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Author(s)	Arata, Yoshiaki; Maruo, Hiroshi; Miyamoto, Isamu; Takeuchi, Sadao
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Quality in Laser-Gas-Cutting Stainless Steel and its Improvement[†]

Yoshiaki ARATA*, Hiroshi MARUO, Isamu MIYAMOTO*** and Sadao TAKEUCHI******

Abstract

The effect of cutting parameters in laser-gas-cutting on the qualities of cuts has been studied in stainless steel plate of 0.5 to 4 mm thickness using 1 kW CO_2 *laser. In conventional method, in which oxygen flow is coaxially arranged with focused laser beam, the quality of stainless steel cut is undesirable because an oxide dross tends to cling to the bottom edge of the cut due to its poor fluidity. For this improvement, the two new cutting techniques, "Pile Cutting" and "Tandem Nozzle Cutting", have been developed. Pile cutting, in which stainless steel is cut with a thinner mild steel piled on it, makes it possible to get perfect dross-free cut, since a molten iron oxide provided by mild steel enhances the fluidity of the molten layer of stainless steel. Tandem nozzle cutting also gets fine cut having little or no dross, in which an off-axial rear gas jet nozzle is used with the coaxial nozzle so as to enhance a dynamic force of gas jet to eliminate the molten metal and oxide effectively. Furthermore, these two techniques are markedly effective to improve surface roughness and out-of-flatness of the cut.*

KEY WORDS: (Laser-Gas-Cutting) (CO_2 Laser) (Oxygen) (Stainless Steel) (Quality) (Dross) (Improvement) (High Speed Movie Picture)

1. Introduction

In recent years Laser-Gas-Cutting technique [1, 2] is widely used in automobile industry, electical engineering and so on. In spite of its wide acceptance [3-10] much potential capability has not been sufficiently revealed.

The conventional laser-gas-cutting technique, in which a gas jet is used together with focused laser beam, makes it possible for various metals to precisely cut, and especially using oxygen jet for oxidizable materials can highly enhance the cutting performance and the quality owing to a combination of oxidation energy to beam energy [11]. For instance, in cutting mild steel plate a perfectly dross-free, fine cut can be easily obtained at much higher speed, for example, 7 m/min for 1 mm thick plate at 1 kW power level [12]. However, for stainless steel plate, which has various industrial uses, laser-gas-cutting as is conventionally employed cannot get a performance high enough to apply to various actual precision processings, because some dross has a tendency to cling to the bottom edge of the cut. For this reason, laser-gas-cutting techniques for stainless steel require an exact study of cutting characteristics, or cut qualities and cutting mechanisms, so as to bring its potential performance to fully play.

In the present study, the relationship between cut qualities and cutting parameters in laser-gas-cutting stainless steels has been described in detail and the dross clinging mechanism has been revealed through observation by high speed filming of cutting region. Furthermore, on the bases of these results, two kinds of new techniques, Pile Cutting Method and Tandem Nozzle Cutting Method, to improve the cut quality have been developed by authors.

2. Experimental Procedures

The data presented here were obtained by using continuous wave CO_2 laser with the maximum output of 1.2 kW, GTE Sylvania, Inc. Model 1971. The laser beam was focused onto the workpiece surface through a ZnSe lens, and beam and oxygen gas flow were coaxially directed through a convergent nozzle with 1.5mmϕ orifice, as shown in **Fig. 1**. The three pieces of lenses with focal length f = 63.5, 127 and 254 mm were used. Austenitic stainless steel plate, SUS304 (18%Cr 8%Ni), was mainly tested here.

It is required for strict estimation of laser-gas-cutting performance to synthetically evaluate the quality of the cut surface. The cut quality can be successfully evaluated in terms of clinging dross, out-of-flatness and surface roughness of the cut, as far as we refer to the existing

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* Professor
** Professor, Faculty of Engineering, Osaka University
*** Lecturer, Faculty of Engineering, Osaka University
**** Research Instructor, Kitami Institute of Technology

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evaluation standards of thermal cut, WES 118 (Japan), DIN 2310 (West German) and IIW's tentative plan. Then the following evaluation method suitable to the laser-gas-cuts of stainless steel as shown in **Fig. 2** was used in the present study. Height of clinging dross H_D was measured with micrometer, out-of-flatness of the cut F was measured with reading micro-scope and surface roughness of the cut R (μR_z) was measured with talysurf meter and expressed as ten points roughness. The talysurf measurement was carried out only on flat surfaces of which roughness variation of less than $150\,\mu R_z$ and the maximum value R_{max} in the three trace lines was regarded as the representative roughness.

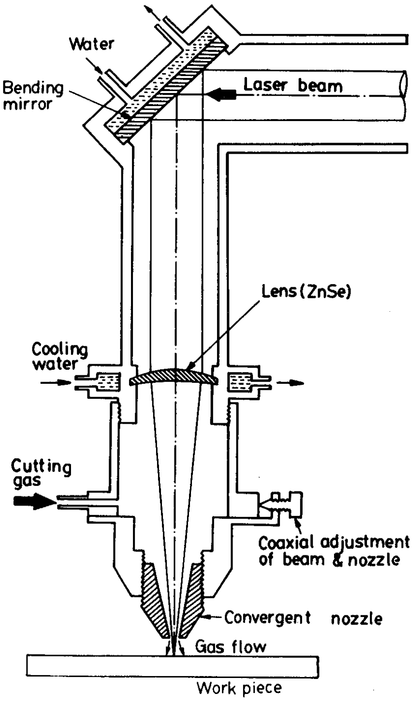


Fig. 1 Schematic diagram of laser-gas-cutting head.

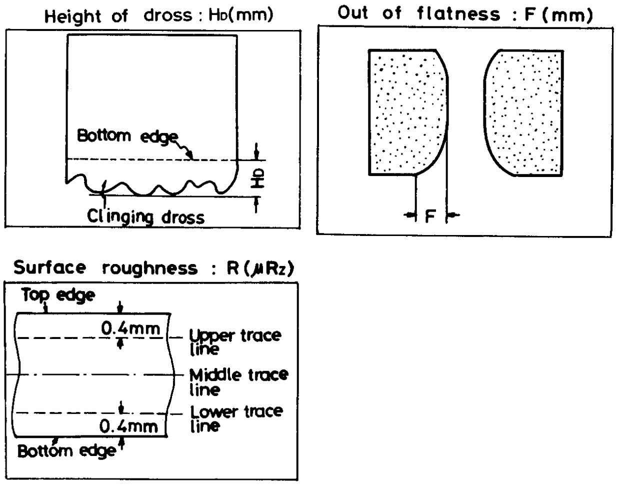


Fig. 2 Evaluation factors of cut quality and those method.

It is sufficiently useful to classify the cuts into several types by those kerf shapes, as a convenient indication of the cut surface characteristics. The five types of the cuts, which was modified from authors' method [12] for mild steel cuts, are shown in **Fig. 3**. These are generated as increase in cutting speed and/or plate thickness. IV_L type is accompanied with a rough zone in the bottom part at the low speed, II type is with a parallel kerf and some dross, III type is dross-free and fine, IV type is with a rough zone at the higher speed and V type is with a gouge at the still higher speed.

