Micro Cutting of Thin Copper Plate by Fiber Laser with Laval Nozzle

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Fiber laser has many advantages such as compact size, high conversion efficiency, good beam mode, air cooling and maintenance free. Therefore, it has high possibility as an industrial light source in the near future. The beam from fiber laser can be focused in a micro spot because of its excellent beam quality. However, the narrow kerf leads to the difficulty of outflow of melted material. Therefore, micro cutting by a single-mode fiber laser is considerably difficult, then the high performance nozzles are strongly required. In the previous work, authors developed a high performance nozzle, which can increase the velocity of assist gas flow and makes it possible to reduce the dross in the micro kerf. Therefore, high performance cutting by a single-mode fiber laser can be expected by using our newly designed nozzle. In this study, the effect of nozzle shape on the machining results in precision cutting of thin copper plate by a Q-switched single-mode fiber laser was experimentally investigated. It was found that the high speed cutting at 30mm/s could be carried out by the high performance nozzle under low pulse frequency condition. Besides, the reduction of the dross and good kerf shape could be attained in the case of nitrogen assist gas.

Keywords: Q-switched single-mode fiber laser, high-performance nozzle, thin copper plate

1. Introduction

In precision laser cutting of thin metal plate, material is melted or vaporized by the absorbed heat and is partly removed by the pressure of vaporization. This scattered material adheres as spatter to the base material again. However, it can be prevented by an anti-adhesive coating. Melted material is mostly carried away downward by the assist gas flow spouted coaxially along the axis of the laser beam. Some part of melted material adheres to the bottom of workpiece as dross, which leads to the deterioration of the surface integrity in micro cutting [1-3].

On the other hand, the fiber laser has many advantages such as compact size, high conversion efficiency, air-cooling and maintenance free. Therefore, it has a high possibility as the industrial light source in the near future [4]. The laser beam from single-mode fiber laser can be focused in a micro spot because of its excellent beam quality. However, a lot of dross are remained at the back surface of workpiece, since the fluidity of melted material becomes lower in the narrow kerf. Therefore, precision micro cutting by a single-mode fiber laser is considerably difficult.

Our previous work made it clear that the pressure of assist gas on workpiece is reduced approximately less than half of the cylinder gas pressure under high pressure condition in the case of conventional nozzle [5]. Therefore, the high-performance nozzles, which can generate the high-pressure assist gas on workpiece, are required in order to perform high performance cutting. Then we developed a high-performance nozzle, which can increase the velocity of assist gas flow spouted from nozzle tip [6, 7]. Thus, high performance cutting by single-mode fiber laser can be expected by using our newly designed nozzle.

In this study, the effects of nozzle shape on the machining results in precision cutting of thin copper plate by Q-switched single-mode fiber laser were experimentally investigated.

2. Experimental procedures

Experimental setup for laser cutting is schematically shown in Fig. 1. Q-switched single-mode Yb:fiber laser was used. Table 1 shows the laser specification. Laser beam of 6mm in diameter was focused on the workpiece surface by a lens of 49.9mm in focal length. Copper of 100um in thickness was used as a workpiece, which was set on the X-Y-Z stage. The feed rate of stage was controlled by the NC controller (MYCOM SNC-440). Oxygen and nitrogen were used as an assist gas, whose pressure was fixed at 600kPa in cutting experiment. The pulse frequency was varied from 20 kHz to 80 kHz. The gap distance between the nozzle tip and the workpiece surface was kept to be 1mm.
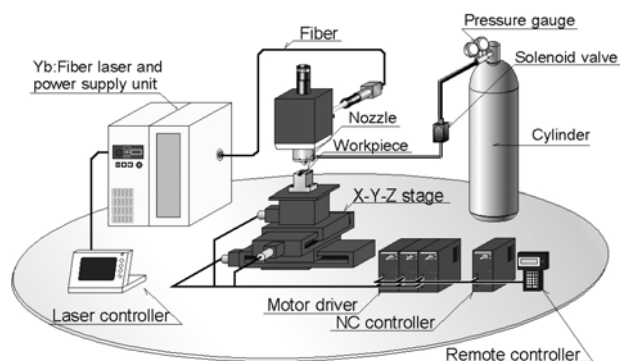
Fig. 1 Schematic diagram of experimental setup

