Notch Formation Mechanism in Low Speed Oxygen Gas Cutting†

Akira MATSUNAWA*, Kazuo AMANO** and Kimiyuki NISHIGUCHI***

Abstract

Notching phenomenon, which is likely to occur in low cutting speed range, makes a troublesome barrier of cutting thicker plate, but its detail has not been clarified. Notch is often formed accidentally in practical cutting process, but it is an intrinsic unstable combustion reaction in very low cutting speed. The authors conducted some fundamental research on this matter to obtain detailed knowledges.

Notching in low speed cutting is characterized by the periodic combustion and extinction at the front cutting wall, and the phenomena are greatly influenced by the flow characteristic of oxygen jet, behavior of thin molten layer at the front wall and thermal stability at the upper part of plate. The paper describes the detailed observation of phenomena and discusses the mechanisms of extinction and its propagation, re-combustion and self-sustaining condition of periodic phenomenon.

KEY WORDS: (Oxygen gas cutting) (Notch) (Impinging jet) (Combustion)

1. Introduction

When a heavy section steel plate is cut by the oxygen gas cutting process, the cutting speed is normally chosen to be low in order to obtain high quality cut surface. But, in the very low speed range, it is easy to bring so called notching phenomenon having rough and irregular surface, and this makes an important barrier to the cutting thick plate.[1)~3)] The greatest problem in practical site cutting is that notching phenomenon is sometimes brought about abruptly in spite of the cutting condition fixed in the range to obtain good quality. This troublesome problem is usually caused by the external perturbation such as mechanical vibration of the equipments and sudden turbulence of the oxygen jet. However, notching appears in very low speed range with good periodicity and high reproducibility, even though the external perturbations are carefully minimized, and hence it is concluded to be an essentially unstable reaction of combustion in low speed cutting. But, systematic studies on this phenomenon have not been conducted and its formation mechanism is not well understood.

The authors have, therefore, examined some fundamental characteristics of notching action. It is empirically known that there exist several kinds of notching phenomena, but in this paper is dealt with the basic mode that has good periodicity, reproducibility and occurrence frequency. The characteristic feature of this kind of notching is that the periodic repetition of burning and extinction takes place at the lower site of the cutting front surface, and the notched surface at the side kerf is observed as the result of the above stated intermittent chemical reaction. In this paper is described the extinction condition of burning reaction as well as the sustaining condition of periodic reaction from the view points of interaction between high speed oxygen jet and cutting front and also from the behaviour of molten metal layer.

2. Notch Formation Phenomena

2.1. Types of notch at low speed cutting

It is very important to reproduce notching phenomenon steadily in order to clarify the mechanism. In usual cutting, however, the notching phenomenon happens accidentally under the normal cutting condition and it is rather difficult to find its cause. On the other hand, it has been empirically known that notched surface is always obtained in the cutting of thick plate when travel speed is greatly reduced.[1),2)] **Figure 1** shows an example of successive notched surface obtained at very low speed with normal oxygen jet. This type of notching is characterized by the good cyclicity and reproducibility and categorized here as the **Type I.** While, another type