Dross clinging phenomena and flowing phenomena of molten material on the cutting front were analyzed by high speed movie pictures as shown in **Fig. 4** and **Fig. 5**. In the former case, the camera was set so as to observe the bottom edge of the cut at 4000 frames/sec and shutter speed 10^{-4} sec, as shown in Fig. 4. In the latter case it was set so as to observe directly the leading face of the cut at 4000 frames/sec and shutter speed of 10^{-5} sec, as illustrated in **Fig. 5** (refer to [12]).

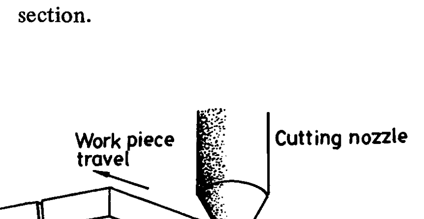


Fig. 3 Classification of laser-gas-cuts based on shape of cross section.

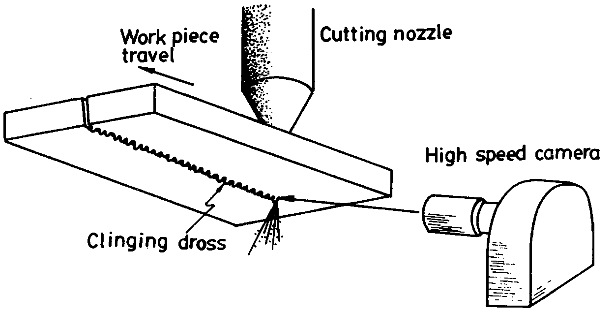


Fig. 4 Arrangement for high speed filming of dross clinging phenomena.

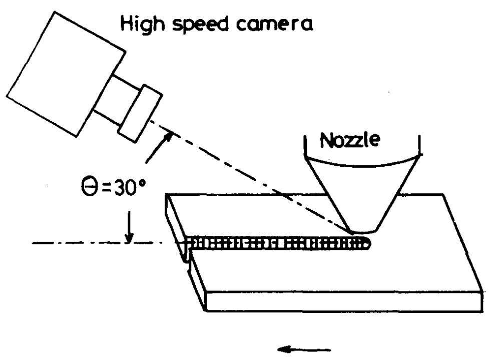


Fig. 5 Arrangement for high speed filming of melting phenomena on cutting front.

3. Performance of Conventional Cutting and its Limitation

From various cutting parameters which influence the cut qualities, cutting speed, laser power, oxygen pressure and focal length were chosen as the most important parameters, and their effects on the cut quality were tested in detail. **Figure 6** shows the result of the three evaluation factors in various incident laser powers W_i and cutting speed v_b, at the thickness of 2 mm. This result indicates that the cut qualities are best synthetically at the medium cutting speed in each power condition. Furthermore with increase in laser power the optimum speed increases gradually and the corresponding qualities also are relatively improved. The similar inclination is noticed in case of various cutting oxygen pressures P_{O_2}, as shown in **Fig. 7**. However the effect of oxygen pressure, unlike laser power, has a limitation, because it has a saturation at the pressure above 2.5 kg/cm^2 as shown in the figure. **Figure 8** shows the effect of the focal length of lens on the cut qualities. The focal length also is a very influential factor and here f = 127 mm gives the best condition to the synthetic cut quality. These results indicate that stainless steel, unlike mild steel [12], is difficult to be cut without any clinging dross in conventional cutting.

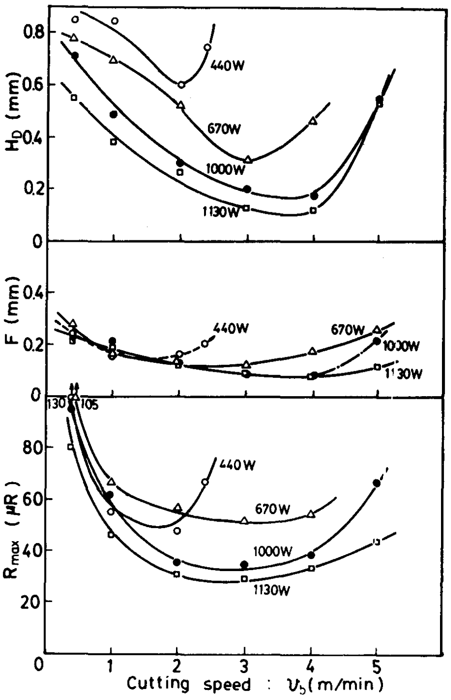


Fig. 6 Effect of laser power and speed on cut qualities. (thickness: 2 cm, oxygen pressure: 1.5 kg/cm^2, focal length: 127 mm)

