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Author(s)	Arata, Yoshiaki; Miyake, Shoji; Innami, Tetsu et al.
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High Power Microwave Plasma Beam as a Heat Source (Report Ⅳ) [†]
—Application to Cutting—

Yoshiaki ARATA*, Shoji MIYAKE**, Tetsu INNAMI*** and Yasuo YOSHIOKA***

Abstract

A plasma beam of about 1 mm in diameter was obtained with a beam temperature over 8000K by using a nozzle system appropirate for cutting experiment. Strong influence of gas turbulence to the beam characteristics and to the cutting ability was ascertained experimentally.

1. Introduction

In the former reports[1,2] detailed analysis was given of microwave plasma beam in a 30 kw-class plasmatron of rectangular waveguide type. The following results were made clear by those investigations:

(1) Stabilization of a plasma by a helical gas flow is substantial for the operation of the plasmatron at such a high power;

(2) Change of pyrex tube diameter gives a strong effect on the plasma parameters. The smaller the diameter, the higher the plasma temperature with the decrease in its volume;

(3) Comparison of experimental results with a theory of energy absorption shows a good agreement if a virtual "gas wall" is assumed to be made by the strong helical gas flow.

From the point of view of applying this type of plasma beam to cutting of various materials, it is desirable to obtain a temperature as high as possible with the least size of the plasma diameter.

To satisfy these requirements experiments were carried out in a tube, which was 10mm in diameter and /or had a nozzle of various dimensions on the one end. In this paper plasma characters in such a small tube are studied and some experimental results of cutting of mild steels are reported phenomenologically.

2. Expermental apparatus

Fig. 1 shows the cross-sectional front view of the plasmatron used in this experiment. The dimenison of the cavity was changed to a value of 250 x 30 x 300 mm. The pyrex tube was exchanged by a ceramic one (BN material) which is 10 mm in diameter and several types of nozzle tips were inserted on the exit

side of the gas flow. This tube was sometimes water-cooled to measure the heat loss to the wall. The direct power loss of the wave to the cooling water was ascertained to be negligible once the plasma was ignited.

Schematic diagram of cutting system is shown in Fig. 2. Distance between the nozzle edge of the plasmatron and the workpiece torch height h was 4 mm
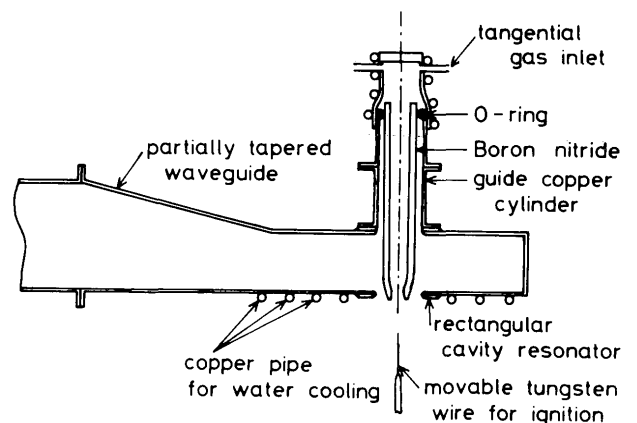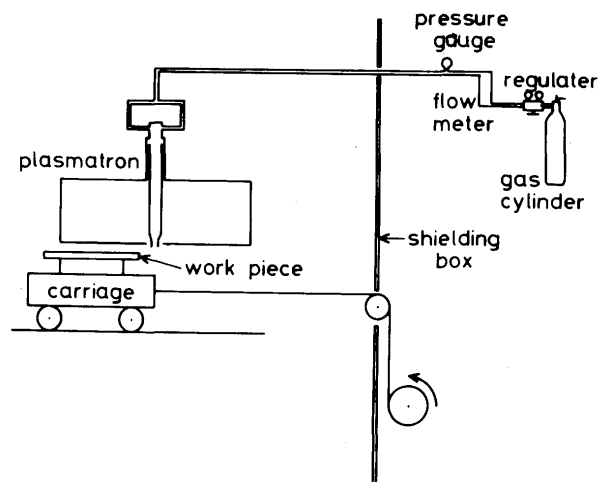

Fig. 1   Cross-sectional front view of plasmatron.

