Development of Drilling Method Using Plasma Arc Technology*

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Drilling is an important aspect of materials processing in industry. Conventional drilling methods cannot completely meet production needs. As a result, the emergence of many new processing methods has become a prominent trend in recent years. However, few reports have been published on drilling processes using plasma arc technology. Plasma arc technology has been applied in various engineering fields including welding, thermal cutting, and heat treatment. This study proposes the use of plasma arc technology as a drilling method. A plasma arc drilling system was set up and a number of experiments were carried out. The geometrical characteristics and quality of holes generated using a plasma arc were analyzed. Various hole shapes were obtained by plasma arc drilling; namely, a conical blind hole, a taper hole, a cylinder hole, and a reverse taper hole. Variations in the volume of removed material and the material removal rate (MRR) of plasma arc drilling were investigated. The experimental results have verified that plasma arc drilling is an effective and high-speed drilling method.

Key Words: Plasma arc drilling (PAD), Hole diameter, Taper angle, Material removal rate (MRR)

1. Introduction

Drilling has been widely used to process materials in various manufacturing sectors. Tool wear is unavoidable in machining, however, and rapid wear of the tool when drilling thick plate or difficult-to-machine materials leads to a decline in both the product quality and processing efficiency1, 2). As a result, a variety of novel drilling technologies have been actively developed in recent years, particularly in the area of electronic technology. Examples include abrasive water jet machining (AWJM), electrochemical machining (ECM), electron beam machining (EBM), ultrasonic machining (USM), electric discharge machining (EDM), and laser beam machining (LBM). Laser drilling has recently come to be considered one of the most promising new methods, especially in the drilling of nonmetallic and thin metal plates. For drilling thick plate, however, this method has the disadvantages of requiring a large output device as well as high purchase and maintenance costs.

A plasma arc is an efficient and economical heat source. Plasma arc technology has been widely employed in materials processing. In the practical plasma arc cutting, a piercing is generally performed before entering into the real cutting. This piercing is very important for influencing directly on cutting performance and its quality. Some reports discussed about the effects of piercing point location3 and the variation of piercing hole depth with time4. However, there are no reports on processing characteristics and availability of plasma arc drilling.

Therefore, we used a high-temperature plasma arc to drill thick mild steel plate in the present study. This report describes the principle of plasma arc drilling and its procedures. The characteristics and quality of holes generated using plasma arc drilling are also described.

2. Principle of plasma arc drilling

The principle of plasma arc drilling is illustrated in Figure 1. A plasma arc, which has high temperature and high energy, is formed between an electrode and the workpiece through a copper nozzle. The plasma arc ejected from the nozzle reaches the workpiece surface, and the thermal energy of the plasma arc is transferred to the workpiece. A high-velocity jet flow of hot ionized gas begins to melt or evaporate the workpiece, the molten metal is removed by the high-pressure gas flow, and a hole is formed.

3. Experiments

3.1 Experimental procedure and drilling conditions

The experimental setup for plasma arc drilling is shown in Figure 2. It consists of five parts: a power supply device, gas supply device, water-cooled torch, workpiece fixture, and time

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Fig. 1 Principle of plasma arc drilling.
control switch. The water-cooled torch is placed perpendicularly against the workpiece, which is fixed on the workbench by the fixture. The electrode, made of hafnium, is connected to the negative pole of the power supply and the workpiece is connected to the positive pole, to form the current circuit for the plasma arc. The arc current and voltage of the drilling process are accurately measured and an equivalent voltage between the torch and workpiece, respectively, and these values are recorded by the memory recorder.

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. Assist gas was employed to cool the nozzle and improve the processing quality. The processing time was adjusted by the time control switch.

To investigate the feasibility of plasma arc drilling and the quality of the holes generated, experiments were carried out under different processing times. The experimental conditions are shown in Table 1.

### 3.2 Arc current characteristics

The arc current characteristics of the power supply used in this study are shown in Figure 3. The actual arc current does not directly reach the set value but consists of two stages: a transient stage and a steady stage. The arc current reaches the set value of 100 A at about 1.14 s.

### 4. Assessment of hole quality

#### 4.1 Measurement of hole diameters

The hole diameters of the entrance and exit sides were measured by a binary method. This method was used because dross is formed around the hole in plasma arc drilling (as shown in Fig. 6), making it difficult to measure the hole diameter using the conventional method. In the binary method, the dross generated around the holes was removed and photographs of the holes were taken by a CCD camera. The photographs were then processed by binary image software, to produce images such as that shown in Figure 4.

The area of the binary image was then measured. The hole diameter is given by Eq. (1):

\[
d = \sqrt{\frac{4S}{\pi}},
\]

where \(d\) is the hole diameter [mm] and \(S\) is the area of the binary image of the hole [mm\(^2\)].