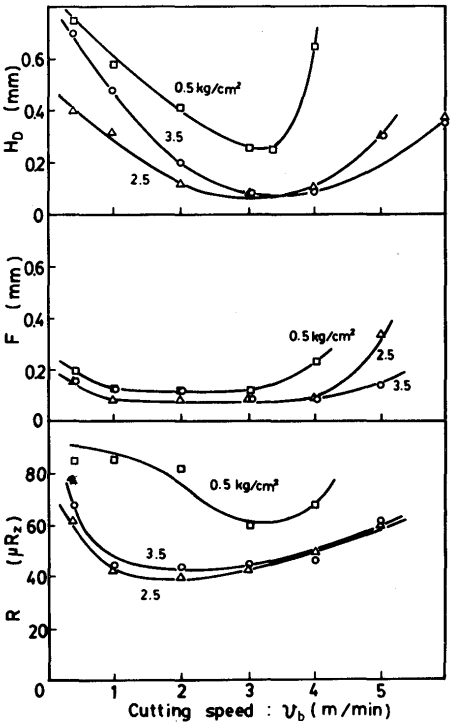
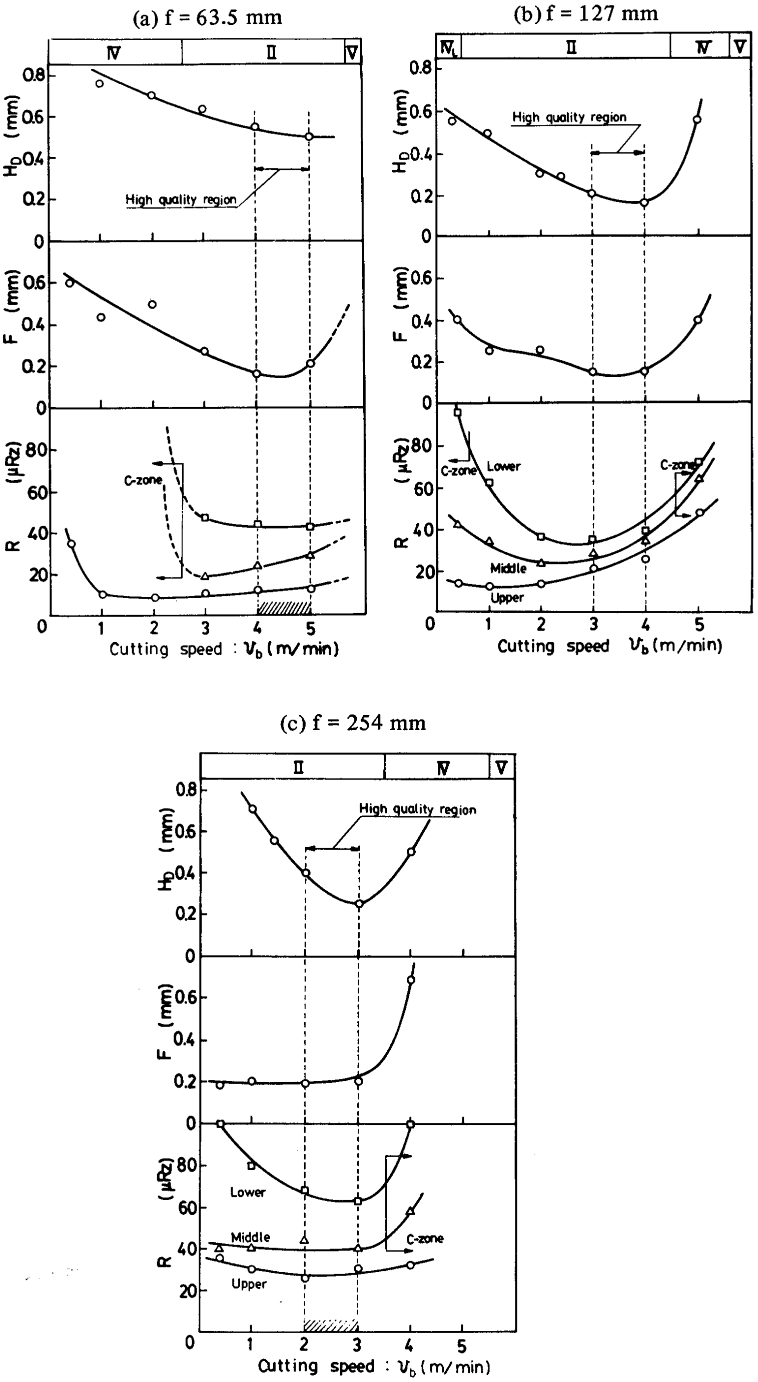


Fig. 7 Effect of oxygen pressure and speed on cut qualities. (thickness: 2 mm, laser power: 1.1 kW, focal length: 127 mm)

The results obtained above have been further studied by examining a correlation between the three evaluation factors. **Figure 9** shows the correlation diagram which involves the data in Fig. 6 and Fig. 7, provided that the plots in IV and IV_L types, having an undoubtedly rough kerf zone, have been already eliminated. The height of clinging dross is in plus correlation with the other factors and the amount of those scatters becomes the smallest in the small H_D region. This is caused by that the cutting state is dominated mainly by the situation of melting flow on the cutting front and therefore out-of-flatness and sur-


(a) f = 63.5 mm

(b) f = 127 mm

(c) f = 254 mm

Fig. 8 Effect of focal length and speed on cut qualities. (thickness: 2 mm, oxygen pressure: 1.5 kg/cm^2, laser power: 1 kW)

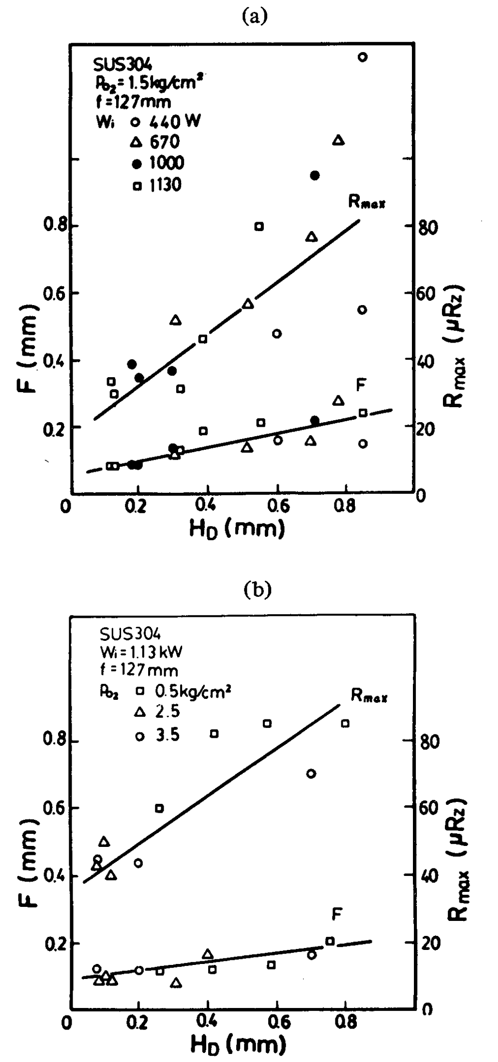


Fig. 9 Correlation between evaluation factors for various laser powers and oxygen pressures.
(a) Various laser powers
(b) Various oxygen pressures

face roughness are finally accomplished as its traces, as well as clinging dross. In view point of actual applications of laser processing, those results are much important for the following reason. In case that the cutting parameters should be determined to obtain the best performance and/or the higher cut quality, those optimum conditions can be almost found out by a visual judgement of the situation of clinging dross and/or by its amount.

4. Observation of Dross Clinging Phenomena

In the previous section, the cutting characteristics by the conventional laser-gas-cutting with a coaxial cutting nozzle were described, and the optimum controle of cutting parameters proved to be effective, but has a limitation to obtain the high cut quality with no dross. Furthermore, the correlation between the evaluation factors implicated a possibility that a further reduction of the clinging dross, if it is possible by a certain new technique, might lead to a synthetic improvement of the cut. For this reason, the study of the dross clinging mechanism is helpful to acquire an idea for improvement technique.

High speed films were taken to observe the dross clinging phenomena, with stainless steel plates of the thickness 2 mm. The results are shown in **Fig. 10** to **12**. Figure 10 shows the typical phenomena at the low speed, in which the cut is accompanied with a large amount of clinging dross. The melting flow makes a stagnated region at the bottom edge. A part of melting flow is ejected out into a large amount of small spherical drosses by the dynamic force of the gas flow. Simultaniously the other part flows backwards through the bottom edge or stays there, and is finally solidified into clinging dross. This phenomena changed remarkably with cutting speed. The dross clinging phenomena in which the dross is the minimum are shown in Fig. 11. The backward melting flow as shown in Fig. 10 is weak in this case, and a long pendent part (1 to 2 mm length) is formated at the ejecting region of the flow, so that the most of spherical drosses are scattered through this pendent part. In this case there exists a small disturbance at the ejecting region (the neck of the pendent part) and it develops into the clinging dross. Figure 12 shows the typical phenomena in the IV type cutting, in which the amount of clinging dross increases again. There exists a greatly disturbed flow, which ejects out along the inclined cutting front as making a rough zone.