Fig. 2   Schematic diagram of cutting system

in typical experiments and the cutting velocity V was varied up to 750 mm/min. Nitrogen was mainly used for spectroscopic measurements and for cutting experiments air was supplied from a compressor. Dimension of the workpiece (SM 41) was 100 ×200 mm with various thickness t (t= 3,4,6 mm).
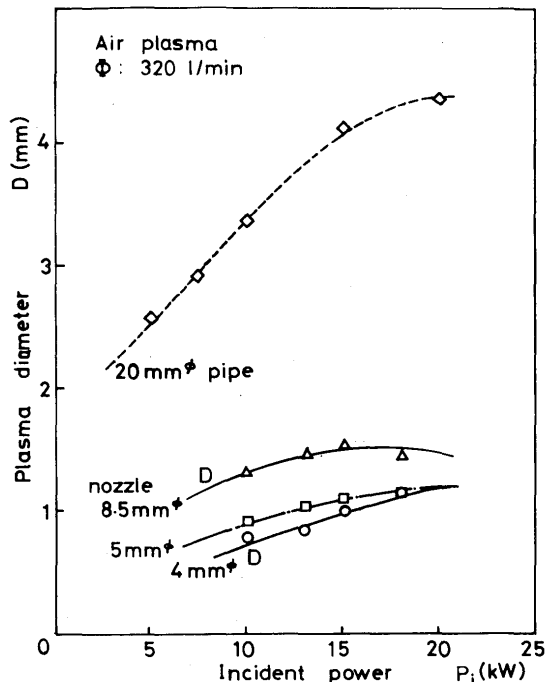

Fig. 3   Dependence of plasma diameter on incident power for various nozzle dimensions.

3. Plasma properties

Dependence of plasma diameter D obtained by spectroscopic method on incident power P_i is given in Fig. 3. Data by a dotted curve is brought from the experiment in a tube of 20^ϕmm in Report III[2]. Solid curves are the results of the present experiment. As was expected in the previous report, the plasma diameter diminishes sharply by the change in tube diameter from 20 to 10 mm. Moreover it becomes smaller with the decrease in nozzle diameter D_n. A plasma beam of about 1mm in diameter, which is satisfactory to be used for cutting experiment, is obtained in a nozzle of D_n=5mm. Unlike to the definition in Report II[1], the length of the plasma beam photographed below the edge of the nozzle is adopted to be plasma length L_p, since only this part of the beam can be used for cutting. Of course, it has similar dependences as that of Report II on input power and L_p=30~50 mm is obtained for typical experimental conditions.

While it was stated in Report III that change of nitrogen flow rate gave little influence on plasma parameters, in the present experiment it has an appreciable effect and the smaller the nozzle diameter, the stronger the decrease in the plasma diameter when the
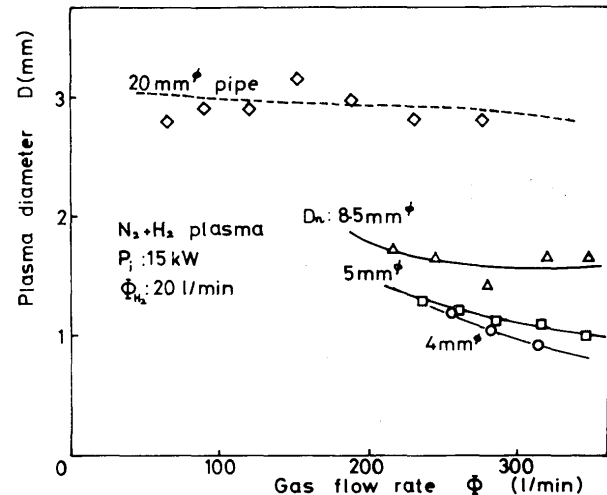

Fig. 4   Change of plasma diameter with gas flow rate.

flow rate is increased. These features are shown in Fig.4. It is easy to consider from these results that the dimension of the nozzle has fundamental effects on the nature of the plasma beam.

As for the influence of the change in nozzle length l on the plasma dimension, it was shown that a long nozzle shortened the beam length, and this tendency was intensified in a stronger gas flow. While the plasma diameter was increased (as is given in Fig. 5) with less brightness of the core when the nozzle length was larger. This suggests that a longer nozzle plays a disadvantageous role to obtain a plasma beam of a high energy density. So that all the data are given with a nozzle of 10 mm in length when it is not noticed in figures.

