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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/cm² gauge and shows 1500 mm/min at 0.5 kg/cm² 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/cm² gauge, when iron powder consumption is constant.

KEY WORDS: (Powder Oxygen Cutting) (Iron Powder) (Stainless Steel) (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. 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 combustion 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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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 grinded before cutting. The chemical compositions and particle size of iron powder used are shown in Table 3.

Table 1 Nozzle number and nozzle diameter

<table>
<thead>
<tr>
<th>Nozz No.</th>
<th>st#2</th>
<th>st#3</th>
<th>st#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>d mm²</td>
<td>1.6</td>
<td>2.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 2 Chemical compositions of steels

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 41</td>
<td>0.13</td>
<td>0.24</td>
<td>0.66</td>
<td>0.016</td>
<td>0.011</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SUS 304</td>
<td>0.06</td>
<td>0.55</td>
<td>0.34</td>
<td>0.025</td>
<td>0.010</td>
<td>0.99</td>
<td>18.38</td>
</tr>
<tr>
<td>SUS 405</td>
<td>0.06</td>
<td>0.52</td>
<td>0.43</td>
<td>0.020</td>
<td>0.013</td>
<td>0.27</td>
<td>13.40</td>
</tr>
<tr>
<td>SUS 310S</td>
<td>0.07</td>
<td>1.17</td>
<td>1.47</td>
<td>0.028</td>
<td>0.012</td>
<td>19.56</td>
<td>25.40</td>
</tr>
</tbody>
</table>

Table 3 Chemical compositions and particle size of iron powder

<table>
<thead>
<tr>
<th>Fe-powder</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Fe-powder</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>+100 mesh</td>
<td>0.02</td>
<td>0.01</td>
<td>0.27</td>
<td>0.006</td>
<td>0.0015</td>
<td>+150 mesh</td>
<td>14.8</td>
<td>27.8</td>
<td>17.9</td>
<td>17.6</td>
<td>21.4</td>
</tr>
<tr>
<td>+200 mesh</td>
<td>+250</td>
<td>+325</td>
<td></td>
<td></td>
<td></td>
<td>-325 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+325 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+200 mesh</td>
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</table>

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/cm² gauge oxygen pressure and 1 kg/cm² 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/cm² gauge); and the flow rate of oxygen for preheating was 17.5 l/min (3 kg/cm² 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/cm² gauge, the effect of consumption of iron powder \( A_{Fe} \),
g/min) on the critical cutting speed at which flameout (lose cut) occurred (V_i 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_i is constant. In this range of A_{Fe}, the cutting of stainless steel is possible and smooth, when cutting speed is below V_i. In such cutting conditions, a good cutting surface as shown in **Photo. 2(a)** is obtained. V_i 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_i is a little lower than with the 12 mm plate, but the dependence of V_i 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 $A_{re}$ on the speed at which
gouging occurs ($V_e$, 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 $V_e$ on $A_{re}$
is the same for both stainless steel and mild steel and
$V_e$ decreases with the increase of $A_{re}$. In this experi-
ment, an increase in $A_{re}$ 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 $V_e$ on $A_{re}$ is due to the decrease of $Q_o$,
as recognized for mild steel. No difference of $V_e$
was deserved between stainless steel and mild steel.

Next, the effect of $Q_o$ on $V_i$ 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 $V_i$ is constant in
spite of change in $Q_o$. This means that the speed at
which flame out 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 ($V_i$). The critical cutting speed for
oxygen cutting of mild steel is usually raised by
increasing the cutting oxygen pressure. That is an
increase of oxygen pressure causes an increase of
momentum of flow. Therefore, in this experiment,
the effect of $P_o$ on $V_i$ was examined.

The results are shown in Fig. 8 ($A_{re}=90$, $t=12$).
$V_i$ is constant and low within the range of pressure
from 4.0 kg/cm$^2$ gauge to 1.5 kg/cm$^2$ gauge. However,$V_i$ 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. $V_i$ 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 $V_i$ 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 $A_{re}$ on $V_i$ 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). $V_i$ increases
linearly with the increase of $A_{re}$, and the iron powder

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{Effect of oxygen flow rate on critical lose-cut speed}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig8.png}
\caption{Effect of oxygen pressure on critical lose-cut speed}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig9.png}
\caption{Effect of powder consumption on critical lose-cut speed
($P_o=1$ kg/cm$^2$ gauge)}
\end{figure}
amount per unit length \( (A_{\text{r}}/V_{i}) \) is constant. \( V_{i} \) depends greatly on the consumption of iron powder. At pressures under 1.5 kg/cm² gauge, \( V_{i} \) 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 \( V_{i} \) increase with the decrease of \( P_{0} \). 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 \((P_{0}=1, A_{\text{r}}=90)\). 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.

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
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 ($V_i$), 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 $V_i$ for mild steel. At this pressure, iron powder is well supplied at the cutting front surface and 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 ($A_{pe}$) or cutting oxygen pressure ($P_o$). Thus, the effect of $A_{pe}$ 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 ($\theta$) between SUS 304 and mild steel at $A_{pe}$=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>
<thead>
<tr>
<th>Cutting front</th>
<th>Cutting condition ($V=1000$ mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>$A_{pe}$ (g/min)</td>
</tr>
<tr>
<td>SS41</td>
<td>0</td>
</tr>
<tr>
<td>SS41</td>
<td>0</td>
</tr>
<tr>
<td>SS41</td>
<td>90</td>
</tr>
<tr>
<td>SUS304</td>
<td>90</td>
</tr>
<tr>
<td>65°</td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td></td>
</tr>
</tbody>
</table>
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, 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 \( V_i \)

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 \( V_i \) 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, \( V_i \) 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

![Graph showing effect of steel on critical lose-cut speed](image)

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

![Graph showing X-ray micro-analysis of Fe and Cr](image)

**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, \( V_i = 500 \) mm/min)

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
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 decreasing 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/cm² gauge, the critical cutting speed \( V_{c} \) for stainless steel approaches \( V_{t} \) 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.

Acknowledgement

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