Table 1 Laser specification

Wave length	1060nm
Max. pulse energy	1mJ/P
Max. average power	20W
Pulse frequency	20-80kHz
Pulse duration	130-250ns

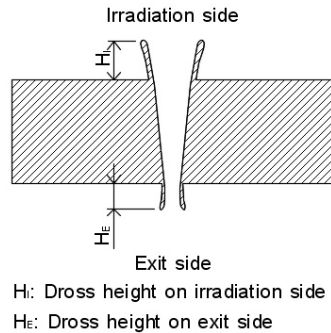H_I: Dross height on irradiation side
H_E: Dross height on exit side

Fig. 2 Definition of dross
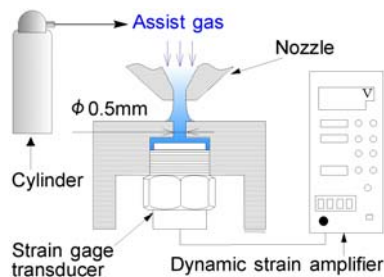
Fig. 3 Measurement method of pressure on workpiece

(a) Nozzle N   (b) Nozzle Laval   (c) Nozzle Laval IEZ
Fig. 4 Shapes of nozzle

Fig. 5 Relationships of pressure on workpiece with cylinder gas pressure with Nozzle N, Laval and Laval IEZ
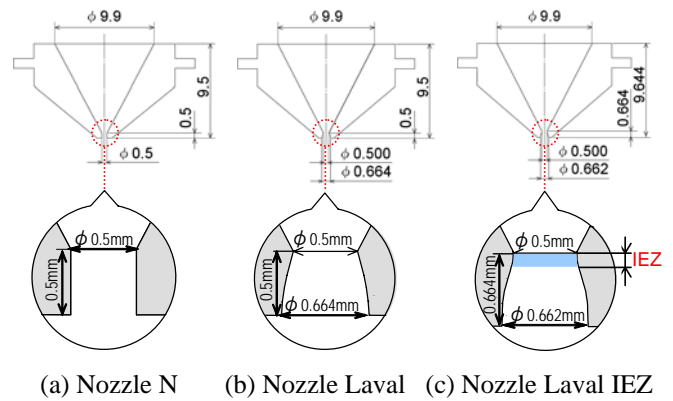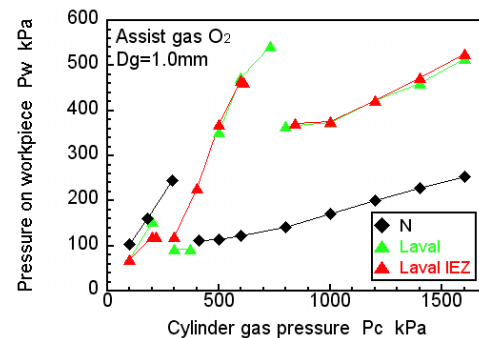
Figure 2 shows the cross section model of the workpiece after cutting experiment. The top is the laser irradiation side, and the bottom is the exit side in the figure. In this study, the dross height on irradiation side is expressed as H_i, and the dross height on exit side is H_e. Each distance between the tip of dross and the workpiece surface is measured as the dross height, which is determined by averaging ten measurements.

The pressure on the workpiece was measured as shown in Fig. 3. The semiconductor strain gage transducer was set under the penetrated hole of 0.5mm in diameter, and its output was recorded as the pressure on workpiece. In this study, the pressure is expressed as P_w (the pressure on workpiece), and the pressure at the exit of cylinder is expressed as P_c (the cylinder gas pressure).

3. High-performance nozzle

Figure 4 schematically shows the section of nozzles used in this study. Figure (a) is Nozzle N, which is a traditional convergent nozzle with straight throat. Figure (b) is Nozzle Laval with the throat shape designed under the condition in which the correct-expansion flow can be obtained at 800 kPa in internal pressure of nozzle, when the external pressure is 101.3 kPa. Figure (c) is Nozzle Laval IEZ, in which the initial expansion zone (IEZ) of 150um is added to Nozzle Laval.