Dross clinging process was deduced also through microscopic observation of the cut kerf. **Figure 13** shows the appearances of the cut near the bottom edge after laser-gas-cutting. The thick solidified metal zone is left over the base metal and is connected with the clinging dross. This fact explains the following cutting process. In cutting a part of molten metal on the cutting front only is beeing oxidized by oxygen and another part in the sublayer remains non-reacted, so that a cohesive force is generated between both layers just when the oxide layer (or dross) is ejected out. This force and the less fluidity of the molten oxide make the flow disturb and suppresses the smooth separation of the molten dross from the bottom edge because there is a great disturbance produced by an intensive burning in the lower part of the kerf as illustrated in Fig. 12.

It is concluded from those results that an inclination of dross clinging is greatly influenced by the melting/flowing conditions of material on the cutting front. Therefore, a basic need in an improvement technique is to enhance relatively the fluidity of molten flow on the cutting front or to further increase the momentum of gas flow, or the gas dynamic force, so as to suppress the stagnation and/or disturbance of the melting flow. From this view point the two kinds of new improvement techniques have been developed as later described.

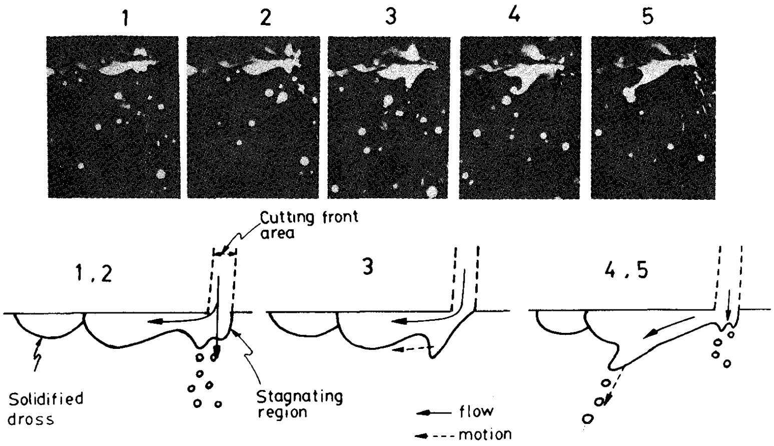


Fig. 10 High speed movie pictures of cutting accompanied with a large amount of clinging dross. (cutting speed: 1.4 m/min, thickness: 2 mm, laser power: 1 kW, oxygen pressure: 1.5 kg/cm², time interval: 0.3 msec)

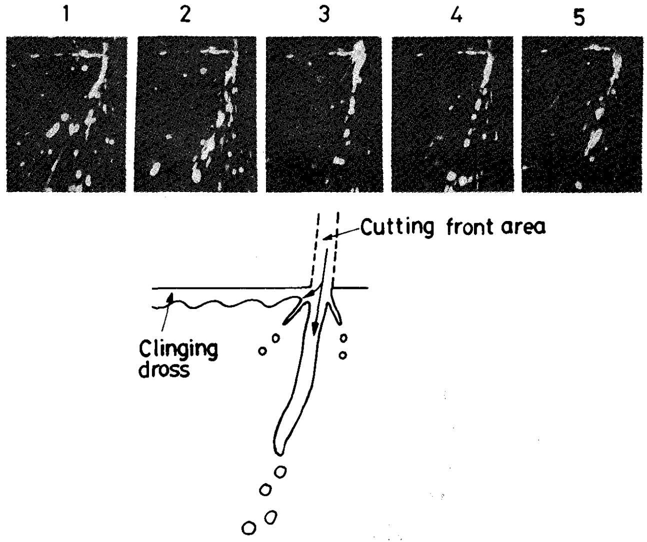


Fig. 11 High speed movie pictures of cutting accompanied with a little amount of clinging dross. (cutting speed: 3 m/min, other conditions: the same as in Fig. 10)

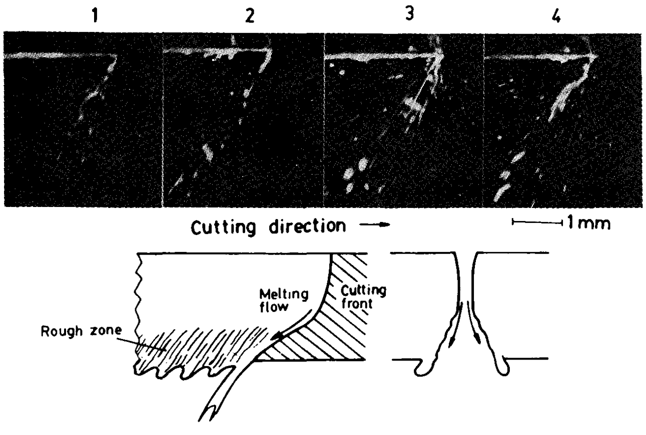


Fig. 12 High speed movie pictures of cutting accompanied with rough kerf zone. (cutting speed: 5 m/min, other conditions: the same as in Fig. 10)

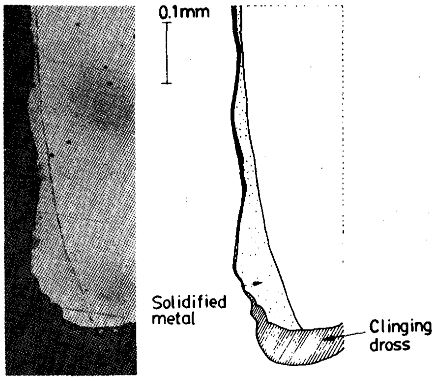


Fig. 13 Appearances of molten metal and clinging dross near bottom edge. (speed: 3 m/min, thickness: 2 mm)

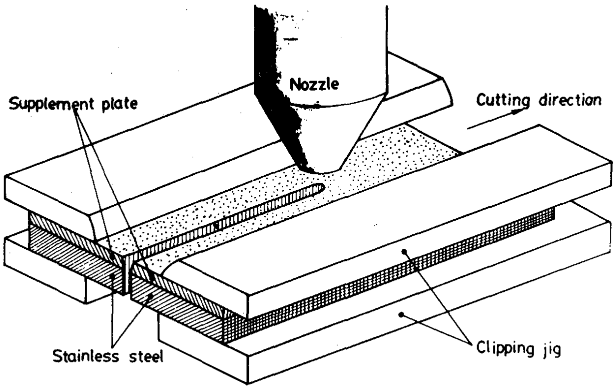


Fig. 14 Schematic diagram of pile cutting method.

5. Improvement of Cut Quality by Pile Cutting Method

5.1. Pile Cutting Method and its Characteristics

Pile cutting method developed by authors to improve the cut quality is illustrated in **Fig. 14**. This method is carried on through the simple procedure that the subject metal is laser-gas-cut together with a thin mild steel plate (supplement plate) piled on it by a small constraint force. The pile cutting characteristics are described here and the cutting mechanism is discussed later.

