Drilling Performance of Plasma Arc Drilling Method*

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Drilling is widely applied in materials processing. Novel drilling methods, including electrical discharge machining, laser drilling, and plasma arc drilling, have emerged in recent years to overcome such problems as tool wear and low efficiency in the drilling of thick plates or difficult-to-machine materials. Plasma arc drilling is an effective method for the drilling of thick plates, and the quality of the drilled holes is also high. However, the drilling performance of the plasma arc drilling method has not yet been fully elucidated. Since drilling performance is an important criterion in practical processing, we conducted a number of experiments to investigate the drilling performance of this method in terms of penetration ability, electrical energy consumption, and material removal rate. The results obtained for the drilling of mild steel plate of 12 mm in thickness were a penetration time of about 0.75 s, a minimum specific energy of about 30 J/mm³, and a maximum material removal rate of about 300 mm³/s.

Key Words: Plasma arc drilling, Drilling performance, Penetration ability, Electrical energy consumption, Material removal rate

1. Introduction

Drilling performance is an important criterion that directly affects production efficiency. In processing by the traditional drilling method, drilling speed is employed to evaluate drilling performance. Drilling speed is affected by many factors including the drill geometry and the drill and workpiece materials. Some studies^{1,2)} have reported that drilling using a coated drill can improve cutting capacity. On the other hand, in the case of nontraditional drilling methods such as laser drilling and electrical discharge machining (EDM), the complex machining mechanism requires more parameters to evaluate drilling performance. These include not only drilling speed but also penetration time, penetration depth, electrical energy consumption, and material removal rate.

A number of studies have been conducted to identify optimal processing strategies to improve drilling performance. The drilling-through time is enhanced by the use of a double-pulse laser, and the pulse energy of the saturation points of the double pulse is lower than that of a single pulse³⁾. Laser drilling is ordinarily troublesome for drilling thick plates, but the drilling time is conspicuously reduced when drilling stainless steel of 5 mm in thickness due to superposition of the radiation⁴⁾. Moreover, the material removal rate has also been investigated as another important criterion by adjusting the processing parameters⁵⁻⁸⁾. Drilling performance has therefore long been a focus of attention.

In our previous study⁹⁾, we proposed a drilling method using a plasma arc and demonstrated its feasibility while also analyzing

factors affecting the hole quality. However, the drilling performance of this method was not examined. In the present study, the drilling performance of the plasma arc drilling method was evaluated in terms of penetration time, cylinder hole formation time, electrical energy consumption, and material removal rate. A number of experiments were carried out in which the experimental parameters (plate thickness, arc current, and torch height) were varied to investigate the drilling performance of this method in detail. The results obtained confirm that plasma arc drilling is a high-speed drilling method with low electrical energy consumption and a high material removal rate.

2. Characterizations

2.1 Temporal features

In a traditional drilling system, because the hole shape is already determined once the tool has been selected, the temporal feature of drilling, i.e., the penetration time, is normally the only evaluation criterion. In the case of plasma arc drilling, on the other hand, the hole shape is not simplex, so there are two important factors for evaluating the drilling-through time: the penetration time and the cylinder hole formation time. Moreover, the formation time of different hole shapes is also an important expression of drilling speed.

Changes in the hole shape with the duration of processing time in the plasma arc drilling method are shown in Figure 1. There are two time points at which the hole shapes can be divided. These are when the workpiece has just been penetrated, as shown in Figure 1 (B), and when the cylinder hole has just been formed, as shown in Figure 1 (D). The hole shape can be controlled once these two time points are grasped; a blind hole is formed before the penetration time, a taper hole is formed between the two time points, and a reverse taper hole is formed after the time at which a suitable cylinder hole is formed.

In our experiments, we used a high-speed digital video

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Fig. 1 Changes in hole shape with duration of processing time.

camera to record the arc motion in the process of plasma arc drilling. The starting and ending points of drilling were captured by the light ray of the arc. The penetration time is therefore given by

$$T_{pe} = (F_{end} - F_{start})/fps, \quad (1)$$

where T_{pe} is the penetration time, F_{start} is the starting point of drilling, F_{end} is the ending point of drilling, and fps is the frame rate of the camera.

However, it is difficult to obtain the formation time of the cylinder hole by this method. Although it is not possible to judge the stages of the hole shape from the arc motion, the formation time can be obtained by varying the processing time so as to drill a cylinder hole according to empirical values.

2.2 Electrical energy consumption

The specific energy is of enormous usefulness in the material removal processes. The drilling specific energy is therefore also an important criterion for evaluating the drilling performance of the plasma arc drilling method.

Drilling specific energy, the energy required to remove a unit amount of material (J/mm^3), is determined as follows:

$$\eta = Q_E / V_{rem}, \quad (2)$$

where η is the drilling specific energy, Q_E is the electrical energy consumption, and V_{rem} is the volume of the hole.

