Some Fundamental Research of New Type Powder Oxygen Cutting Method for Stainless Steel†

Akira OHMORI*, Ikuo OKAMOTO and Yoshiaki ARATA****

Abstract

This investigation is carried out so that we clear the main action of iron powders on cutting of stainless steel, and obtain higher cutting efficiency.

In this study, we adopted the new type cutting method, in which the iron powders are aspirated into cutting oxygen stream by giving the pressure difference between inlet and outlet of powder dispenser. The experiment was done to know the effect of various factors, such as the iron powder consumption, cutting oxygen pressure and etc. on the cutting speed of stainless steel.

The cutting speed was regulated by lose-cut phenomena (flame out) generated during cutting, whose critical speed was mainly depended on iron powder consumption and cutting oxygen pressure. The critical lose-cut speed was not influenced by the plate thickness and cutting oxygen flow rate. The critical cutting speed increases sharply with decrease of cutting oxygen pressure under 1.5 kg/cm^2 gauge and shows 1500 mm/min at 0.5 kg/cm^2 gauge.

From the behavior of Cr element at the cutting surface of stainless steel, it is considered that the action of iron powder on cutting of stainless steel is based on diluting of molten alloy and oxide layer formed at cutting surface.

The dilution by iron powders assists the favorable combustion of stainless steel at cutting surface during cutting, so that the cutting of stainless steel can continue without lose-cut phenomenon. The favorable supply of iron powders is obtained at lower cutting oxygen pressure than 1.5 kg/cm^2 gauge, when iron powder consumption is constant.

KEY WORDS: (Powder Oxygen Cutting) (Iron Powder) (Stainless Seel) (Flame out) (Gouging)

1. Introduction

The process of oxygen cutting of mild steel has been adapted to the cutting of other metals and alloys. However, the alloying element, chromium, which imparts the desirable properties to stainless steels, makes these steels difficult or impossible to process by normal oxygen cutting. This is because the chromium, which has a higher affinity for oxygen than the iron, immediately forms the highly refractory chromium oxide on the cutting front. Therefore, adding other materials to the cutting oxygen jet, such as iron powder, permits oxygen cutting of stainless steel. However, the efficiency of the process is not very good, for the cutting speeds are slow. With the advent of plasma cutting method, studies on powder cutting of stainless steels have rarely been done.[1)~3)] The iron powder cutting of stainless steel, especially its cutting phenomena, has not been studied fundamentally, and the effect of iron powder on cutting has not been made clear. Iron powder is used for cutting stainless steel because it has the following functions:

1. Releases intense heat during combusion of iron powder
2. Products of combustion provide chemically fluxing action
3. Mechanical removal of chromium oxide layer

However, such action has not been studied precisely.

This experiment was done to determine the effect of various factors, such as iron powder consumption, cutting oxygen pressure, etc, on the cutting speed of stainless steel. Moreover, our work has been directed toward the high efficiency of this cutting method and is intended to clarify the action of iron powder on cutting of stainless steel.

2. Experimental method and materials used

The apparatus and its arrangement for a new type of powder cutting is shown schematically in **Fig. 1.** The difference is in iron powder supply. In conventional iron powder cutting methods, the powder in the dispenser is picked up by the compressed air flow through the ejection and is supplied at the cutting surface from outside the nozzle preheat flame.

In this experiment, a new type of powder cutting method is adopted, in which iron powder is introduced directly into the cutting oxygen stream from the powder dispenser. The iron powder is aspirated into the cutting oxygen stream by the pressure difference between inlet and outlet of the dispenser. The amount of powder aspirated into the cutting oxygen stream

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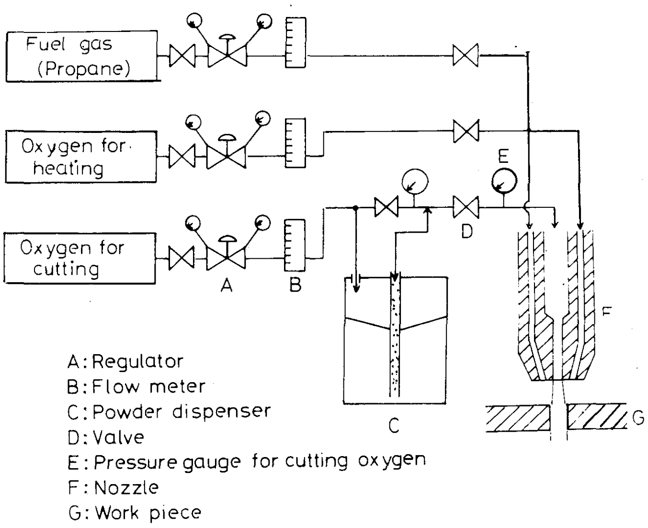