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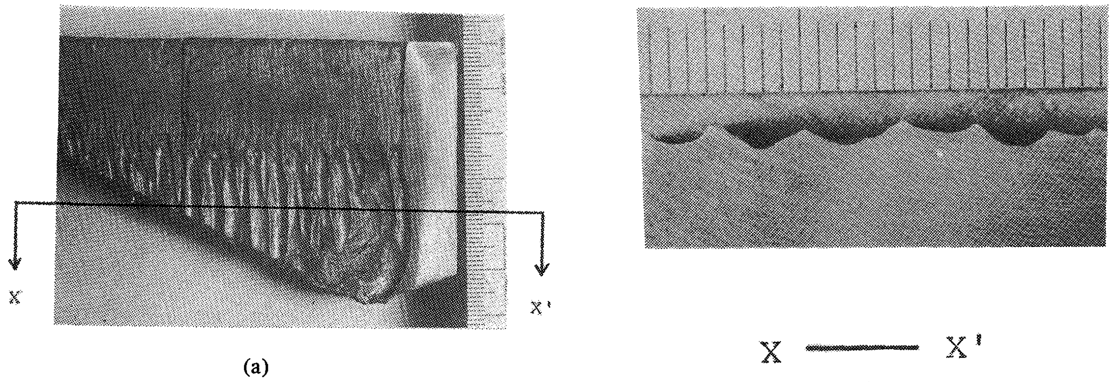
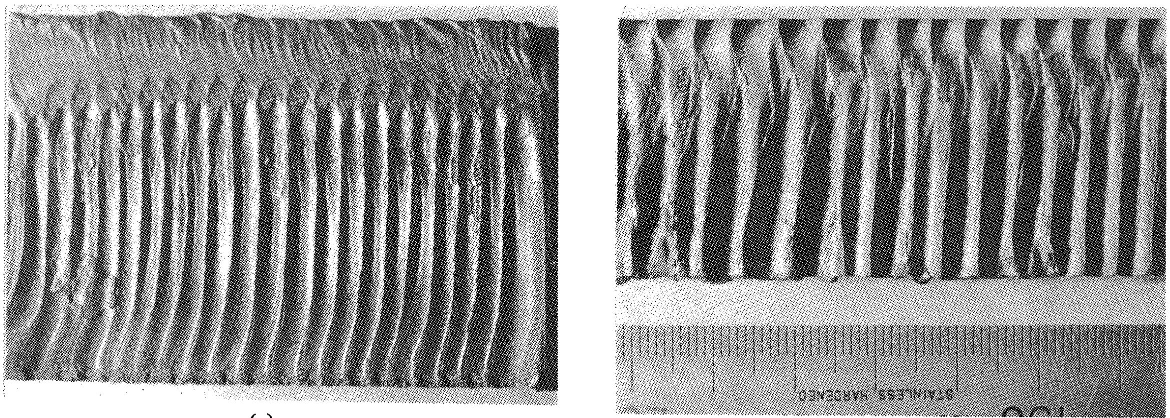


(a) (b)

Fig. 1 Typical shape of notch in very low speed cutting (Type I)



(a) (b)

Fig. 2 Shapes of notch (Type II) when asymmetric jet is used

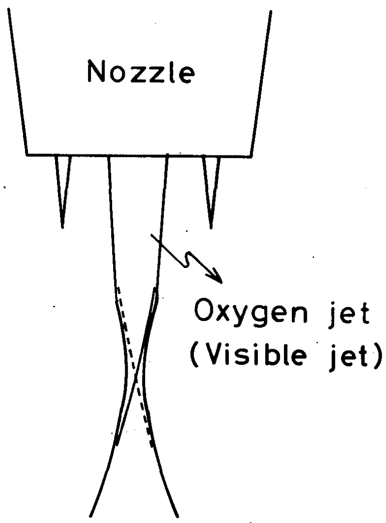


Fig. 3 A twisted oxygen jet

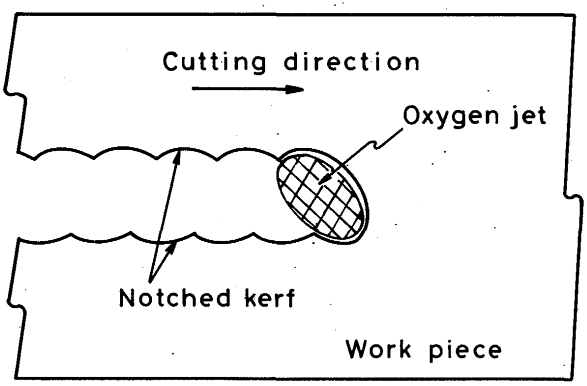


Fig. 4 Notch formation when a noncircular jet is used

of notching phenomenon the authors have clarified is obtained as shown in **Figure 2**, when a distorted oxygen jet is used. This also represents good periodicity as seen in the figures but reproducibility is very poor, and this is called **Thep II** in this paper. Figure 2(a) is an example when used a twisted oxygen jet as illustrated in **Figure 3** which is often realized by the spattering adhesion at the nozzle. Figure 2(b) shows a surface when a noncircular jet is used as shown in **Figure 4.** In this case, the notch reaches up to the plate surface.