Fig. 6 shows the change of plasma temperature T on incident power P_i for various nozzle diameters. It was measured at a point whose distance was 2.5 mm apart from the edge of the nozzle in the axial direction. Dotted line is brought from Report III as in Fig. 3. The nozzle of 4 mm in diameter raises the plasma temperature steeply with the incident power.

Occurrence of a considerable difference in the temperature compared with the data of Report III was already assumed as well as the beam diameter and a favorable increase of T from 6900 to 8100 K at P_i=20 kW is obtained by the change of the tube configurations. Theoretical analysis also offers such a tendency. Figure 7 gives a theoretical dependence of plasma temperature on incident power per unit length P_0 for various tube or nozzle radii R. By decreasing R, T is increased by thermal pinching effect and a sharper rise in temperature is obtained in a smaller radius. It should be emphasized that these features corresponds qualitatively well to the data in Fig. 6.

As the plasma diameter decreases remarkably with the increase in nitrogen flow rate (Fig. 4), the beam temperature also changes noticeably with the gas flow

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in contrast to the data in the early paper. Fig. 8 shows the dependence of plasma temperature on gas flow rate ϕ at two points in the axial direction. The position $z=0$ corresponds to the edge of the nozzle. Near the exit of the nozzle ($z=2.5$ mm) T increases with ϕ causing thermal pinching, while at $z=7.5$mm the beam becomes colder. This shows that a strong nonuniformity of T appears with the increase of ϕ, which will cause a considerable influence on cutting experiment.

The gas glow will freely expand after the passage of the nozzle reigon. If the flow is laminar in the nozzle
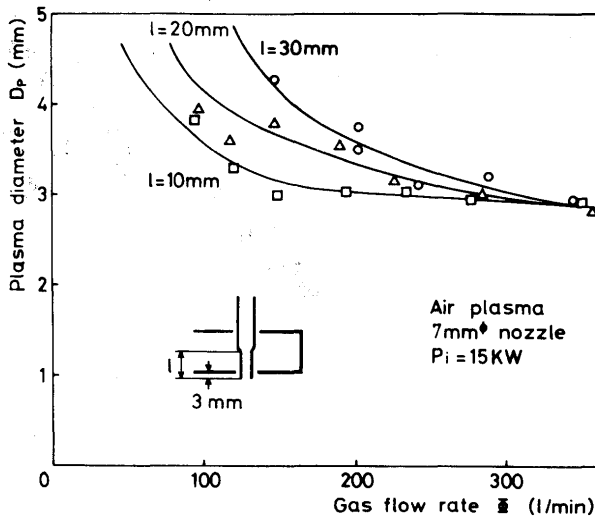

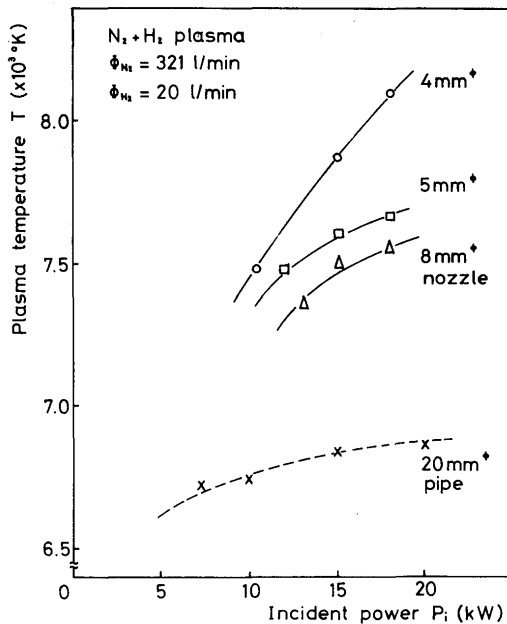Fig. 5   Dependence of plasma diameter on gas flow rate.

Fig. 6   Relation between plasma temperature and incident power.

region the heat towards the free space in the axial direction will flow smoothly with a small radial loss. But in a turbulent flow, the radial loss will be greatly augmented, resulting in a large temperature gradient in the flow direction.