Fig. 1 Schematic diagram of experimental apparatus

can be controlled by a needle valve attached to the conductor pipe of the outlet. In this way, iron powder supply and the combustion are constant and stable during cutting. **Table 1** shows the size and number of straight type nozzle used in this experiment. Propane was used for the fuel gas and pure oxygen (99.8 %) for preheating and cutting. **Table 2** contains a list of the materials and their chemical compositions used in the experiments. The specimen size for cutting was 100 mm in width and 300 mm in length. Thicknesses were 12 mm, 32 mm and 60 mm. The specimen surface was grindered before cutting. The chemical compositions and particle size of iron powder used are shown in **Table 3**.

Table 1 Nozzle number and nozzle diameter

Nozz.No.	st#2	st#3	st#4
d mm$^{\phi}$	1.6	2.0	2.4

Table 2 Chemical compositions of steels

Material	Chemical composition (wt%)						
	C	Si	Mn	P	S	Ni	Cr
SS 41	0.13	0.24	0.66	0.016	0.011	——	——
SUS 304	0.06	0.55	0.94	0.025	0.010	8.99	18.38
SUS 405	0.06	0.52	0.43	0.020	0.013	0.27	13.40
SUS 310S	0.07	1.17	1.47	0.028	0.012	19.56	25.40

Table 3 Chemical compositions and particle size of iron powder

	Chemical compositions (wt%)				
	C	Si	Mn	P	S
Fe-powder	0.02	0.01	0.27	0.006	0.0015

+100 mesh	+150 mesh	+200 mesh	+250 mesh	+325 mesh	-325 mesh
0.5	14.8	27.8	17.9	17.6	21.4

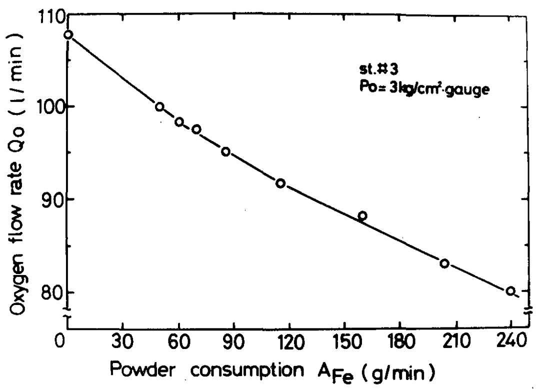

Fig. 2 Relation between powder consumption and oxygen flow rate

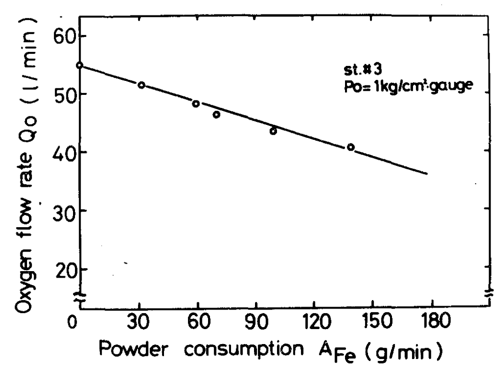

Fig. 3 Relation between powder consumption and oxygen flow rate

3. Preliminary experiment

In this experiment, iron powder was introduced directly into the cutting oxygen stream. The relation between the consumption of powder and cutting oxygen flow rate is shown in **Fig. 2** and **Fig. 3** for 3 kg/cm^2 gauge oxygen pressure and 1 kg/cm^2 gauge, respectively. In cutting, the supplied amount of iron powder was measured in both figures by measuring the cutting oxygen flow rate. After preliminary experiments, the following cutting conditions were adopted: the distance between specimen surface and nozzle tip was 15 mm; the flow rate of propane was 5 *l*/min (pressure, 0.5 kg/cm^2 gauge); and the flow rate of oxygen for preheating was 17.5 *l*/min (3 kg/cm^2 gauge). Cutting was evaluated by measuring the limit of the cutting speed at which flameout (loss of cut) or gouging occurred.