Due to the high reproducibility, the authors employed the experimental conditions where the type I notching is obtained.

2.2. Effect of notching on the maximum plate thickness of cutting

The maximum seperable plate thickness for a give oxygen nozzle is an important concern in the thermal cutting process, and this ability, which is called the maximum cut thickness or gouging ability, is much dependent on the cutting speed and flow rate of oxygen jet. Nishiguchi et al.[1] investigated this from the view point of heat balance at the cutting front surface considering oxygen diffusion through impurified boundary layer, and concluded that the maximum cut thickness is expressed as follow in the normal cutting range.

$$\nu T_m = K (Q/d) \quad (1)$$

where, ν = cutting speed
T_m = Maximum cut thickness
Q = oxygen gas flow rate
d = nozzle diameter of oxygen jet
K = constant

In actual gas cutting, the oxygen pressure is selected above 2 kg/cm^2 ab. Namely, the flow velocity at the nozzle throat is always sonic and hence the flow rate is linearly proportional to the pressure itself. Thus, the equation (1) is expressed as

$$\nu T_m = K' (p_o/d) \quad (2)$$

where, p_o = absolute oxygen pressure.

These relations were experimentally well verified in the normal cutting speed range where smooth kerf surface was obtained.

Figure 5 shows the effect of cutting speed on the maximum cut thickness under the given nozzle condition, in which one can see the validity of equation (1) in the range higher than 15 cm/min. While, in the lower speed less than 15 cm/min, the cutting ability is greatly reduced from the expected one from equations (1) and (2). This reduction is primarily due to the steady formation of notching at the lower part of plate. The notch height increases with the oxygen pressure as shown in **Figure 6**, and thus the separable plate thickness, though it increases with the oxygen pressure, is still much lower than the estimated thickness from equation (2).

It is, therefore, evident from Figs. 5 and 6 that the notching phenomenon restricts the ability to increase the thickness of high quality cutting as well as the maximum

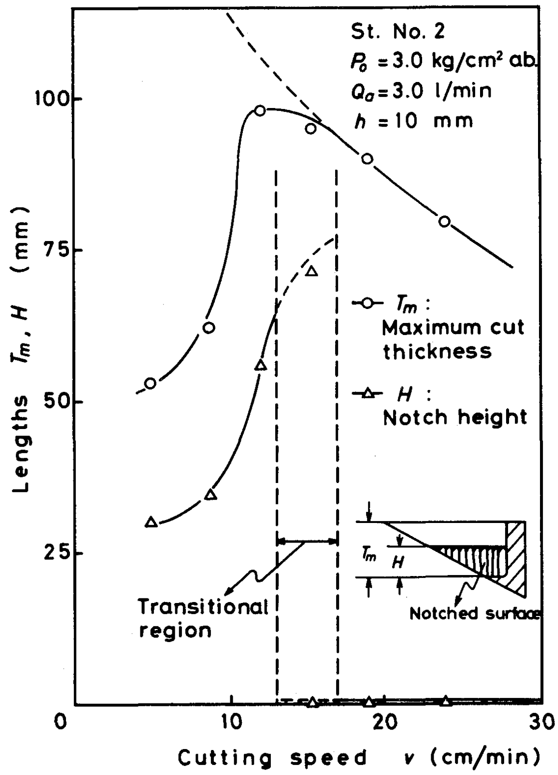


Fig. 5 Effect of cutting speed on maximum separable thickness (Nozzle used; Straight No. 2)