Figure 5 shows the relationships of the pressure on workpiece with the cylinder gas pressure using Nozzle N, Nozzle Laval and Nozzle Laval IEZ. As can be seen from the figure, the pressure on workpiece for these nozzles increased with increasing the cylinder gas pressure until the first unstable region. In the unstable region, the pressure on workpiece changes periodically, then the results are not plotted on the graph. The unstable region appears only once in the case of Nozzle N, while Nozzle Laval and Nozzle Laval IEZ have three and two unstable regions respectively. Thus, the cylinder gas pressure should be carefully set. However, the unstable region of Nozzle Laval IEZ is narrower than that of Nozzle Laval, so the initial expansion zone is effective for decreasing the unstable region.

On the other hand, the pressure on workpiece after second unstable region using Nozzle Laval and Nozzle Laval IEZ are approximately four times higher than Nozzle N around 600kPa in cylinder gas pressure. In this case, the pressure on workpiece is about 70 % of cylinder gas pressure. This means that the energy loss of assist gas flow using Nozzle Laval and Nozzle Laval IEZ are much lower than Nozzle N. They are very effective for increasing the pressure on workpiece under proper cylinder gas pressure condition. Therefore, the cutting experiment was carried out at 600 kPa in cylinder gas pressure in this study.

4. Results and discussion

Table 2 shows the cutting results for various pulse frequencies using Nozzle N, Nozzle Laval and Nozzle Laval IEZ using oxygen assist gas. Laser beam was irradiated from the edge to the surface of workpiece in cutting experiment. When the workpiece was completely separated, it was judged as the possible condition to cut. On the other hand, it was judged as the impossible condition to cut, when the workpiece could not be separated individually. As
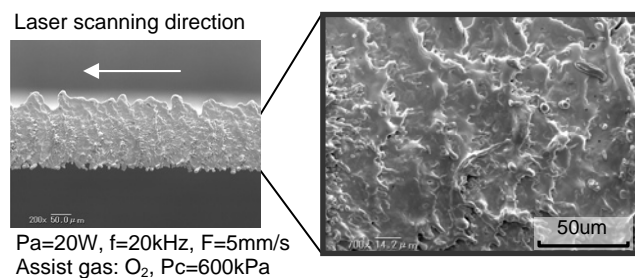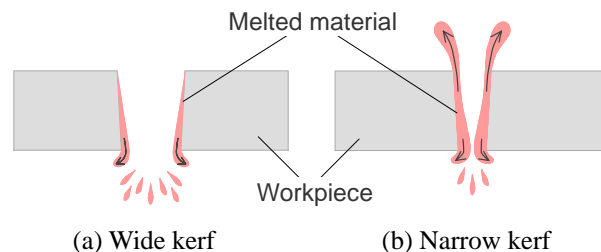
Table 2 Maximum cutting speed for various pulse frequencies with Nozzle N, Laval and Laval IEZ using O_2

	20kHz	30kHz	40kHz	60kHz	80kHz
N	11mm/s	4mm/s	1mm/s	-	-
Laval	30mm/s	13mm/s	10mm/s	6mm/s	1mm/s
Laval IEZ	30mm/s	25mm/s	12mm/s	8mm/s	2mm/s

(a) Irradiation side

(b) Exit side
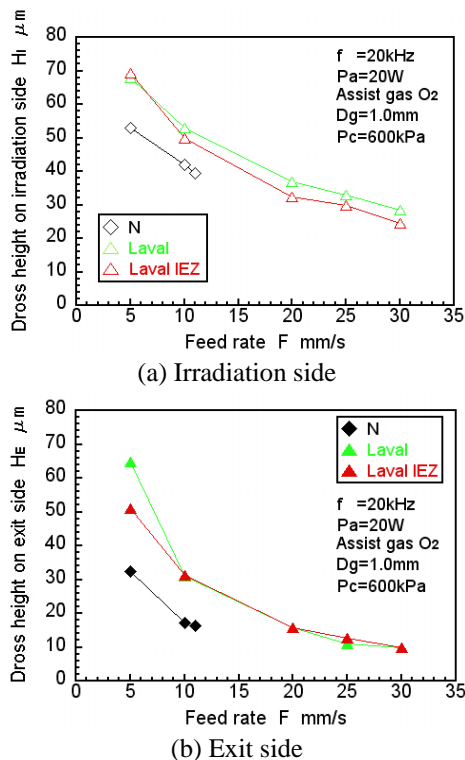
Fig.6 Relationships between dross height and feed rate with Nozzle N, Laval and Laval IEZ using O_2