As is well known Reynold's number R_L is proportional to (ϕ/D_n). Under our experimental conditions R_L
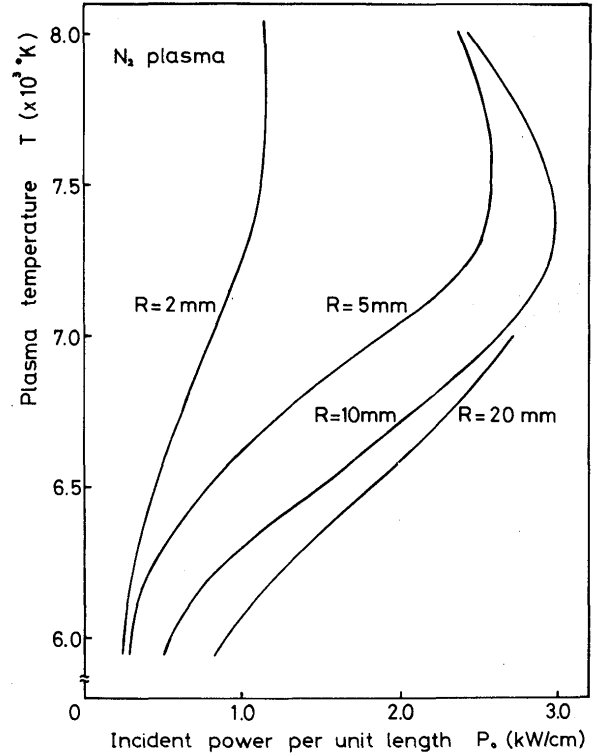

Fig. 7   Dependence of plasma temperature on incident power per unit length calculated from Meierovich's analysis.
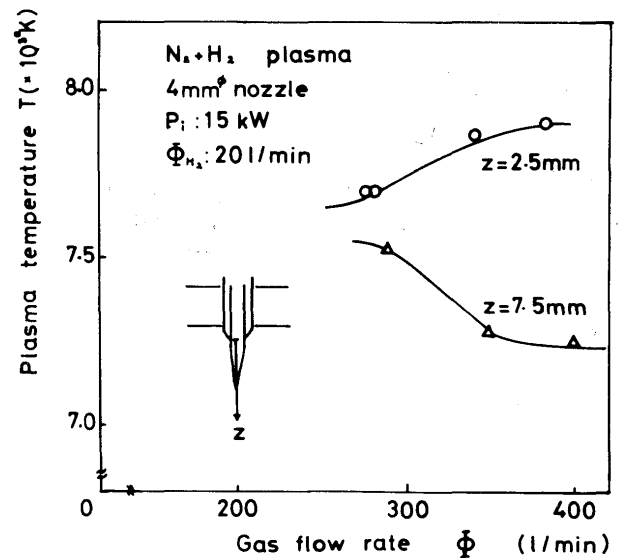

Fig. 8   Change of plasma temperature with gas flow rate at two points in the axial direction

is larger than 10^4, which is sufficient to consider that the plasma flow is turbulent[4]. So that a plasma beam out of a nozzle of a small D_n might have a large nonuniformity in the axial direction (Fig.8). Experimentally observed diminishing of the beam length L_p with the increase in ϕ is also considered to come from the increase in R_L.

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4. Cutting experiment

Fig. 9 shows typical photographs of cutting front (a), and cutting kerfs (b) (c), of a mild steel. The front is smooth and molten metal remains unremoved within cutting groove when the cutting speed is high (V=375 mm/min).

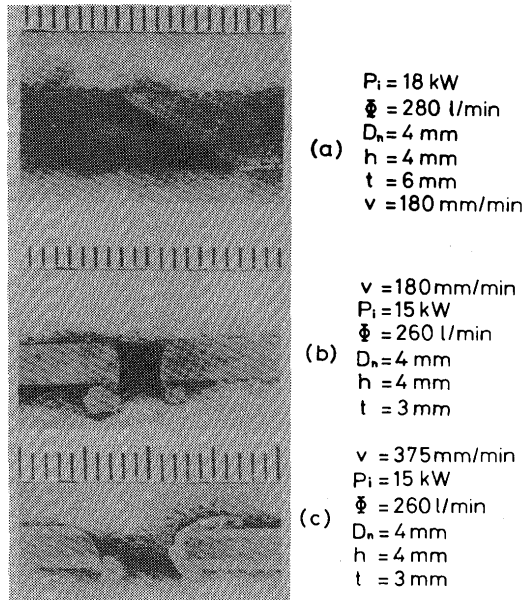In Figs. 10 and 11 dependence of top and bottom