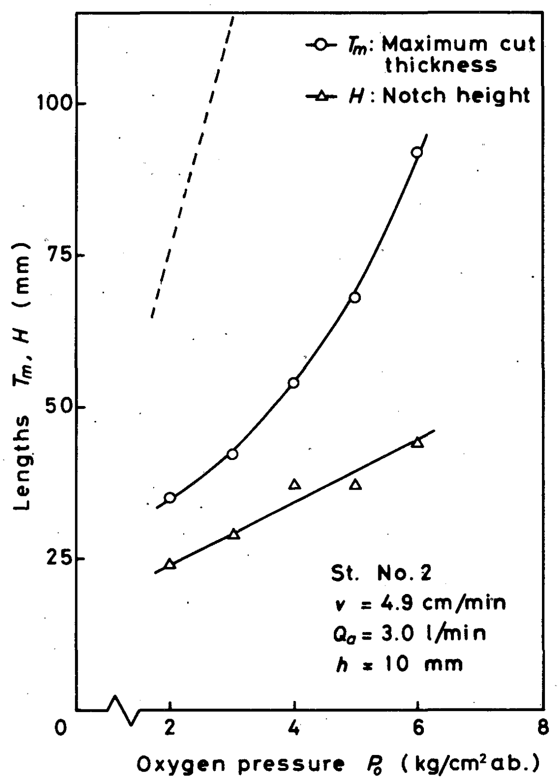


Fig. 6 Effect of oxygen pressure on maximum separable thickness and notch height

cut thickness. In other words, it would be possible to increase the cutting ability if the notching was successfully eliminated.

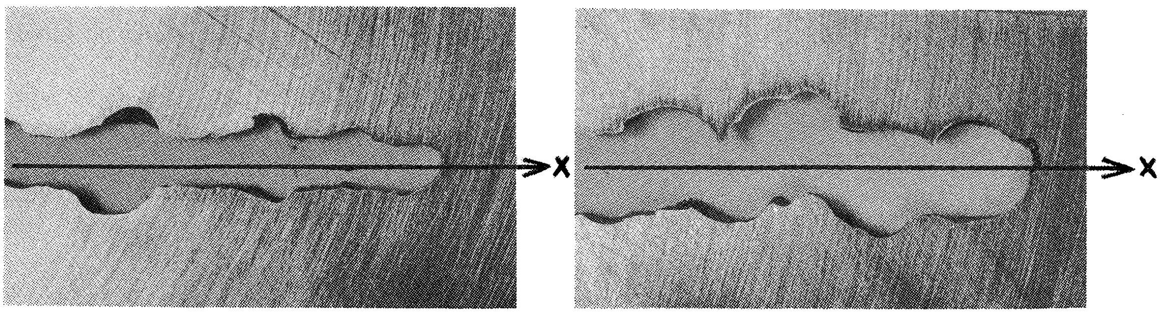
2.3. General feature and direction of notch formation

As described in the previous section, the Type I notch appears only in the lower side of kerf and it is clearly observed that notch is formed as the result of intermittent burning and extinction at the lower part of cutting front wall, in spite of the upper side being continuously burning.

Figure 7 shows the horizontal cross section of lower part of the specimen at which the combustion reaction was suddenly interupted by inserting a plate between the oxygen nozzle and plate during notching phenomena being repeating. As seen in the picture, there observed two types of moving direction of cutting front. One is that the burning front goes straight forward and notched kerf is symmetric in respect to the x-axis (cutting direction). Another is a case that the cutting front advances alternatively turning aside from the x-axis having an angle of θ, and the notched kerf meanders as seen in Fig. 7 (b).

The latter case, i.e., a gooseneck motion, is the general behavior during notching, and the bigger the angle the more deeply the notch is formed along the cut surface. The most important fact to be noted here is that each notched trace completely corresponds with the one cycle of the **extinction – re-ignition/combustion – extinction** process at the cutting front wall.

In **Figure 8** is shown a schematic diagram of gooseneck motion at the place where notching is taking place. Supposing that the present position of cutting front is **BFE** and re-ignition started from the point D and combustion developed to **OD** direction. If the combustion is intercepted at the point **F** due to the lack of necessary oxygen for burning, the next re-ignition will occur at the nearest point G when the oxygen jet arrives at the point P and the burning direction tends to another side, thus resulting in mindered kerf left along the cut surface. It is, therefore, obvious that the previous Fig. 7 (a) is a special case when θ is zero.