Pa=20W, f=20kHz, F=5mm/s
Assist gas: O_2, Pc=600kPa

Fig.7 Cut surface with Nozzle N using O_2

(a) Wide kerf   (b) Narrow kerf

Fig. 8 Melted material in wide and narrow kerf

shown in the table, every nozzle takes the highest maximum cutting speed at lowest pulse frequency. It is considered that high speed cutting is possible, since the peak power becomes higher under lower pulse frequency. When the pulse frequency was 20 kHz, the maximum cutting speed was 11mm/s in the case of Nozzle N. On the other hand, cutting could be carried out at 30mm/s in the case of Nozzle Laval and Nozzle Laval IEZ, and they are approximately three times higher than that of Nozzle N. Here, the cutting speed of 30mm/s is the fastest feed rate of stage system used in this study, so the cutting experiments were not carried out at the feed rate over 30mm/s. Besides, the use of Nozzle Laval and Nozzle Laval IEZ made it possible to cut even under higher pulse frequency condition, because the pressure on workpiece using Nozzle Laval and Nozzle Laval IEZ are approximately four times higher compared to Nozzle N. Moreover, the maximum cutting speed of Nozzle Laval IEZ is approximately two times higher than that of Nozzle Laval. The pressures on the workpiece for both nozzles are equal as shown in Fig. 5. However, the maximum cutting speed of Nozzle Laval IEZ is higher than Nozzle Laval under every pulse frequency condition. It is considered that these results show the effects of improvement in the straightness of assist gas flow owing to the initial expansion zone.

Figure 6 shows the relationships between the dross

height and feed rate using oxygen assist gas. The dross height using every nozzle decreased with increasing the feed rate. The dross height of Nozzle N is smaller than Nozzle Laval and Laval IEZ. This is considered in the following. Since the pressure on the workpiece with Nozzle N is low, the maximum cutting speed is low. Therefore, it could not remove the melted material effectively. Thus, in the case of Nozzle N, the amount of removed material from the kerf to the bottom side becomes little compared to Nozzle Laval and Nozzle Laval IEZ. Therefore, it is considered that the dross height using Nozzle N was small under the same feed rate condition. Besides, the dross height on irradiation side was larger than that of exit side for every feed rate.

Figure 7 shows the SEM photographs of cut surface with Nozzle N using oxygen assist gas. The laser beam was scanned from right to left side in the figure. As can be seen from the figure, melted material flows not only downward but also upward. In general, melted material can be removed away downward by the assist gas flow in the case of wide kerf as shown in Fig. 8 (a). However, since the kerf is very narrow in the case of single-mode fiber laser, it is difficult to push out the melted material downward from the kerf as shown in Fig. 8 (b). Thus, it is considered that melted material is spouted out upward.

Table 3 shows the cutting results for various pulse frequencies using Nozzle N, Nozzle Laval and Nozzle Laval IEZ using nitrogen assist gas. As shown in the table, it was impossible to cut under any feed rate and pulse frequency condition in the case of Nozzle N. The oxidation reaction does not occur, since the nitrogen assist gas is inert gas. Material is melted or vaporized only by the absorbed energy of laser beam, and melted material is mainly removed by the assist gas pressure. Therefore, it is considered that cutting ability of Nozzle N is inferior to other nozzles, since the pressure on workpiece of Nozzle N was lower. On the other hand, in the case of Nozzle Laval and Nozzle Laval IEZ, the maximum cutting speed 30mm/s could be obtained, when the pulse frequency was 20kHz. However, it was impossible to cut under any feed rate condition, when

Table 3 Maximum cutting speed for various pulse frequencies with Nozzle N, Laval and Laval IEZ using N_2