(a)
$P_i = 18$ kW
$\Phi = 280$ l/min
$D_n = 4$ mm
$h = 4$ mm
$t = 6$ mm
$v = 180$ mm/min

(b)
$v = 180$ mm/min
$P_i = 15$ kW
$\Phi = 260$ l/min
$D_n = 4$ mm
$h = 4$ mm
$t = 3$ mm

(c)
$v = 375$ mm/min
$P_i = 15$ kW
$\Phi = 260$ l/min
$D_n = 4$ mm
$h = 4$ mm
$t = 3$ mm

Fig. 9   (a) Typical photographs of cutting front of a mild steel (t=6mm, V=180mm/min,ϕ=280l/min, P_i=18 KW); (b), (c) photographs of cutting kerf for two values of cutting velocity

kerf widths, W_T and W_B respectively, of the groove on the cutting velocity V is given. Both W_T and W_B show a complex change with V. When a constant heat input is
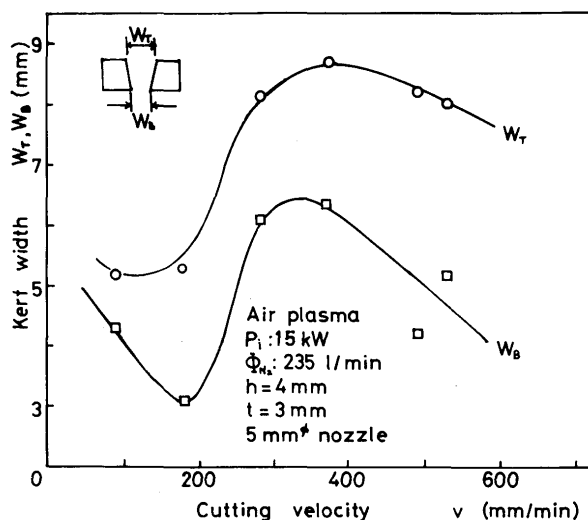
supplied to a meterial, kerf widths should decrease with the velocity, since the heat input per unit length along the cutting direction will diminish in propeortion to V. This process is acomplished when $V \leq 200$ mm/min and the molten metal is efficiently blown off downwards. In the range $200 \leq V \leq 400$ mm/min the secondary melting effect is dominant. In this case momentum change of the plasma stream will occur within the groove and flow of the molten metal towards the side wall of the groove causes a further melting of the workpiece. A resultant increase in K_T and K_B with V is shown in the figure. In the last region of $V \geq 400$ mm/min, the secondary melting effect becomes relatively small and a curve similar to the first region is again obtained. A wider kerf in a smaller gas flow rate obtained in Fig. 11 comes from a larger diameter of the plasma beam (Fig. 4).

Dependence of drag d of the cutting line on cutting velocity V is shown in Fig. 12 for various gas flow rates ϕ. The relation of d with ϕ is reversed near $V = 400$ mm/min. At a constant gas flow rate it is usual that the drag increases with the velocity because of the momentum change of plasma stream decaying in the flow direction. In a relatively-low velocity the plasma stream flows directly below the workpiece and the upper part with a higher temperature remains within the groove. In this case a smaller drag is expected in a high gas flow rate by the increase in the beam temperature (Fig. 8). But when the cutting velocity is large, the plasma stream decays in the flow direction within the groove. The decay is stronger in the higher gas flow. This results in the occurrence of a large drag causing a reversion in the figure.