4. Results and Discussion

4.1 Effect of cutting factors on cutting of stainless steel (SUS 304)

At the cutting oxygen pressure (P_o) of 3 kg/cm^2 gauge, the effect of consumption of iron powder (A_{Fe},

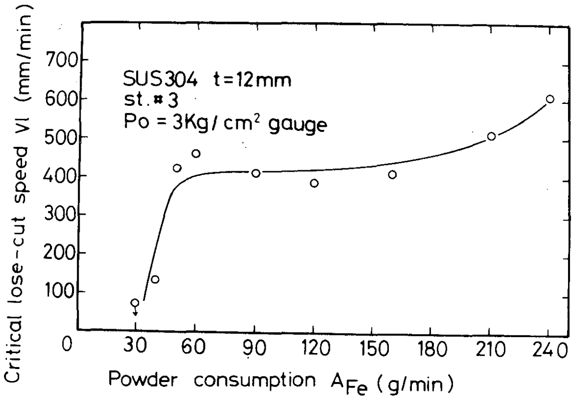

Fig. 4 Effect of powder consumption on critical lose-cut speed (t=12 mm)

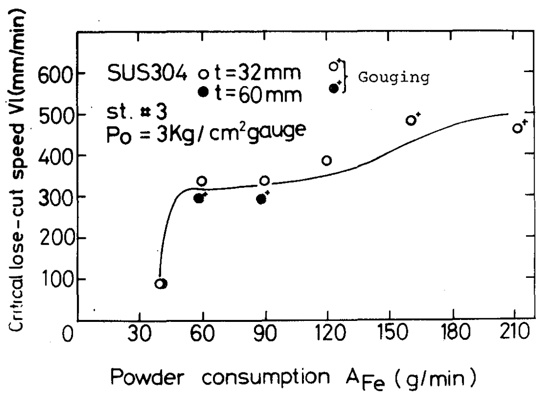

Fig. 5 Effect of powder consumption on critical lose-cut speed (t=32,60 mm)

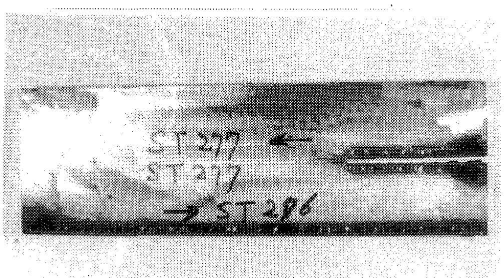

Photo. 1 Appearance of lose-cut (P_o=2 kg/cm² gauge, A_{Fe}=90 g/min, V_l=500 mm/min)

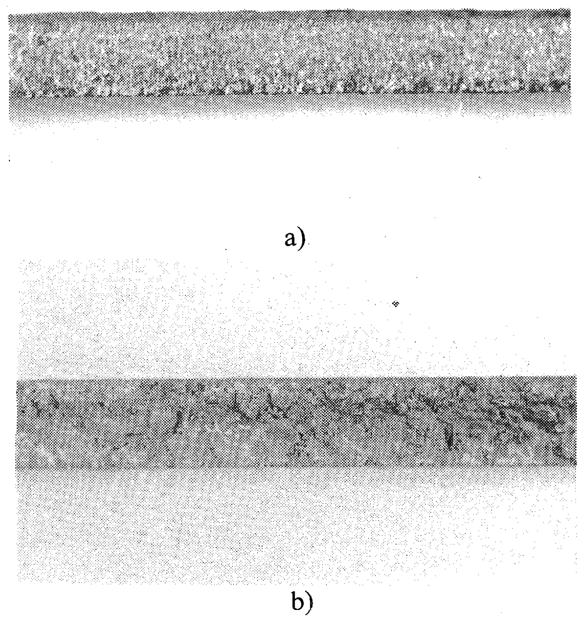

Photo. 2 Appearance of cut surface (t=12 mm)
a) P_o=3 kg/cm² gauge, A_{Fe}=90 g/min, V=250 mm/min
b) P_o=3 kg/cm² gauge, A_{Fe}=240 g/min, V=550 mm/min

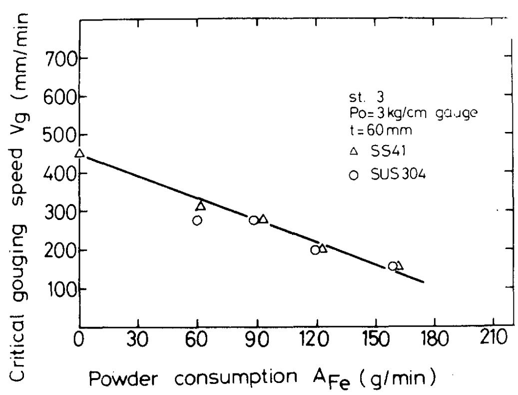

Fig. 6 Effect of powder consumption on critical gouging speed (t=60 mm)

g/min) on the critical cutting speed at which flameout (lose cut) occurred (V_l mm/min) was tested. The results are shown in **Fig. 4** and **Fig. 5**, for plate thicknesses(t) of 12 mm, 32 mm and 60 mm, respectively. The "+" mark in this figure shows the occurrence of gouging. As seen in Fig. 4, the cutting speed of a stainless steel plate of t=12 mm is limited by flameout, which results from a half of combustion reaction. **Photograph 1** shows one example of a specimen surface on which flameout occurred during cutting.