(a) (b)

Fig. 7 Direction of cutting front at notched part

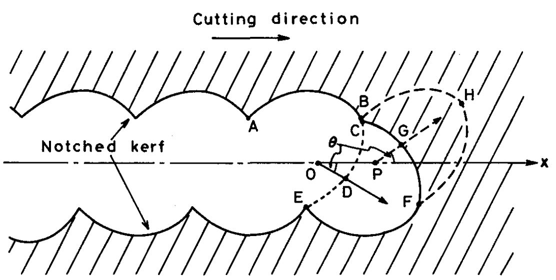


Fig. 8 Schematic illustration of gooseneck motion of cutting front during notching

2.4. Observation of cutting front during notching

In order to clarify the notching phenomena more in detail, the authors conducted direct observation of the state of cutting front under the condition that the gooseneck motion could be well neglected ($\theta = 0$).

Figure 9 shows a typical state of cutting front during a period of unstable combustion observed from the rear side of kerf. At the beginning of each cycle, the combustion at the bottom part of reacting front is interupted and solidified wall appears. The solidified surface develops upward gradually as the time passes, and after reaching to the maximum height which is still lower than the plate surface (No. 4), the re-ignition occurs suddenly and the whole solidified wall burns again with high combustion rate. In general, the re-ignition starts at the upper part and the

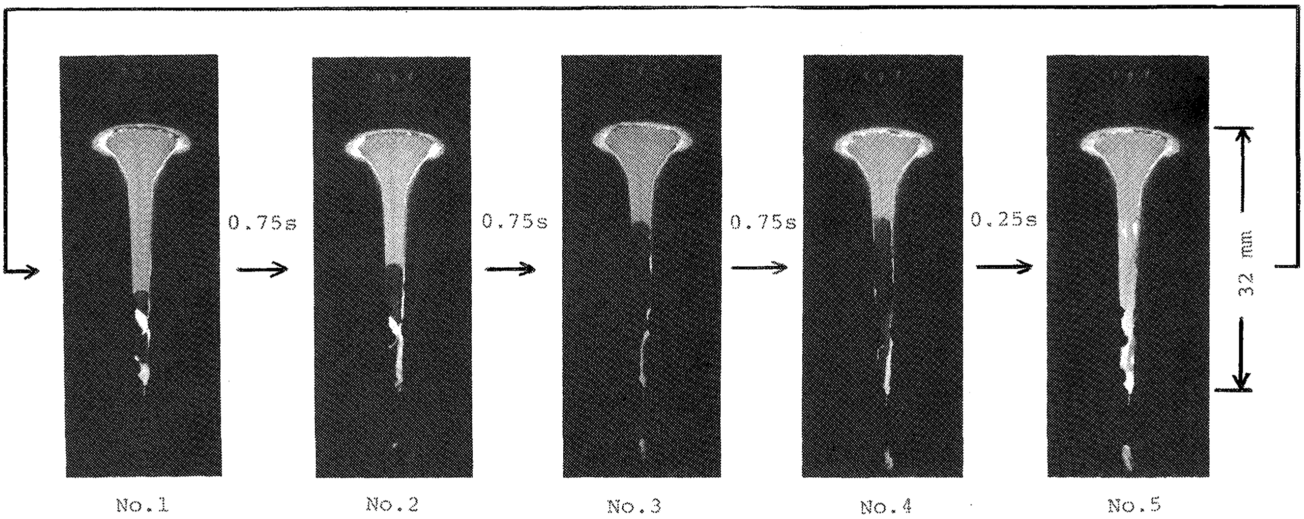


Fig. 9 Periodic unstable combustion at the cutting front when notching phenomena take place (ν = 3.5 cm/min, P_O = 4 kg/cm^2 ab., Q_a = 2.6 l/min N.T.P.)

combustion propagate rapidly downward, but an opposite process is sometimes associated when enough amount of molten slag or metal remains at the bottom of the cutting front.