In this study, therefore, the electrical energy from the plasma power supply is employed to evaluate the energy consumption of plasma arc drilling. Here, Q_E can be obtained from the recorded current (I) and voltage (U) in experiments using the following expression:

$$Q_E = \int_0^{t_{pe}} (U \times I) dt, \quad (3)$$

where t_{pe} is the processing time.

2.3 Material removal rate

The material removal rate (MRR) is another criterion of drilling performance. Machining efficiency is commonly assessed by the MRR. A considerable amount of research has been conducted on variations in MRR with time in nontraditional drilling processing, because the MRR contains important practical information. We therefore investigated the relationships between the MRR and experimental parameters.

The MRR in drilling is the ratio of the volume of removed material to the processing time, as follows:

$$MRR = \frac{V_{rem}}{t_{pe}}, \quad (4)$$

In terms of different hole shapes, the volume of removed material (i.e., V_{rem}) of a blind hole and a through hole are respectively given by Equations 5 and 6:

$$V_{rem} = \frac{1}{3} \times \pi \times \left(\frac{d_{en}}{2} \right)^2 \times h, \quad (5)$$

$$V_{rem} = \frac{1}{12} \times \pi \times (d_{en}^2 + d_{en}d_{ex} + d_{ex}^2) \times t, \quad (6)$$

where d_{en} is the entrance hole diameter, d_{ex} is the exit hole diameter, h is the penetrated hole depth and t is the plate thickness.

3. Experimental procedure

The setup for our plasma arc drilling experiments is shown in Figure 2. The main components were a power supply device, gas supply device, water-cooled torch, workpiece fixture, and time control switch. The water-cooled torch was placed perpendicularly against the workpiece, which was fixed on the workbench by the fixture. The electrode was connected to the negative pole of the power supply and the workpiece was connected to the positive pole, to form the current circuit for the plasma arc.

A high-speed video camera was positioned to observe the arc motion of drilling. The camera was arranged horizontally to the material. In order to attenuate the strong light radiated from the plasma arc, a neutral density (ND) filter was fitted to the video camera lens. The position and photographic conditions of the camera are shown in Figure 3.

Fig. 2 Experimental setup.

Fig. 3 Position of camera and photographic conditions.

Table 1 Experimental conditions.

Material	: SS400
Plate thickness	: 6, 9, 12 mm
Arc current setting	: 100, 120, 140 A
Torch height	: 6, 8, 10 mm
Nozzle diameter	: 1.7 mm
Operating gas	: Oxygen
Assist gas	: Air
Gas flow rate	: O ₂ = 20 l/min, air = 20 l/min
Gas pressure	: O ₂ = 0.49 MPa, air = 0.49 MPa

Fig. 4 Electrical characteristics of plasma arc.

The workpiece used in the present study was mild steel (SS400) plate with overall dimensions of 40 × 40 mm and a thickness of 12 mm. The operating gas, which flowed into the nozzle in a spiral configuration, was high-purity compressed oxygen. The processing time was adjusted by the time control switch.

To investigate the effects of different experimental parameters on the drilling performance, experiments were carried out under different processing times. The experimental conditions are shown in Table 1.

The arc current and voltage of the drilling process were measured by a clamp meter (Clamp On AC/DC HiTester model 3285, Hioki) and an equivalent voltage circuit, respectively, and these values were recorded by the memory recorder (Memory HiCorder model 8826, Hioki). The electrical characteristics of the plasma arc are shown in Figure 4. In this study, the actual arc current consisted of a transient stage and a steady stage. The duration of the transient stage was consistently around 1.14 s, even when the arc current setting was changed. After 1.14 s, the actual arc current became equal to the set arc current. This is an arc current characteristic of plasma arc drilling. Moreover, only the representative arc voltage at an arc current setting of 120 A and torch height of 6 mm is shown, because the arc voltages under different arc current setting and torch height have almost same waveform, but only have a tiny change in the amplitude.

4. Results and discussion

4.1 Observation of arc motion

Figure 5 shows the arc motion in the plasma arc drilling process captured by the high-speed digital video camera. The

Fig. 5 Changes in arc motion with processing time.

ejection of the plasma arc (the white ray) from the nozzle can be clearly seen in these photographs. When the workpiece is penetrated, the plasma arc is strongly ejected from the exit side of the hole. Thus, the starting and penetrating points during drilling can be accurately grasped and the stage of drilling can also be roughly estimated.

4.2 Effects of experimental parameters on temporal features

The effects of the arc current on the temporal features are shown in Figure 6. The penetration time of the workpiece of 12 mm in thickness varies between about 0.82 s and 0.68 s. The penetration time shows a slight reduction with increasing arc current. Hence, when the processing time is controlled so as to be shorter than the penetration time, a blind hole is formed. The cylinder hole formation time decreases from 2.6 s to 1.9 s with increasing arc current. As a result, the zone of taper hole formation at a low arc current is wider than that at higher arc currents.