Cutting is difficult when the consumption of iron powder (A_{Fe}) is in the range of 0~30, but becomes possible when A_{Fe} is 30~60. Between 60 g/min and 160 g/min, V_l is constant. In this range of A_{Fe}, the cutting of stainless steel is possible and smooth, when cutting speed is below V_l. In such cutting conditions, a good cutting surface as shown in **Photo. 2**(a) is obtained. V_l increases slowly, when A_{Fe} is above 160 g/min. However, the cutting surface becomes rough as shown in photo. 2(b). When t=32 mm or 60 mm, V_l is a little lower than with the 12 mm plate, but the dependence of V_l on A_{Fe} is similar.

As shown in the figure, gouging becomes more frequent with the increase of plate thickness. In the case of t=60, the effect of A_{Fe} on the speed at which gouging occurs (V_g, mm/min) is shown in **Fig. 6**, in which the similar results from mild steels are shown also. As can be seen, the dependence of V_g on A_{Fe} is the same for both stainless steel and mild steel and V_g decreases with the increase of A_{Fe}. In this experiment, an increase in A_{Fe} causes a decrease in cutting oxygen flow rate (Q_o, *l*/min) (Fig. 2 and Fig. 3), as result of introducing iron powder directly into the flow of cutting oxygen. It is considered that the dependence of V_g on A_{Fe} is due to the decrease of Q_o, as recognized for mild steel[4]. No difference of V_g was deserved between stainless steel and mild steel.

Next, the effect of Q_o on V_l was examined. Q_o was changed from 58 *l*/min to 142 *l*/min using three different nozzles (st#2, st#3 and st#4) at a constant oxygen pressure of 3 kg/cm^2 gauge. The results are shown in **Fig. 7**. They show that V_l is constant in spite of change in Q_o. This means that the speed at which flameout occurs is not affected by variation in Q_o or plate thickness.

As the above results show, the cutting speed for stainless steel is lower than the speed for mild steel and is limited by flame out when the cutting oxygen flow rate is sufficient. For powder cutting of stainless steel to be feasible, it is necessary to raise the critical cutting speed (V_l). The critical cutting speed for oxygen cutting of mild steel is usually raised by increasing the cutting oxygen pressure.[4] That is an increase of oxygen pressure causes an increase of momentum of flow. Therefore, in this experiment, the effect of P_o on V_l was examined.

The results are shown in **Fig. 8** (A_{Fe}=90, t=12). V_l is constant and low within the range of pressure from 4.0 kg/cm^2 gauge to 1.5 kg/cm^2 gauge. However, V_l increases sharply when P_o equals 1 kg/cm^2 gauge. At this pressure, Q_o becomes insufficient with the increase of cutting speed, resulting in gouging which starts at 700 mm/min, while flame out does not occur until 1100 mm/min. V_l increases with the lowering of P_o to reach the speed of 1500 mm/min at P_o=0.5 kg/cm^2 gauge, at which pressure flameout occurs with mild steel as well. This rapid rise in V_l at low oxygen pressures is one of the most important findings of this research.

In order to know more about the cutting phenomena at low pressure, the effect of A_{Fe} on V_l was studied at 1 kg/cm^2 gauge. The results are shown in **Fig. 9**. At this pressure, the cutting is easy even with only 30 g of iron powder per min., an amount at which cutting is impossible at P_o=3 (Fig. 4, 5). V_l increases linearly with the increase of A_{Fe}, and the iron powder