The above periodic phenomena which characterized the notching were further analized by the method described in **Figure 10**, where the light intensity emitted from the small spot (0.8 mmϕ) of cutting front was detected by a photo-transistor.

Figure 11 shows the typical light signals at five points on the cutting front wall. In the oscillograms, the high level signal corresponds to burning state and ground level shows that of extinction. As seen in the figure, the upper part (No. 1) is continuously burning, while other parts (Nos. 2 – 5) show intermittent combustion and extinction with rather good periodicity of about 3 seconds. Here, it should be noted that the re-ignition at every point takes place instantly almost at the same time and the brightness, i.e., temperature at the re-ignition is high, and also that the lower the position, the higher the temperature and the shorter the combustion duration become.

It is important to know how the cutting front, particularly the lower part advances in the cutting direction during the notching. It was, therefore, conducted that the moving front at an arbitrary time was preserved by rapid shutting off the oxygen jet inserting a plate between the jet and plate, and the time was recorded by the method shown in Figs. 10 and 11. **Figure 12** shows thus obtained front shapes in different times during one cycle (note that the horizontal axis is exaggerated in the graph), and the open and solid circles on each curve show that the light signal is high or zero respectively. Since these front shapes were obtained from five different specimen and the periodicity of phenomena was not good enough to reproduce the same front shape, there found some discrepancies especially when combustion was intercepted. For the sake of explanation, the above changes in front shape is schematically described in **Figure 13** in which the