#### 4.2 Taper angle

The hole taper angle has been evaluated in laser drilling studies as an important criterion of hole quality\(^6\). Similarly to

![Fig. 2 Experimental setup.](image2)

![Fig. 3 Characteristics of arc current.](image3)

![Fig. 4 Hole appearance and obtained binary image.](image4)
laser drilling, the taper angle is an inherent attribute of plasma arc drilling. We therefore investigated the taper angle of holes generated using plasma arc drilling.

As shown in Figure 5, the taper angle is defined as the angle $\alpha$. The value of the taper angle is calculated using an expression similar to Eq. (2), based on the hole diameters and plate thickness:

$$\alpha = \tan^{-1}\left(\frac{d_{en} - d_{ex}}{2t}\right) \times \frac{180}{\pi},$$

where $\alpha$ is the taper angle [°], $d_{en}$ is the hole entrance diameter [mm], $d_{ex}$ is the hole exit diameter [mm], and $t$ is the material thickness [mm].

### 4.3 Volume of removed material and material removal rate (MRR)

In the conventional drilling process, the drilling speed, that is the drilling length per minute, is usually investigated as an important parameter. As a thermal processing method, however, plasma arc drilling differs from machining processing in that the volume of removed material shows an irregular variation with processing time. This means that the speed of drilling using a plasma arc cannot be estimated in terms of length. We therefore investigated the relationship between the volume of removed material and processing time to assess the drilling speed in plasma arc drilling. Through observations of the hole formation process (as shown in Fig. 10), it was found that calculation of the hole volume can be divided into two cases according to whether or not penetration has occurred. Before penetrated, the volume of a blind-tapered hole can be calculated by Eq. (3), based on the entrance hole diameter and the penetration depth. After penetrated, a penetrable conical hole is formed, and its volume can be calculated by Eq. (4), based on the entrance and exit hole diameters and plate thickness.

$$RV = \frac{1}{12} \times \pi \times \left(\frac{d_{en}}{2}\right)^2 \times h,$$

where $RV$ is the hole volume [mm$^3$] and $h$ is the depth of a blind hole [mm].

Moreover, the machining efficiency and performance are commonly assessed by the material removal rate (MRR); that is, the volume of removed material per unit time. The MRR is calculated by Eq. (5):

$$MRR = \frac{RV}{T_i},$$

where $MRR$ is the material removal rate [mm$^3$/s] and $T_i$ is the processing time [s].

### 5. Results and discussion

#### 5.1 Observation of region around hole

Burring and frictional phenomena frequently occur around a hole in the machining process, degrading the quality of the hole. We therefore observed the regions around holes in plasma arc drilling.

In the plasma arc drilling experiments, the molten metal of the removed material was not entirely blown away because of the viscosity of the molten metal, and the residual molten metal cooled to form dross.

Figure 6 shows typical appearances around the entrance and exit sides of a hole before and after the removal of dross. From the results of our experiments, the generation of dross is considered to be inevitable in plasma arc drilling. The volume of

**Fig. 5** Definition of taper angle.

**Fig. 6** Appearances of the entrance and exit sides of a hole formed at processing time 2.6 s, before and after dross was removed.
dross and area to which it is attached are greater on the entrance side than on the exit side. Moreover, the dross attached around the entrance hole can be removed relatively easily, while that around the exit hole adheres firmly to the plate.

This phenomenon can be explained by the action of the molten metal in plasma arc drilling. The molten metal upwells before penetration occurs and then spouts in a downward direction after penetration. As a result, the molten metal on the entrance side begins to cool before the process has ended and becomes dross after penetration occurs. The volume of dross and area to which it is attached remain stable after penetration. On the other hand, all of the molten metal from the exit hole is blown out by the pressure of the ejecting gas when penetration occurs, and the pressure of the gas passing through the hole then decreases as the diameter of the exit hole increases. Consequently, in the case of the exit side, the molten metal remains around the hole and is ultimately combined with the workpiece, in a manner similar to the arc welding process, with the passage of processing time.

5.2 Variations in hole diameter

Variations in the hole diameter with processing time and photographs showing the appearances of the holes (plate thickness: 12 mm, arc current: 100 A, torch height: 6 mm) are shown in Figures 7 and 8, respectively. The diameters of the holes on both the entrance and exit sides increase as the processing time becomes longer, and the ratio of increase of the latter is larger than that of the former. The entrance diameter remains almost constant at a specific value (about 7.8 mm) as the processing time approaches 1.78 s. A cylindrical hole is obtained when the entrance and exit diameters become equal, at about 2.6 s. When the processing time exceeds 2.6 s, the diameter of the exit side becomes larger than that of the entrance side.