Figure 15 shows the typical cuts of stainless steel (SUS 304) 2 mm in thickness by this method. Perfectly dross-free cuts can be obtained between 2 to 4 m/min. A comparison of conventional laser-gas-cutting and pile cutting characteristics is made in **Fig. 16**. In the conventional cutting any dross-free cuts are not obtained in each thickness, as known from the height of dross H_D in Fig. 16 (a). Compared with this, pile cutting makes the stainless steel plate up to 4 mm in thickness perfectly dross-free, as shown in Fig. 16 (b). Such an excellent performance has been further confirmed by the three evaluation factors of the cut quality described in the previous section, and the result is shown in **Fig. 17**. Using this method, not only height of dross H_D but out-of-flatness F and roughness R are improved quitely well (refer to Fig. 8 (b)).

It was also confirmed that this method was surfficiently effective to the 18% Cr stainless steel and 13% Cr stainless steel. Thus pile cutting method is considered to be much applicable to most of stainless steels.

This technique was tested also for nickel plate (1 mm thick) and aluminum plate (1 to 2 mm), and proved to be much effective. For the nickel, some clinging dross was inevitable in conventional laser-gas-cutting, as well as stainless steel, but the pile cutting method not only made it perfectly dross-free but also enhanced the maximum limit of cutting speed up to 130%. For the aluminum, the dross-free cut could not be obtained also by pile cutting, but the maximum limit of cutting speed was enhanced by it up to 250 to 350%. Thus, this method has a great possibility to apply to various materials and is expected to be further examined.

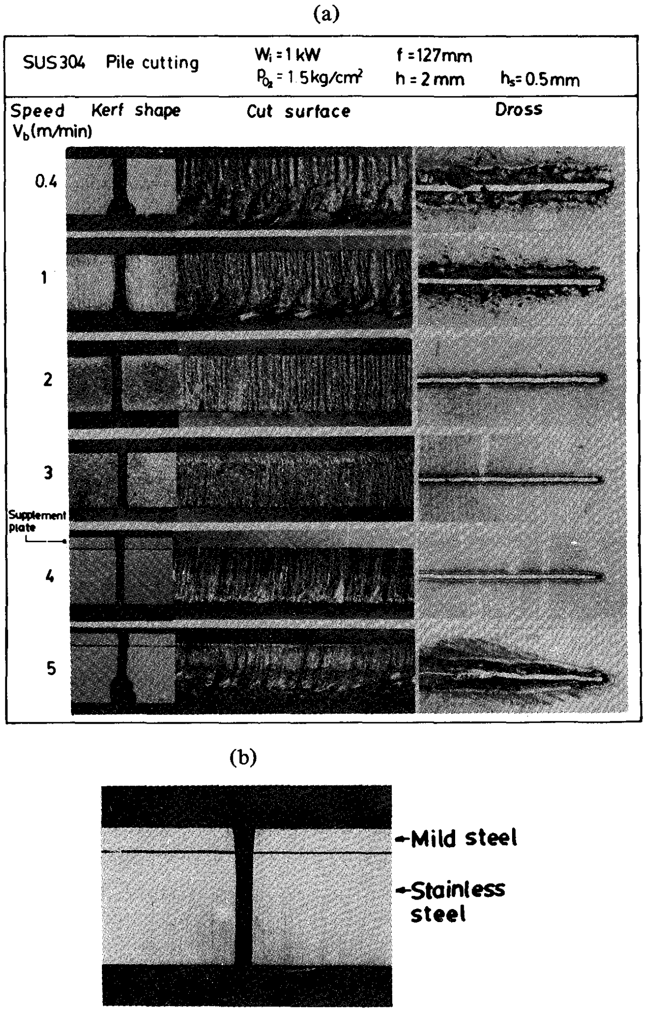


Fig. 15 Cut appearances in pile cutting stainless steels.
(a) dependence on cutting speed (2 to 4 m/min: dross free)
(b) typical kerf shape of dross-free cut (speed: 4 m/min)

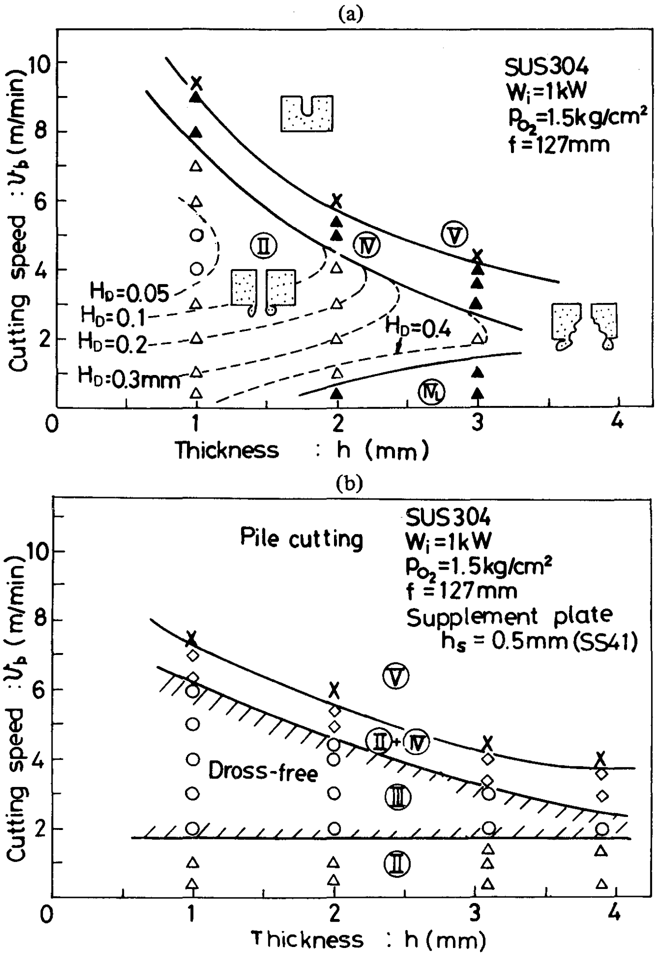


Fig. 16 Comparison between conventional cutting and pile cutting.
(a) conventional cutting characteristics
(b) pile cutting characteristics

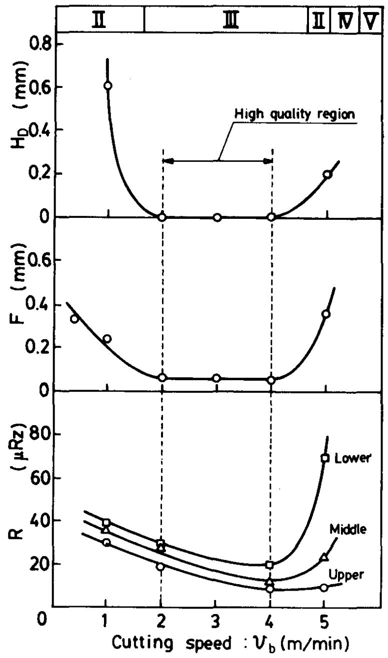


Fig. 17 Evaluation of pile cut qualitities of stainless steel plate. (thickness: 2 mm)