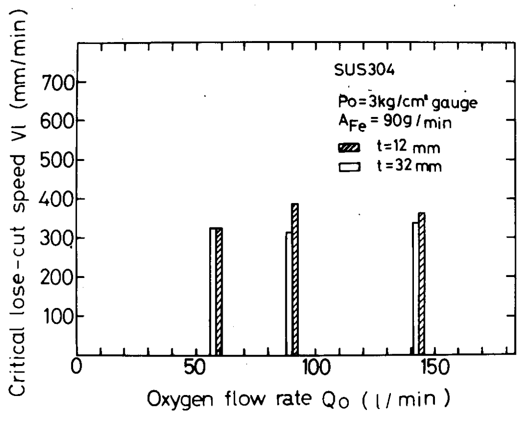

Fig. 7 Effect of oxygen flow rate on critical lose-cut speed

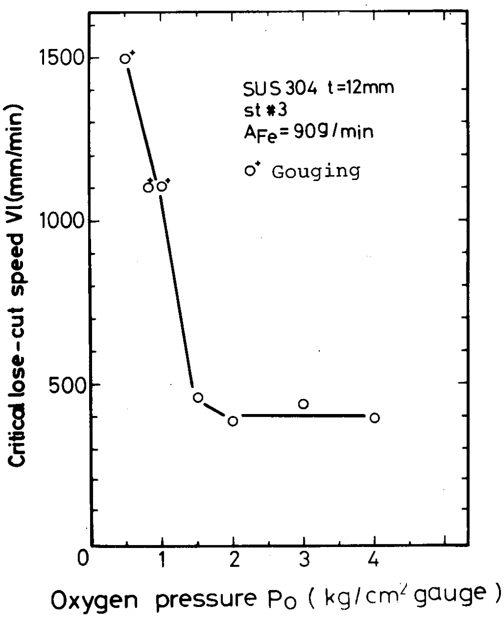

Fig. 8 Effect of oxygen pressure on critical lose-cut speed

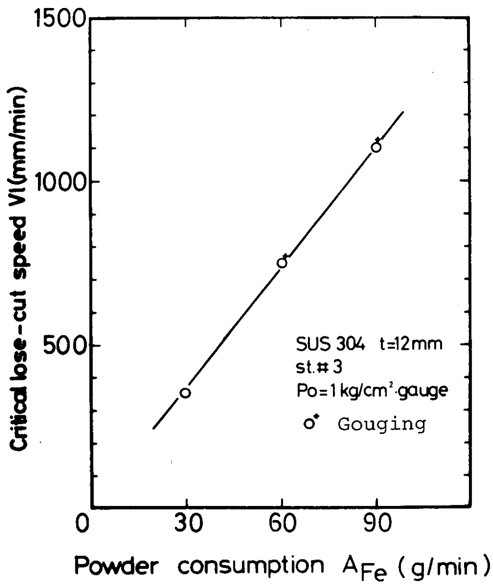

Fig. 9 Effect of powder consumption on critical lose-cut speed (Po=1 kg/cm^2 gauge)

amount per unit length (A_{Fe}/V_l) is constant. V_l depends greatly on the consumption of iron powder. At pressures under 1.5 kg/cm^2 gauge, V_l increases rapidly, because the supply of iron powder on the cutting surface is more effective than at higher pressures, due to lowering of gas flow momentum.

4.2 Behavior of elements in stainless steel at cutting surface

The oxygen cutting of stainless steel is difficult, because the element Cr is oxidized easily at higher temperatures, forming on the cutting front surface, so that the burning of stainless steel can not continue. However, the cutting of stainless steel is possible by adopting the iron powder oxygen cutting method. As described in the previous sections, the powder cutting of stainless steel depends greatly on the speed at which flameout occurs, and V_l increase with the decrease of P_o. Since flame-out occurs due to the interruption of the burning reaction at the cutting front surface, the behavior of Cr at the cutting surface is of interest.

We investigated the distribution of Cr from the inside of the stainless steel material to the cutting surface by EPMA analysis. Cross sections of cutting surfaces were analyzed by EPMA after cutting, in order to determine the effect of cutting speed on the distribution of Cr, Fe, and Ni. The results are shown in **Fig. 10** for cutting speeds of 200, 500 and 1100 mm/min (P_o=1, A_{Fe}=90). In this figure, the analysis curves in the vicinity of cutting edge do not show the true value of element content, because it is due to influence of the size of beam diameter to the edge. The element content at S point indicated on the horizontal axis in the figures is true value in the cutting edge. The following figures (Fig. 11, 12 and 14), also are similar to Fig. 10. The analysis of a mechanically cut stainless steel surface is shown also for comparison. In the case of V=1100, the cutting front surface was also analyzed. It can be seen that a Cr-depleted layer is found on the cutting surface when flameout does not take place. The faster the cutting speed, the thinner the layer. The surface of the flameout sample (V=1100) is very similar to the mechanically cut surface. However, the change in Ni is not observed after powder cutting. From these analyses, we can consider that Cr reacts more easily with oxygen than the other elements, and transfers from inside the stainless steel to the cutting front, so that a Cr-depleted layer is formed on the cutting surface. The formation of this Cr-depleted layer is observed as long as the cutting of stainless steel proceeds smoothly without flameout. Flameout occurs on the cutting front when there is no Cr-depleted layer.