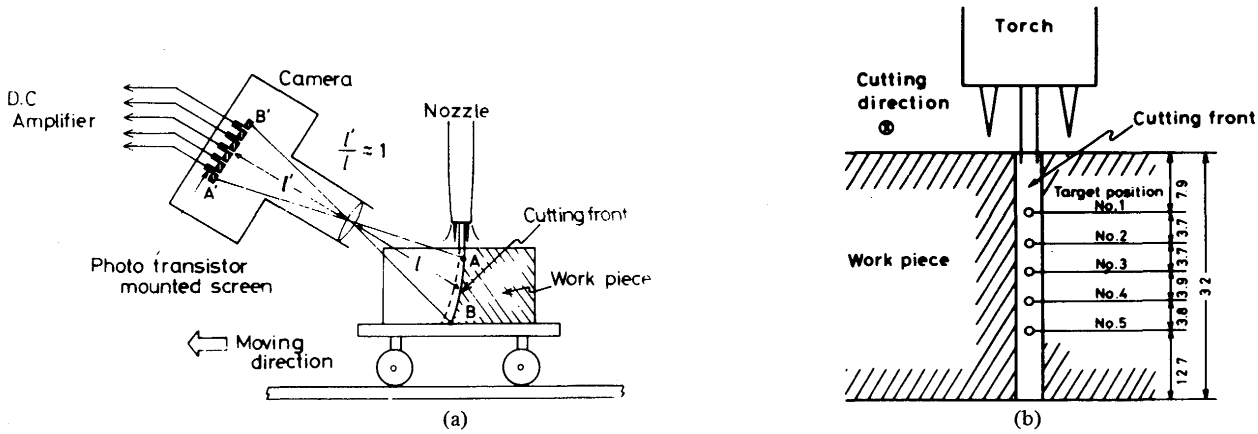


Fig. 10 Observation method of light intensity at cutting front

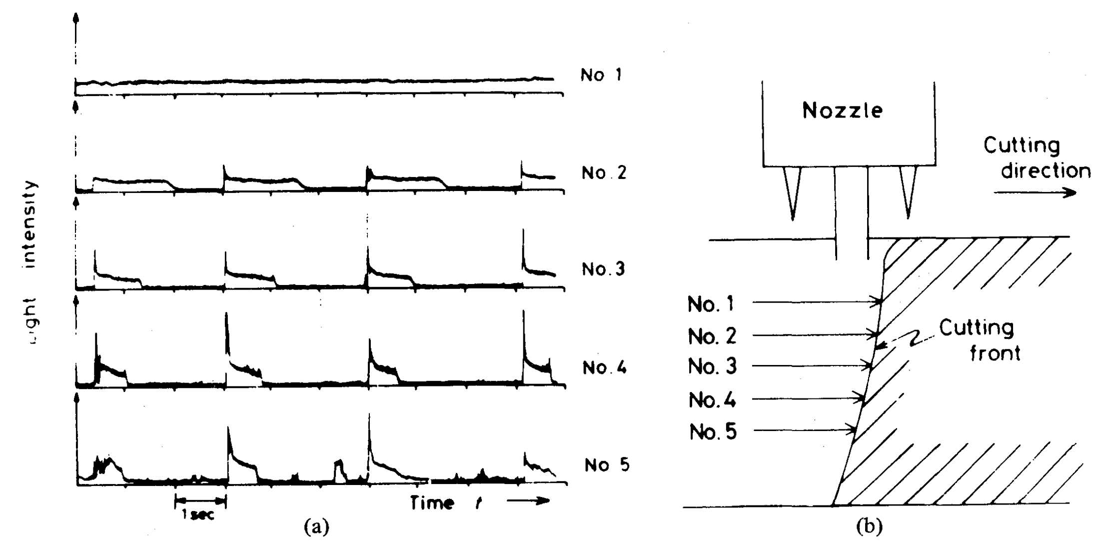


Fig. 11 Light signals emitted from cutting front during notching

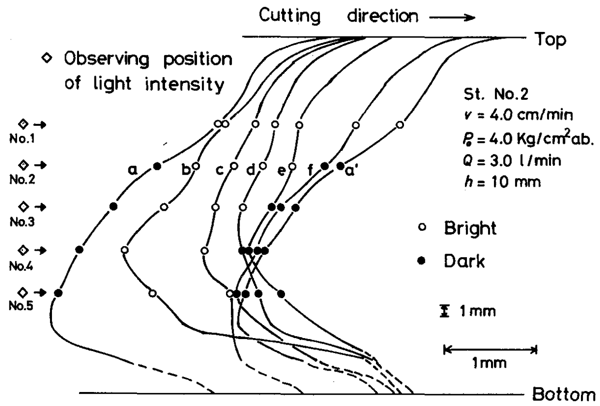
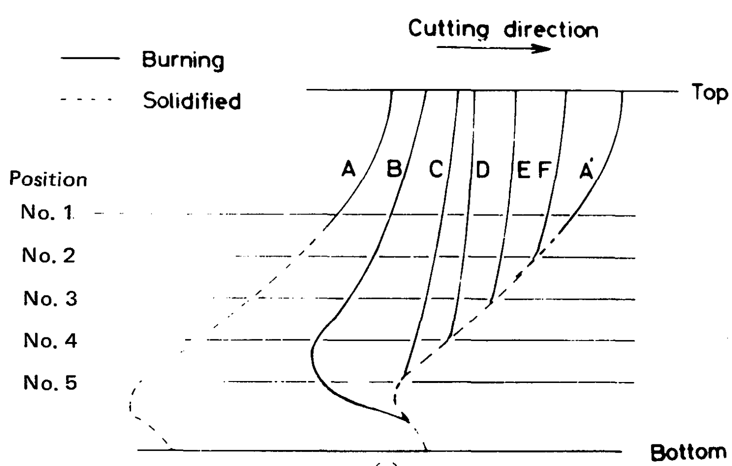


Fig. 12 Change of front shape during one cycle of unstable combustion (Note that the horizontal axis is exaggerated)

solid and dashed curves indicate the state of combustion and extinction respectively.