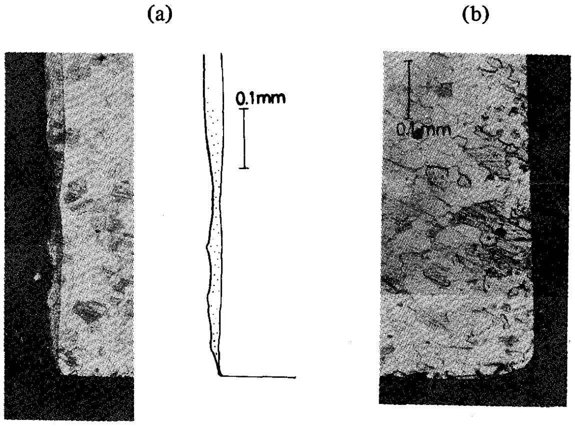


Fig. 18 Appearances of pile cut near bottom edge.
(a) pile cutting of stainless steel
(b) conventional cutting of mild steel

5.2. Discussion of Pile Cutting Mechanism

Detailed observation of the cut kerf and the melting state in pile cutting stainless steel is made and on the bases of those results the improvement mechanism is discussed here.

The kerf shapes of mild steel and stainless steel have a good continuity as shown in Fig. 15 (b). This means that the melting state of mild steel is smoothly kept on to stainless steel side. **Figure 18 (a)** shows the molten zone near the bottom edge after pile cutting. Compared with the cut by conventional cutting method (Fig. 13), this molten layer is quitely thin in the bottom edge, and is, therefore, comparatively close to the dross-free cut of mild steel **(Fig. 18 (b))**. This means that the molten material on the cutting front is much fluid in pile cutting, as well as cutting mild steel. The melting phenomena were actually confirmed by the high speed movie pictures of the cutting front. **Figure 19** shows the pictures filmed, in which **(a)** and **(b)** correspond to the front zones of mild steel (dross-free) and stainless steel (dross clinging) by the conventional cutting method respectively, and **(c)** corresponds to the stainless steel's one by the pile cutting method (dross-free). In the conventional cutting of stainless steel (b) the flow is in great disturbance, while in the conventional cutting of mild steel (a) and in the pile cutting of stainless steel (c) it is in no disturbance and almost in steady state. Furthermore in the pile cutting (c) the molten oxide from the supplement mild steel proves to flow smoothly into the stainless steel side. These results show the state in pile cutting stainless steel is very close to the state in the dross-free cutting of mild steel.

To deduce the pile cutting process, the scattered dross ejected from the bottom edge in cutting were collected and analyzed by X-ray diffractometer. It was proved from this that the main oxidized product was FeO in cutting only mild steel by conventional method, while it was FeO and Cr oxides (Cr_2O_3 and $FeCr_2O_4$) in pile cutting stainless steel. The FeO-Cr_2O_3 phase diagram, **Fig. 20**, means that such Cr oxides have high melting points in comparison of iron oxide. Cr oxides act as a restrainer for oxygen diffusion through the molten layer of cutting front, because they tend to make minute solid regions in the molten layer of the cutting front.

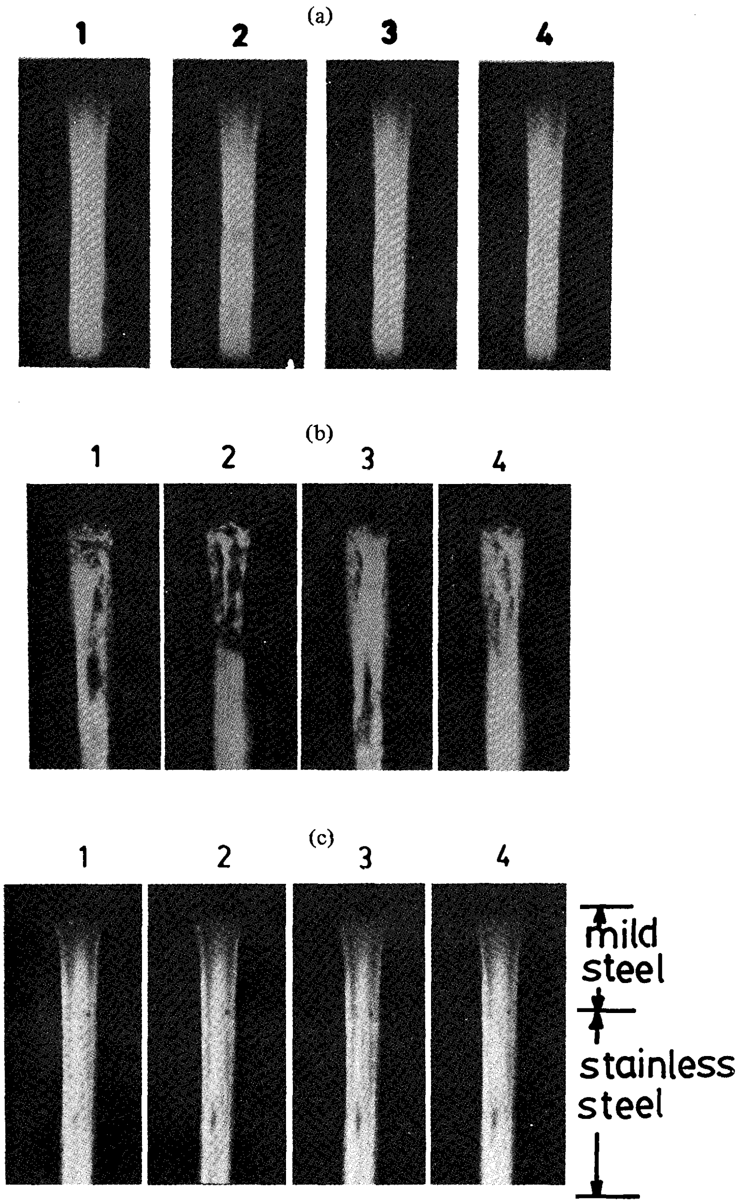


Fig. 19 High speed movie pictures of cutting front in cutting (time interval of pictures: 0.3 msec).
(a) conventional cutting of mild steel
(b) conventional cutting of stainless steel
(c) pile cutting of stainless steel

Based on those results, the effect of the supplement mild steel on the improvement is explained by the following cutting process. In pile cutting, the oxide supplied from mild steel has an effect to dilute the Cr oxides which are restrainers of oxygen diffusion, so that the molten zone of the cutting front becomes more oxidizable according to Fig. 20, that is, reaches the single liquid phase region. A raized oxidation reaction through such a process leads to reduce the thickness of molten metal layer. In this case the effect of viscosity of molten oxide and metal should be also considered. **Figure 21** shows the relationship between the viscosities of molten FeO [13] and stainless steel [14]. This means an increase in the amount of FeO in pile cutting makes it possible to enhance the fluidity in sufficiently high temperature region. Thus the melting flow whose fluidity has been raised through such a whole process is easily removed from the bottom edge by the dynamic force of gas jet.