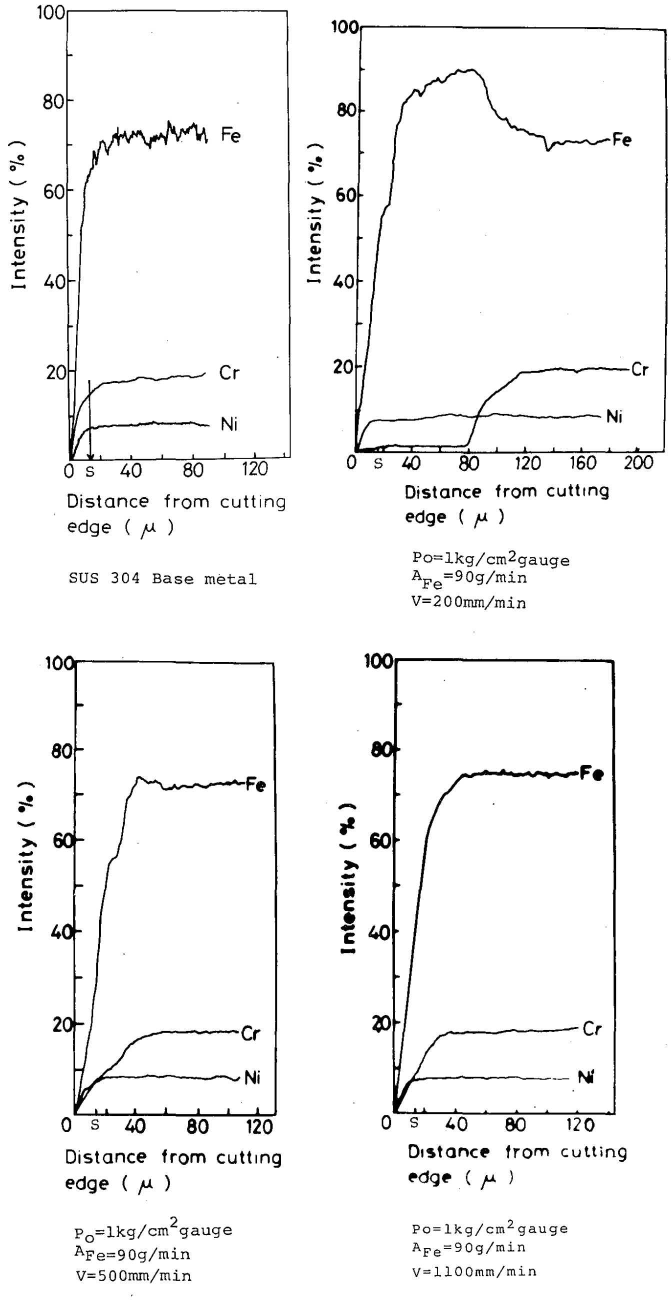

Fig. 10 X-ray micro-analysis of Fe, Cr and Ni of cross section of cutting side and lose-cut front
Note: In this figure, the analysis curves in the vicinity of cutting edge do not show the true value of element content, because it is due to influence of the size of beam diameter to the edge. The element content at S point indicated on the horizontal axis in the figures is true value in the cutting edge.

Cutting surfaces at which flameout took place under other cutting conditions were also analyzed by EPMA. The results are shown in **Fig. 11**. These cutting surfaces are very similar to the mechanically cut surface. They lack, the Cr-depleted layer. From

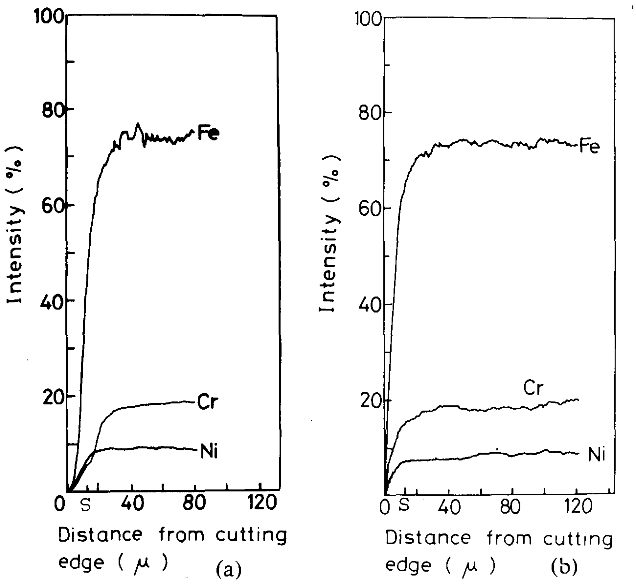

Fig. 11 X-ray micro-analysis of Fe, Cr and Ni of cross section of lose-cut front; (a) $P_o=3$ kg/cm² gauge, $A_{Fe}=90$ g/min, $V_l=400$/min, (b) $P_o=3$ kg/cm² gauge, $A_{Fe}=210$ g/min, $V_l=550$ mm/min