The effects of the torch height on the temporal features are shown in Figure 7. The penetration time shows a negligible increase with increasing torch height. The cylinder hole formation time, on the other hand, shows a large linear increase with increasing torch height, from about 2.2 s at a torch height of 6 mm to about 3.3 s when the torch height is increased to 10 mm. The taper hole formation zone is consequently enlarged.

The penetration of a hole at the different arc current setting and torch height is confirmed at the transient stage of arc current, where the input electrical energy is almost same as shown in Figures 9 and 10. Thus, the penetration time has a tiny change. On the other hand, the reason for the difference of the cylinder hole formation time is related to the input electrical energy and the heat source distribution of plasma arc. On the variation of arc current setting, the input electrical energy at the larger arc current setting is larger as shown in Figure 9, consequently the cylinder hole formation time is shorter. When the torch height is raised, the heat source departs from the workpiece to cause an increase of the cylinder hole formation time.

Figure 8 shows the effects of the plate thickness on the temporal features. Both the penetration time and cylinder hole formation time show significant increases with increasing plate thickness.

It can therefore be seen that the most important factor affecting the penetration time is the plate thickness. All of the experimental parameters have a large effect on the cylinder hole formation time, which decreases with increasing arc current and increases with increasing torch height and plate thickness. These results demonstrate that the drilling speed of the plasma arc drilling method is much faster than that of other methods^{10,11)}.

Fig. 6 Effects of arc current on temporal features.

Fig. 7 Effects of torch height on temporal features.

Fig. 8 Effects of plate thickness on temporal features.

4.3 Effects of experimental parameters on electrical energy consumption

The variations in electrical energy consumption and specific energy with the processing time at different set arc currents and

torch heights are shown in Figures 9 and 10, respectively. The electrical energy consumption exhibits a parabolic increase with increasing processing time. Moreover, it increases with increasing arc current at the same processing time, but does not show large differences when the torch height is changed. The specific energy reaches its minimum value near the point of penetration regardless of the experimental parameters. The minimum specific energy is about 30 J/mm^3 , which is lower than that of laser drilling¹²⁾. Subsequently, the specific energy shows a rapid increase with increasing processing time, and increases with increasing arc current and decreasing torch height.

When the arc current is at the transient stage, the arc energy increases with an increase of processing time, and meanwhile the removed volume also rapidly increases. However, the increase rate of the removed volume (ΔV) is larger than that of the arc energy (ΔQ), consequently, the special energy decreases before a hole is penetrated. And then, as the distance from the heat source to the hole wall increases with the expansion of a hole, the

increase rate of the removed volume decreases to cause an increase of the special energy.

4.4 Effects of experimental parameters on material removal rate

The volume of removed material generally contains important information that is assigned to specific machining features and related to specific machining processes. In particular, the volume of removed material is considered to contain information on the hole shape, and it is thus a key factor in grasping the process of plasma arc drilling.

Variations in the MRR with processing time at different set arc currents and torch heights are shown in Figures 11 and 12, respectively. Overall, the MRR initially increases to its maximum value, which is reached immediately after the workpiece is penetrated. It then slightly decreases with increasing processing time. This is because the removed volume is increasing until the plasma arc completely ejects from the exit side of a hole. The

Fig. 9 Variations in electrical energy consumption and specific energy with processing time at different set arc currents.

Fig. 11 Variations in MRR with processing time at different set arc currents.

Fig. 10 Variations in electrical energy consumption and specific energy with processing time at different torch heights.

Fig. 12 Variations in MRR with processing time at different torch heights.

MRR mostly exceeds 200 mm³/s, except at the starting point. Moreover, the MRR does not exhibit obvious variations with the arc current at the same processing time, but shows a clear increase with increasing torch height.

5. Conclusions

In this study, we investigated the drilling performance of plasma arc drilling through a number of experiments. The drilling speed, specific energy, and material removal rate were evaluated by changing the experimental parameters. The main results are summarized as follows:

- (1) The penetration time in the case of mild steel plate of 12 mm in thickness is almost same about 0.75 s.
- (2) The cylinder hole formation time decreases with increasing arc current setting and decreasing torch height and plate thickness. The cylinder hole formation time is short at about 2.2 s to 3.3 s.
- (3) The drilling specific energy is in the range of about 30 J/mm³ to 100 J/mm³, depending on the combination of experimental parameters. The minimum value is appeared at around the penetration of a hole.
- (4) The torch height has a larger influence on the material removal rate than the arc current setting. The material removal rate normally reaches about 200~300 mm³/s.

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