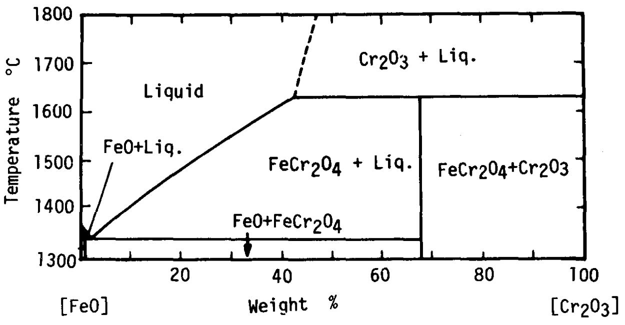


Fig. 20 FeO-Cr_2O_3 phase diagram.

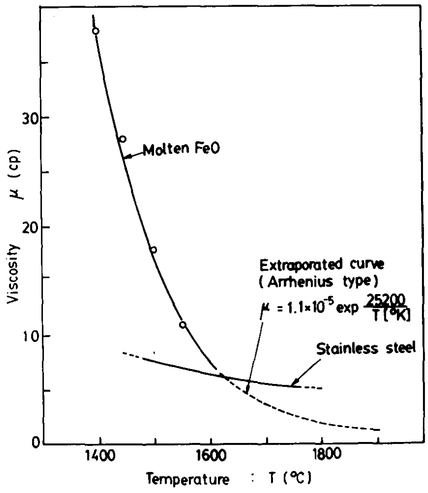


Fig. 21 Viscosity of molten FeO and stainless steel depending on temperature [13, 14].

6. Improvement of Cut Quality by Tandem Nozzle Cutting Method

It was shown in the previous section that in coventional laser-gas-cutting with a coaxial nozzle the increase in oxygen pressure of nozzle contributed to reduce the amount of clinging dross (Fig. 7), but its effect was saturated above 2.5 kg/cm^2, so that a perfectly dross-free cut could not be obtained finally. The purpose of tandem nozzle cutting shown in the present section is to overcome such a limitation of gas dyramic force in conventional laser-gas-cutting.

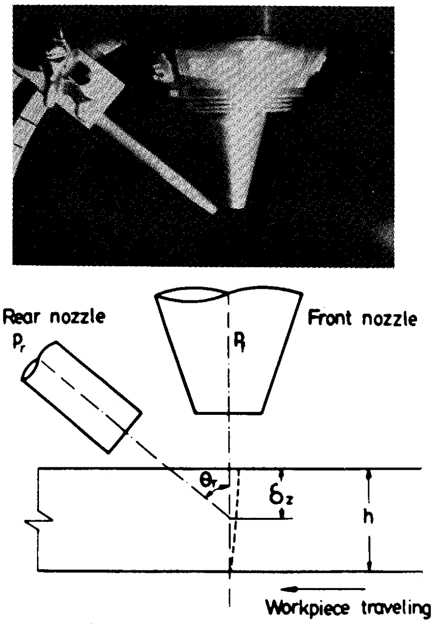


Fig. 22 Schematic diagram of tandem nozzle cutting method.

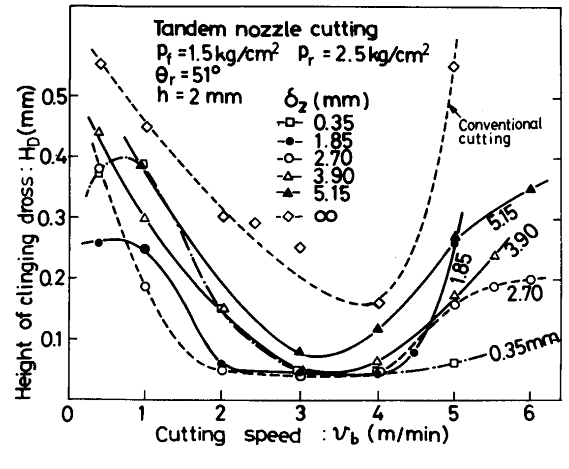


Fig. 23 Relationship between height of clinging dross and aiming position of rear nozzle in various speeds.

The tandem nozzle cutting method is illustrated in **Fig. 22.** The off-axial nozzle (rear nozzle) is arranged behind the coaxial nozzle (front nozzle) and the gas jets from these nozzles are used cooperatively. The rear nozzle conditions are much influential factors. These optima were experimentally determined by checking the height of clinging dross H_D. In case of the rear nozzle pressure P_r, the height of dross H_D decreased gradually with increase in P_r and was saturated at $P_r \gtrsim 2.5$ kg/cm^2 at the fixed front nozzle pressure $P_f = 1.5$ kg/cm^2. In case of the aiming angle θr, the optimum proved to be about 50°. This allowance was considerably limited because the H_D increased twice at ± 10° of the optimum. In case of the aiming position δ_z, when it was set near the bottom edge of the cutting front, the effect of rear nozzle became the best as shown in **Fig. 23.** This means that the rear nozzle is most effective when its jet is blown off so as to suppress the stagnation or the backward melting flow along the bottom edge. **Figure 24** shows a comparison between the appearances of the tandem nozzle cutting and the conventional cutting. The region of scattered drosses proves to be successfully removed with a small spreading angle by the tandem nozzle. **Figure 25** shows

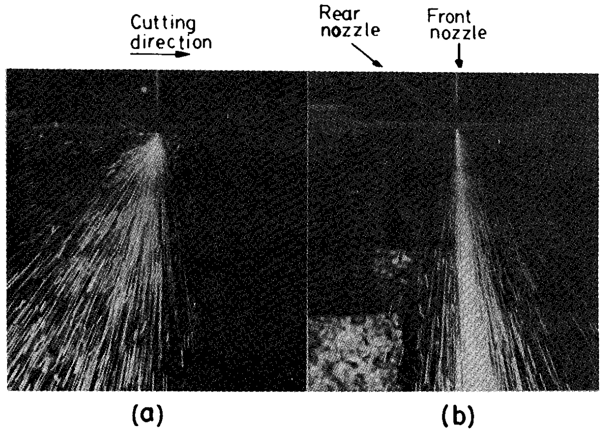


Fig. 24 Appearances of ejecting drosses.
(a) conventional cutting
(b) tandem nozzle cutting

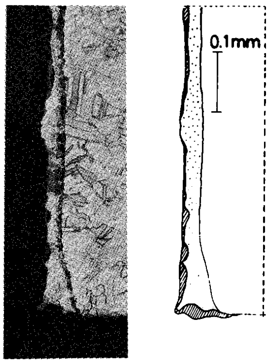


Fig. 25 Appearances of tandem nozzle cut near bottom edge.

the molten zone near bottom edge after tandem nozzle cutting. It presents an appearance that the molten layer is teared off by a strong force, and the amount of the clinging oxide dross is less than it of the cut by conventional cutting method (Fig. 13). This means that the dynamic force of gas jet heightened by the rear nozzle contributes effectively to remove the melting flow along the cutting front.