The hole evolution can be estimated by the appearances of the holes, as shown in Fig. 8. It can be seen that the holes drilled using the plasma arc method have good circularity. The increase in diameter of the holes tends to become smaller as the processing time becomes longer. Further, the variability of the hole diameter becomes greater with increasing processing time. It can also be noted that the variability of the exit hole diameter is greater than that of the entrance hole diameter. This is related to the degree to which the dross surrounding the hole can be removed.

5.3 Variations in taper angle

The hole taper angle is one of the inherent problems associated with plasma arc drilling. Variations in the taper angle with processing time are shown in Figure 9, and examples of cross-sectional photographs are shown in Figure 10.

The taper angle decreases as the processing time becomes longer. Initially, a conical blind taper hole, which is difficult to achieve by the machining process, is formed before penetration occurs. Then a taper hole is formed, with a taper angle of about 0° to 14°. When the taper angle becomes zero, at around 2.6 s, a cylindrical hole is formed. This is an important hole shape in practical applications. When the processing time exceeds 2.6 s, the diameter of the exit hole exceeds that of the entrance hole and the taper angle becomes negative. That is, a reverse taper hole is formed, as shown in the cross-sectional photographs. Therefore, the plasma arc drilling method has been shown to be able to produce zero-tapered holes as well as positively and negatively

![Fig. 7 Variations in hole diameter.](image1)

![Fig. 8 Appearances of plasma arc drilled holes.](image2)
tapered holes. It is concluded that a variety of holes with different taper angles can be generated by controlling the processing time of plasma arc drilling.

### 5.4 Variations in volume of removed material

In process planning, the volume of removed material can be decomposed into various elements, which are assigned to specific machining features and related to the specific machining processes. The volume of removed material is considered to contain information about the hole shape, and is thus a key element in grasping the process of plasma arc drilling. Variations in the volume of removed material with processing time and the MRR were therefore investigated, and are plotted in Figure 11.

The volume of removed material tends to increase as the processing time becomes longer. Moreover, the increase in volume of removed material gradually becomes smaller as the processing time becomes longer. These findings correspond to the variations in the cross sections of the drilled holes shown in Fig. 10.

The results obtained show that the MRR of plasma arc drilling is not a constant value but varies with processing time. The penetration time in the case of a 12 mm workpiece is about 0.82 s, and the forming time of a cylinder hole is about 2.6 s. The plasma arc drilling process can therefore be divided into three zones: the blind hole zone, taper hole zone, and reverse taper hole zone. In the blind hole zone, the MRR increases with processing time. In the taper hole zone, the MRR is about 250 mm³/s. The MRR begins to decrease after the reverse taper hole zone is entered. The increase of MRR in the early stage is due to the increase of arc energy with increasing arc current. The maximum of MRR is when the arc current reaches the setting value.

To elucidate the advantages of the plasma arc drilling, we made a comparison with the conventional drilling process using a drill bit. The MRR of drilling using a drill bit can be obtained by Eq. (6):

\[
MRR = \frac{\pi D^2}{4} f N / 60 ,
\]

where \(D\) is the diameter of the drill [mm], \(f\) is the feed rate [mm/rev], and \(N\) is the rotational speed [rev/min].

The recommended drilling parameters can be readily found in resources such as the Machinery Handbook. Some essential parameters are the diameter of the drill bit (7.8 mm), the rotational velocity (1240 rev/min), and the feed speed (0.18 mm/rev). Hence, the drilling time in the case of mild steel of 12 mm in thickness is calculated to be about 3.23 s and the drilling MRR to

Fig. 9 Variations in taper angle.

Fig. 10 Cross sections of plasma arc drilled holes.

Fig. 11 Variations in volume of removed material and MRR.
be about 177 mm/s. From a comparison of these data, it can be seen that the MRR of the plasma arc drilling method are higher than those of the others. It is therefore found that plasma arc drilling is a high-speed drilling method.

6. Conclusions

We have carried out a fundamental study of plasma arc drilling using a plasma arc. The purpose of this study was to examine the feasibility of plasma arc drilling and the characteristics of the generated holes. The results of our experiments demonstrate that plasma arc drilling is a high-efficiency drilling method. The experimental results are summarized as follows:

(1) Drilling of thick mild steel using a plasma arc has a relatively good effect.

(2) The hole diameters on the entrance and exit sides increase as the processing time becomes longer. The entrance hole diameter shows a tendency to approach a definite value.

(3) Various hole shapes with different taper angles can be generated by adjusting the processing time. These hole shapes are, respectively, a blind hole, a taper hole, a cylinder hole, and a reverse taper hole.

(4) Plasma arc drilling is characterized by a high material removal rate and high machining performance.

References