these results, we may hypothesize that cutting is possible by effectively supplying iron powder at the cutting surface, either by lowering cutting speed or by lowering cutting oxygen pressure. This is because Cr can burn smoothly without exposure to the oxygen flow at the cutting front surface, due to an effective supply of iron powder and dilution of the molten layer by iron powder. However, with the increase of cutting speed the thickness of the Cr-depleted layer decreases, because the supply of iron powder becomes insufficient. At the critical cutting speed (V_l), the base material is easily exposed to contact with oxygen, so that only Cr oxide forms easily at the cutting front surface and the burning of stainless steel becomes difficult.

Next, at the lower pressure of 0.8 kg/cm² gauge, the formation of the Cr-depleted layer is shown in **Fig. 12**. The layer is thicker even at a higher cutting speed (900 mm/min). These results show that, the powder cutting of stainless steel can continue without flameout at lower cutting speeds and lower cutting oxygen pressure due to the formation of a Cr-depleted layer. Under such cutting conditions, the supply of iron powder at the cutting front surface increases greatly so that the burning of Cr does not stop, and base metals are not exposed to the oxygen flow at the surface. At the lowest pressure of 0.5 kg/cm² gauge, the critical cutting speed reaches 1500 mm/min, which is similar to V_l for mild steel. At this pressure, iron powder is well supplied at the cutting front surface and

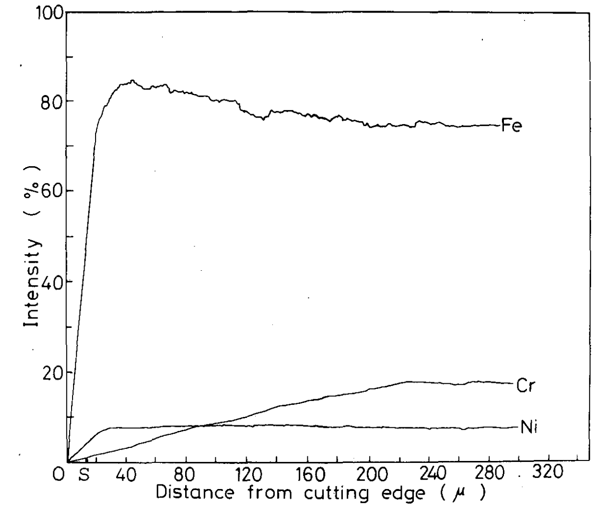

Fig. 12 X-ray micro-analysis of Fe, Cr and Ni of cross section of cutting side.
($P_o=0.8$ kg/cm² gauge, $A_{Fe}=90$ g/min, V=900 mm/min)

the cutting surface stainless steel may become similar to the cutting front surface of mild steel.

4.3 Change of cutting front shape during cutting

It is considered that the shape of the cutting front influences greatly the critical cutting speed, and varies with the consumption of iron powder (A_{Fe}) or cutting oxygen pressure (P_o). Thus, the effect of A_{Fe} and P_o on the shape of the cutting front, especially, the slope, was examined at the constant cutting speed of 1000 mm/min. The results are shown in **Table 4.** From this table, it can be seen that there is no difference of slope (θ) between SUS 304 and mild steel at $A_{Fe}=90$, and $P_o=1$. At $P_o=3$, the slope increases with the use of iron powder in comparison with the slope without iron powder. However, the difference in the slope with use of iron powder is more remarkable between the lower oxygen pressure of 1 kg/cm² gauge

Table 4 Effect of cutting conditions on cutting front shape

Cutting front ←C.D	Cutting condition (V=1000mm/min)		
	Steel	A_{Fe} (g/min)	Po (kg/cm² gauge)
4°	SS41	0	3
65°	SS41	0	1
20°	SS41	90	3
65°	SS41	90	1
65°	SUS304	90	1

and 3 kg/cm² gauge. Moreover, it is known from observing cutting phenomena that the iron powder is supplied more concentratedly at the cutting front surface at $P_o=1$ than at $P_o=3$. That is, at the oxygen pressure lower than 1.5 kg/cm² gauge the momentum of oxygen flow decreases and the molten layer remains thicker than at higher oxygen pressure. So that, the lowering of Cr concentration is due to the dilution of Cr content in the molten layer by iron powder, and is promoted by the increase in slope of the cutting front. The burning of Cr with oxygen does not stop, thereby forming the Cr-depleted layer at the cutting front surface.