	20kHz	30kHz	40kHz	60kHz	80kHz
N	-	-	-	-	-
Laval	30mm/s	-	-	-	-
Laval IEZ	30mm/s	-	-	-	-
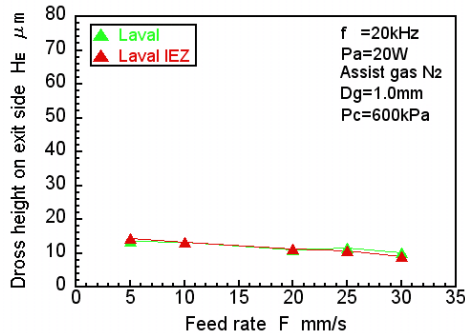
Fig.9 Relationships between dross height on exit side and feed rate with Nozzle Laval and Laval IEZ using N_2

the pulse frequency is more than 30kHz. The maximum cutting speed of Nozzle Laval IEZ is the same to Nozzle Laval in the case of nitrogen assist gas. In the case of oxygen assist gas, Nozzle Laval IEZ could perform more efficient cutting compared to Nozzle Laval. Similarly in the case of the nitrogen assist gas, efficient cutting by Nozzle Laval IEZ can also be expected, when the feed rate becomes higher.

Figure 9 shows the relationships between the dross height on exit side and the feed rate using nitrogen assist gas. In the figure, the results of the Nozzle N are not plotted, because it was impossible to cut under any feed rate conditions as mentioned above. The dross heights of both Nozzle Laval and Nozzle Laval IEZ are almost the same under any feed rate conditions. These dross heights using nitrogen assist gas are smaller compared to that with using oxygen assist gas.

The cross sections of workpiece with Nozzle Laval and Nozzle Laval IEZ using nitrogen assist gas are shown in Fig. 10, where the cutting speed is 30mm/s. As can be seen from the figure, the heat affected zone was very small. Besides, more straight cutting shape can be obtained using Nozzle Laval IEZ. Furthermore, the kerf shape in the case of nitrogen is straighter, and the dross height was smaller compared to oxygen assist gas as shown in Figure 11. Therefore, Q-switched single-mode fiber laser using Nozzle Laval IEZ proved to be available and useful in cutting of thin copper plate.

5. Conclusions
Main conclusions obtained in this study are as follows:
(1) High speed cutting of 30mm/s could be carried out with Nozzle Laval and Nozzle Laval IEZ, since high assist gas pressure could be supplied on the workpiece.
(2) Change of assist gas from oxygen to nitrogen made it impossible to cut completely in the case of Nozzle N. On the other hand, equivalent cutting speed could be obtained in the case of Nozzle Laval and Nozzle Laval IEZ regardless of kind of assist gas under low pulse frequency condition.
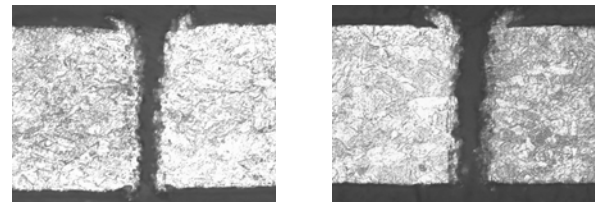
(a) Laval   (b) Laval IEZ
Pa=20W, f=20kHz, F=30mm/s
Assist gas: N_2, Pc=600kPa
$\underline{\quad 50um \quad}$

Fig.10 Cross section with Nozzle Laval and Laval IEZ using N_2
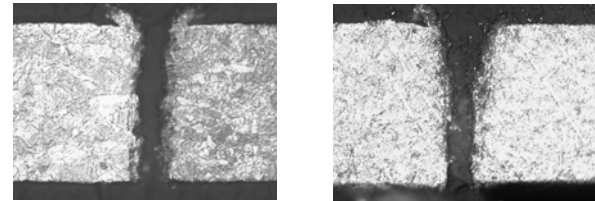
(a) Nitrogen   (b) Oxygen
Pa=20W, f=20kHz, F=10mm/s
Pc=600kPa, Nozzle Laval IEZ
$\underline{\quad 50um \quad}$
Fig.11 Cross section with Nozzle Laval IEZ

(3) Nozzle Laval IEZ with initial expansion zone made it possible to cut more efficiently under higher pulse frequency condition in the case of oxygen assist gas.
(4) Dross height on irradiation side was larger than that on exit side. Both dross heights became smaller with increasing feed rate.
(5) Nitrogen assist gas led to the reduction of dross generation and the straight kerf shape.

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