Account of the critical cutting velocity V_C is

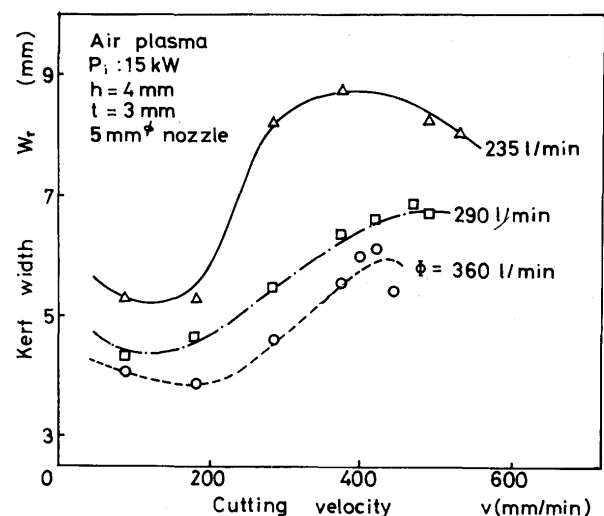Fig. 10   Dependence of top and bottom kerf widths on cutting velocity.

Fig. 11   Change of top kerf width on cutting velocity.

important as a standard of the capacity of a heat source. Fig. 13 shows the dependence of the critical velocity on the incident power. Broken and dot-dash lines correspond to the critical velocity V_c for two values of ϕ.
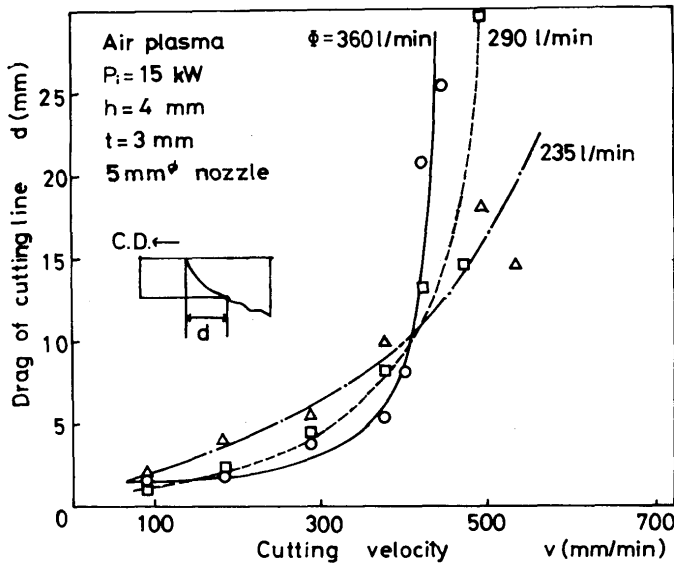

Fig. 12   Relation between drag of cutting line and cutting velocity for three values of gas flow rate.

It increases with the incident power and $V_C = 600$ mm/min is obtained for P_i=18 kW in a workpiece of t = 3 mm. The sharp decrease of V_c below 10 kW comes from the fact that the beam length becomes too small to be used for cutting. While dependence of the critical velocity on the gas flow rate is shown in Fig. 14. Naturally a larger velocity is obtained in a smaller nozzle due to a larger energy density, but the decrease of V_c with ϕ is stronger in a smaller nozzle.

The latter phenomenon is caused by strong decay of the plasma temperature in relation to the increase of the flow rate, which is essentially the result of the turbulent
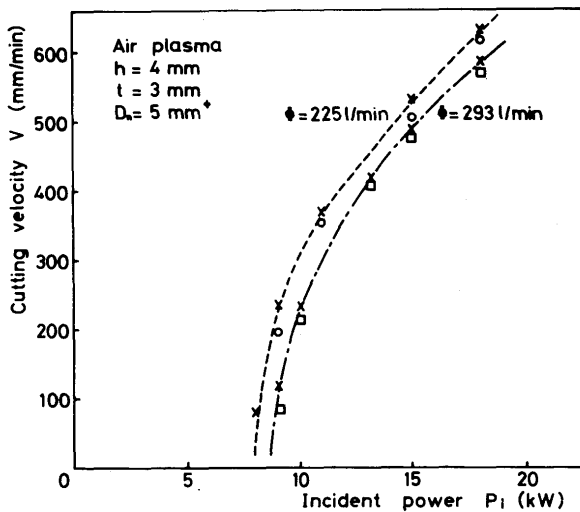
heat flow described in Sec. 3. Effect of the axial temperature decay on the cutting efficiency is shown in a more distinct fashion in Fig. 15. By increasing the torch height h the critical cutting velocity sharply falls away at $h \geq 6$mm. This result ascertains well the result in Fig. 8, and the curve can be considered to be the temperature profile of the plasma beam in the axial direction.

