at the larger arc current and lower torch height. Based on the above observations, the mechanisms of hole formation and ejection of molten metal are simulated in **Fig. 4**. The plasma ejected from the nozzle heats the work-piece to melting point or boiling point. The molten metal is ejected from the entrance side by the high-pressure gas (a). However, because of its viscosity, the molten metal is not entirely blown away and some remains around the entrance side of the hole before penetration occurs (b). After penetration, almost all of the molten metal is ejected from the exit side (c), and the quantity of molten metal at the entrance side thus remains unchanged. With the passage of processing time, the exit hole diameter continues to enlarge (d), with a cylinder hole (e) and then a reverse taper hole (f) being formed. Meanwhile, some of the molten metal remains around the exit hole.

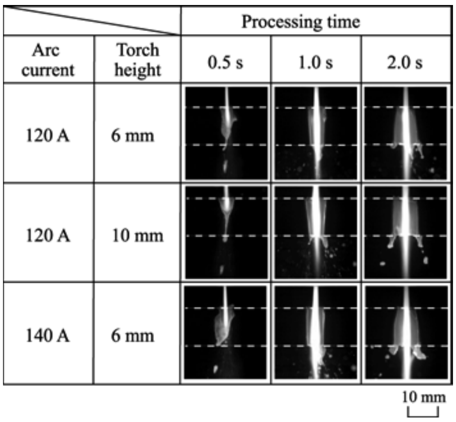

Fig. 3 Observations of hole formation on the end surface.

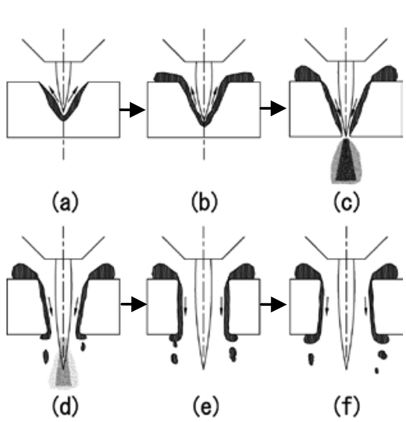

Fig. 4 Mechanisms of hole formation and ejection of molten metal.

Fig. 5 shows the representative appearances of a hole with dross and after dross removal at both the entrance and exit sides. Circular dross was formed around the entrance hole, while partial dross was produced around the exit hole. Although the amount of residual dross at the entrance side is greater than that at the exit side, it is relatively easy to remove. Comparing the appearances of both the entrance and exit sides after the dross is removed, it can be seen that the entrance side is cleaner while some indelible dross still remains at the exit side. This can be explained by the mechanism of ejection of the molten metal. As a consequence of prolonged continuous processing, residual hot molten metal constantly remains around the exit side until the drilling is completed. The work-piece is partly melted and fuses with the residual molten metal. The combination makes dross removal difficult. At the entrance side, however, the work-piece is not fused with the residual molten metal, with the result that the dross and the work-piece are readily separated.

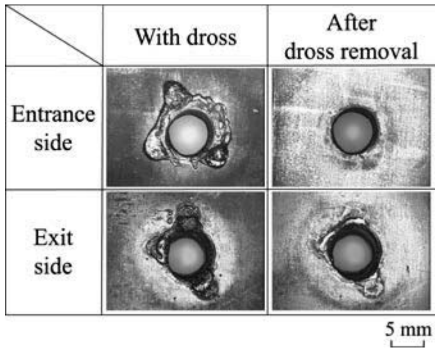

Fig. 5 Appearance with dross and after dross removal of a hole produced at an arc current of 140 A, torch height of 6 mm, and processing time of 2.7 s.

In addition to the above findings, a peculiar phenomenon observed inside the hole is a discharge from the plasma arc, in which an anode spot moves on the hole inwall at super-high speed. A representative anode spot is shown in **Fig. 6**. The discharge contributes to local thermal input in the metal removal process. Moreover, the electric attraction assists in removing part of the molten metal accumulated around the exit side.

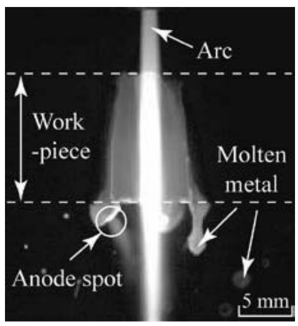

Fig. 6 Representative anode spot.

4. Conclusion

The process of hole formation during plasma arc drilling was observed using a high-speed video camera. The evolution of the hole from a blind taper hole to a taper hole, cylinder hole, and reverse taper hole was clearly observed under different conditions. The mechanisms of hole formation with the passage of processing time and ejection of molten metal at the entrance and exit sides were clarified by analysis of the process phenomena. An understanding of these mechanisms will be useful to improve hole quality and reduce dross around the hole.

References

[1] K. T. Voisey, S. S. Kudesia, W. S. O. Rodden, D. P. Hand, J. D. C. Jones, T. W. Clyne: Mater Sci Eng, A356 (2003), pp. 414-424.
[2] D. K. Y. Low, L. Li, A. G. Corfe: J. Mater. Process. Tech., 118 (2001), pp. 179-186.
[3] D. K. Y. Low, L. Li, P. J. Byrd: J. Mater. Process. Tech., 139 (2003), pp. 71-76.
[4] C. F. Cheng, Y. C. Tsui, T. W. Clyne: Acta Metall. Mater. 46 (1998), p. 4273.
[5] A. Luft, U. Franz, A. Emsermann, J. Kaspar: Appl. Phys. A, 63 (1996), p. 93.
[6] K. Kusumoto, H. Sun: Nat'l. Meeting of JWS, 82 (2008-4), pp. 114-115.
[7] H. Sun, K. Kusumoto: Nat'l. Meeting of JWS, 83 (2008-9), pp. 74-75.