Figure 26 shows the cuts by this method in the optimum conditions; $P_r = 2.5$ kg/cm^2 ($P_f = 1.5$ kg/cm^2), $\theta_r = 51°$ and $\delta_z = 2.7$ mm. It is clearly shown in this figure that the fine cuts with little or no dross can be obtained at speed of 2 to 4 m/min. **Figure 27** shows the cut qualities of the tandem nozzle cutting. Compared with the conventional cutting (Fig. 8 (b)), this method can reduce the height of dross up to 1/3, but cannot get the perfectly dross-free cut. Therefore this is, so to say, imperfect in comparison of pile cutting method. However, in another view point, this method is much convenient and effective to various actual applications, because a simple nozzle only is set up additionally to the conventional cutting method.

It was also tested whether this method was effective to other materials. As well known, laser-gas-cutting of titanium is inevitable with a rough cut kerf when oxygen gas jet is used, because it is too oxidizable and with an explosive burning. For this reason, an inert gas jet is desirable, though a large amount of clinging dross is inevitable. **Figure 28** shows the effect of tandem nozzle cutting on this material. It proves to be much effective not only to reduce the clinging dross but to improve the kerf shape. Thus, this method has a great possibility to apply to various materials.

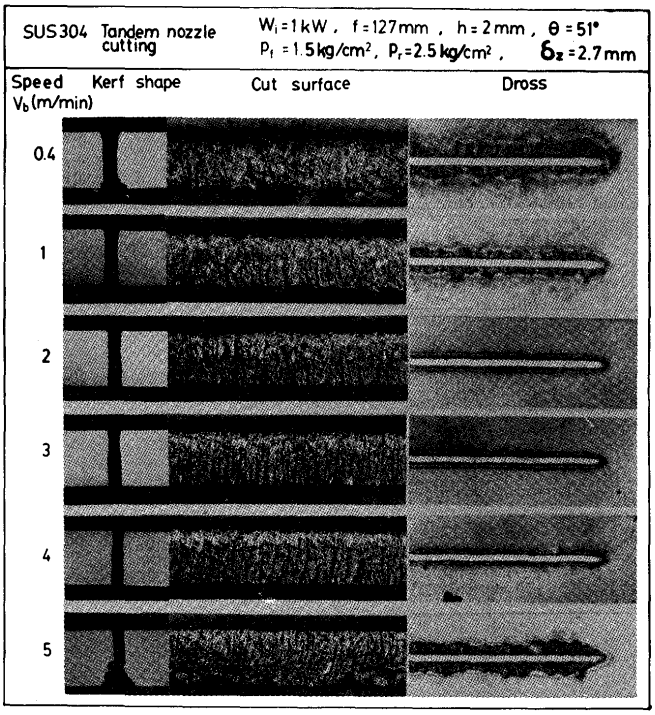


Fig. 26 Cut appearances by tandem nozzle cutting of stainless steels.

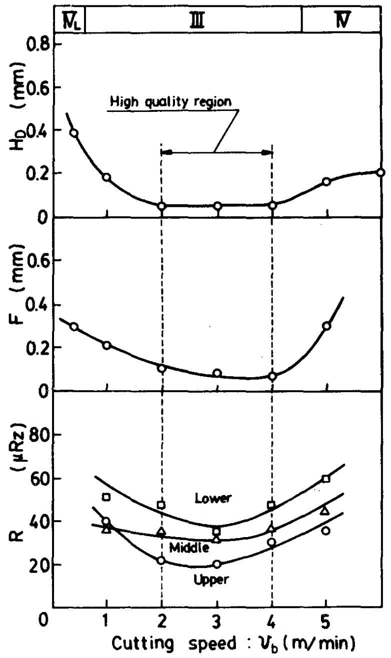
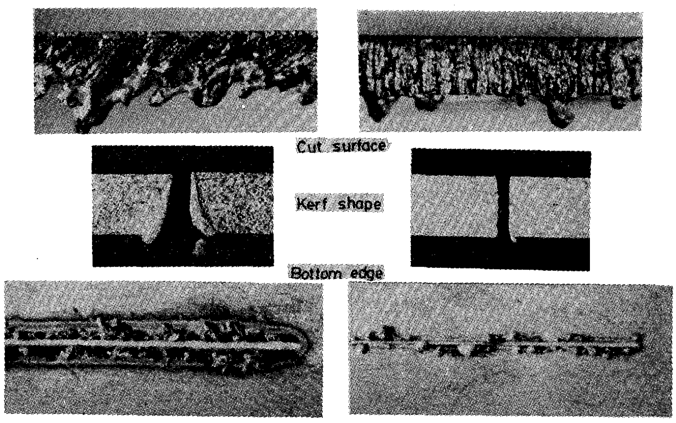


Fig. 27 Evaluation of tandem nozzle cut qualities. (thickness: 2 mm)



(a) Conventional cutting (p_r = 0kg/cm^2)

(b) Tandem nozzle cutting (Pr = 2.5kg/cm^2)

Fig. 28 Effect of tandem nozzle cutting on titanium plate. (Argon assist, front nozzle pressure: 1.5 kg/cm^2, thickness: 2 mm, cutting speed: 1 m/min)

7. Summary

Laser-gas-cut quality of stainless steel with using 1 kW class CO_2 laser and oxygen jet is detailed through the evaluation of height of clinging dross, out-of-flatness and cut surface roughness, and the dross clinging mechanism is discussed through the observation of the cut by high speed moive pictures. Furthermore, on the bases of these results the new improvement techniques for laser-gas-cutting are developed to overcome a limitation of the cut quality by conventional laser-gas-cutting technique. Conclusion obtained from this study is summarized as follows.

(1) Laser power, oxygen pressure and focal length of lens are much influential factors to laser-gas-cut quality, and it is raised with increase in laser power and oxygen pressure. However, such an improvement procedure in conventional laser-gas-cutting has a limitation to obtain a dross-free cut.

(2) The inclination of dross clinging in cutting is greatly influenced by the melting and flowing conditions of materials on the cutting front, and the stagnation and disturbance at the bottom edge of the cutting front make the molten oxide cling to the cut edge.

(3) Pile cutting, in which stainless steel is cut with a thin mild steel piled on it, makes it possible to get perfectly dross-free cut. A molten oxide provided by mild steel enhances the fluidity of the melting flow on the cutting front of stainless steel, and promotes the separation of the molten oxide dross.

(4) Tandem nozzle cutting also gets fine cut having little or no dross. The off-axial gas jet nozzle used together with the coaxial nozzle enhances a dynamic force of gas jet, and promotes the removement of the molten metal and oxide in cutting.

(5) These two techniques can improve also out-of-flatness and surface roughness of the cut in cutting stainless steel, and these have a great possibility to apply to other various materials.

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