From these results it should be concluded that a strong decay of the beam temperature along the flow direction has a substantial unfavorable effect on the cutting characters. To improve this property a plasma beam formed in a water-cooled nozzle system should be used with a flow rate below 200 1/min, since a rather long, uniform temperature distrubution in the axial direction can be obtained in a small gas flow rate.
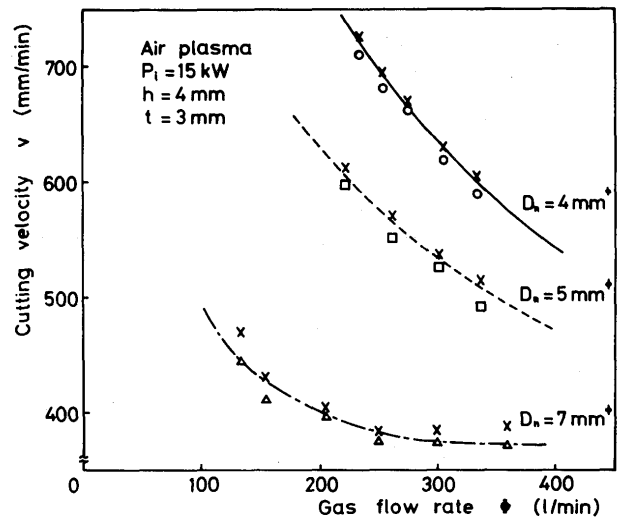

Fig. 14   Dependence of critical cutting velocity on gas flow rate for various nozzle dimensions.
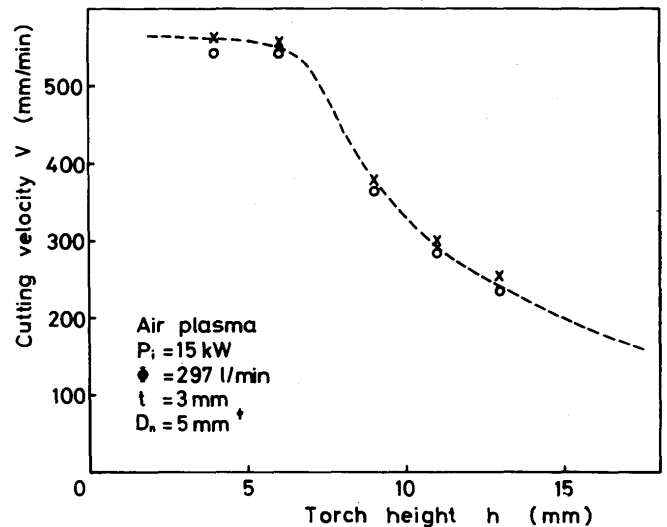

Fig. 13   Critical cutting velocity versus incident power.

' Fig. 15   Change of critical cutting velocity with torch height The torch height is the distance from the torch exit to the workpiece.

5. Conclusion

In this report plasma properties to be used for the cutting of various materials were investigated experimentally in a plasmatron with a nozzle of a small diameter lower than 10mm. Some experimental results of cutting of mild steels were also obtained. Several concluding remarks are given in the following:

1) By using a nozzle of 4mm in diameter a plasma beam of about 1mm in diameter is obtained with the beam temperature over 8000 K;

2) Strong increase in the plasma temperature with the power input in such a small nozzle was experiment- ally clarified, which was also expected from theoretical estimation;

3) Considerble change of the plasma diamter and its temperature with the gas flow rate are observed in proportion to the decrease in the nozzle diameter;

4) Within the region of the plasma beam to be used for cutting, temperature gradient becomes stronger with the gas flow, which is considered to come from turbulent flow of the gas in the nozzle region;

5) In cutting experiment kerf widths are strongly affected by the effect of the secondary melting;

6) Since critical cutting velocity is decided mainly by the energy density of the beam within the cutting groove, degree of temperature decay in the flow direction has an important effect.
    Strong temperature decay in a large gas flow gives an unfavorable result, showing a sharp decrease in the critical velocity with the increase of the distance between the torch and the workpiece;

7) Studies of the turbulent flow should be performed in detail to reform the applicability of this type of plasma beam for cutting or welding various materials.

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