4.4 Effect of Cr content in steels on V_l

In powder oxygen cutting for stainless steel (SUS 304), the Cr-depleted layer forms on the cutting surface, when cutting proceeds smoothly. Optimum cutting is maintained by continuous burning of Cr due to the dilution of the molten layer by iron powder. Therefore, the critical cutting speed of flameout, which occurs when burning of Cr stops, may be influenced greatly by the Cr content contained in various stainless steels. Therefore, we investigated the effect of steels on V_l using various steels such as, SUS 310S (28%Cr), SUS 304 (18%Cr), SUS 405 (13%Cr) and SS41 (0%Cr).

The results at $P_o=3$ and $A_{Fe}=90$ are shown in **Fig. 13**. As shown in this figure, V_l increases with the decrease of Cr content. SUS 310S is difficult to be cut at these cutting conditions. When flameout occurred in the case of 13%Cr steel, the cutting front surface was similar to the surface of 13%Cr steel cut mechanically, without the Cr-depleted layer shown in **Fig. 14**. In the powder cutting of various stainless steels, the cutting speed is recognized to be dependent mainly on the Cr content in steels. The higher the Cr content of stainless steel is, the easier the occurrence of flameout becomes and the lower the critical cutting speed becomes. The cause is considered to be as follows: when the Cr content in steel is higher, the diffusion of Cr from inside the steel to the cutting front surface by burning of Cr becomes easier. Flameout takes place more easily when the cutting speed becomes faster because the diluting action of the molten layer through the addition of iron powder becomes more difficult. Consequently, in the cutting of higher Cr steel, the increase of the supply of iron powder is more necessary than for the lower Cr steel. Therefore, V_l for higher Cr steel is lower than for lower Cr steel.

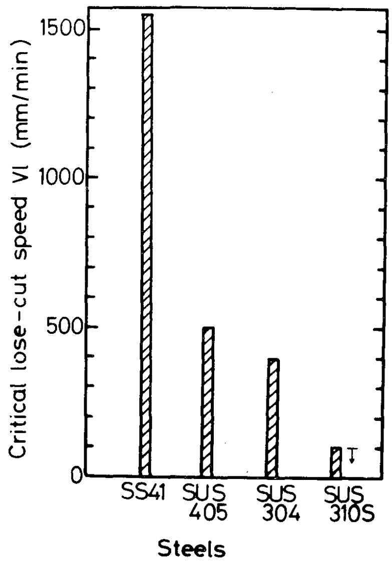

Fig. 13 Effect of steel on critical lose-cut speed

5. Conclusions

The results of these investigations are summarized as follows:

1) The critical cutting speed of powder cutting for stainless steel is regulated by flameout, which occurs when the burning of stainless steel stops. However, the cutting speed is also controlled by gouging when the cutting oxygen flow rate is insufficient. Formation of a Cr-depleted layer is

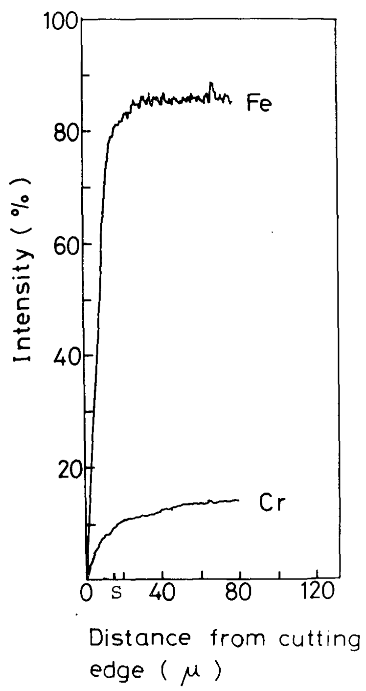

Fig. 14 X-ray micro-analysis of Fe and Cr of cross section of lose-cut front for SUS405.
($P_o=3$ kg/cm² gauge, $A_{Fe}=90$ g/min, $V_l=500$ mm/min)

seen on the cutting surface when cutting continues without the occurrence of flameout.

2) The critical cutting speed is influenced greatly by the Cr content of stainless steels and flameout takes place more easily in higher Cr steel. When the flameout occurs, the cutting front surface is similar to the surface of material cut mechanically. Cr content on the cutting front surface is lowered through effective supply of iron powder by decreaseing cutting speed and cutting oxygen pressure.
3) For the effective supply of iron powder at the cutting front, it is necessary to lower the cutting oxygen pressure. At the oxygen pressure of 0.5 kg/cm^2 gauge, the critical cutting speed (V_l) for stainless steel approaches V_l for mild steel. It was recognized that a higher speed cutting of stainless steel might be possible if the supply of iron powder is sufficient.

Acknoweledgement

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