In the figure, the curve A shows when the solidified wall develops upward maximumly, and in a moment after this situation, the re-ignition takes place and at the time B the whole front surface burns violently. Especially, the lower the place, the higher the generated heat density, i.e., the higher combustion rate, which leads to increase the distance between the center line of oxygen jet and cutting front, and thus the combustion at lower part can not be sustained due to the shortage of necessary oxygen. Once the extinction happens at lower side, the solidified wall develops upward as shown by the process C-D-E-F as the time passes and finally reaches to A′ which is the same condition with the initial stage. The mechanism of upward development of extinction will be disscussed in the later section.

In the following will be described the measured speed of the upward solidification development and re-ignition



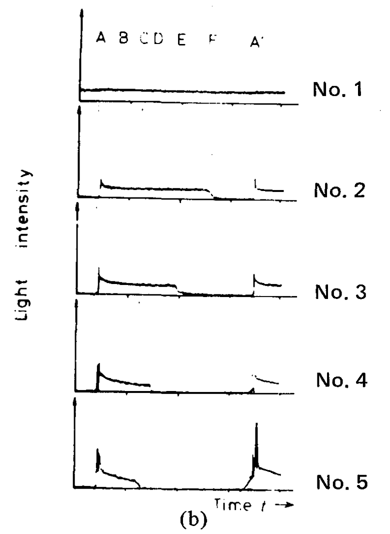


Fig. 13 Schematic diagram of notching process

propagation along the front wall, which were obtained from the light signal analysis. **Figure 14** shows how the solidification develops along the front wall with time, from which it is seen that the extinction propagates almost linearly with time. The calculated speed in the case of the figure is about 3.3mm/s (20cm/min) and its x-component (cutting direction) which was calculated from the measured angle of solidified wall agrees well with the travel speed of jet, and this fact suggests that upward propagation of solidification is closely related with flow

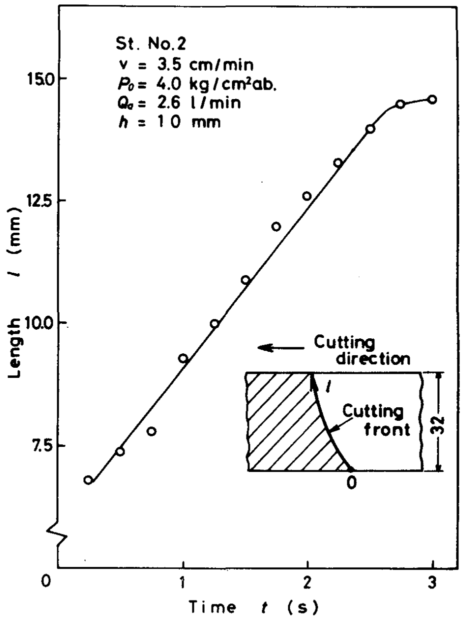


Fig. 14 Upward development of solidified wall along cutting front

characteristics of oxygen jet along the cutting front.

In **Figure 15** is shown the changes in light signals at the re-ignition and its propagation characteristics. When the re-ignition starts and propagate downward, the speed is very high reaching up to about 110 cm/min at the lower part of front wall. While, in case that the re-ignition propagates from the lower to upper part, its speed is very low as seen in **Figure 16**. The probability of happening this type of re-ignition is rather a few and the phenomenon is only observed, as shown in Fig. 16 (b), when the previous combustion at the bottom part was unstable due to the adhesion of plenty of molten slag or metal. And the burning state after the re-ignition is also very unstable.

3. Notch Formation Mechanism

3.1. Extinction of combustion and its propagation

In the previous sections were described the characteristic phenomena during notching, but the question was why the reaction was intercepted at the bottom and the solidified wall developed upward. Here will be discussed this matter from the view point of fluid mechanical interaction between the jet and front wall.

When a free jet is impinged on a inclined wall, a wall jet is newly developed after the momentum change near the impingement point[4), 5)] If the angle of impingement is increased, the amount of momentum change increases, which results in reduction of down stream velocity. Namely, a thick boundary layer is developed along the wall jet as schematically described in **Figure 17**, and the diffusion rate of oxygen becomes worse. It is, therefore, necessary

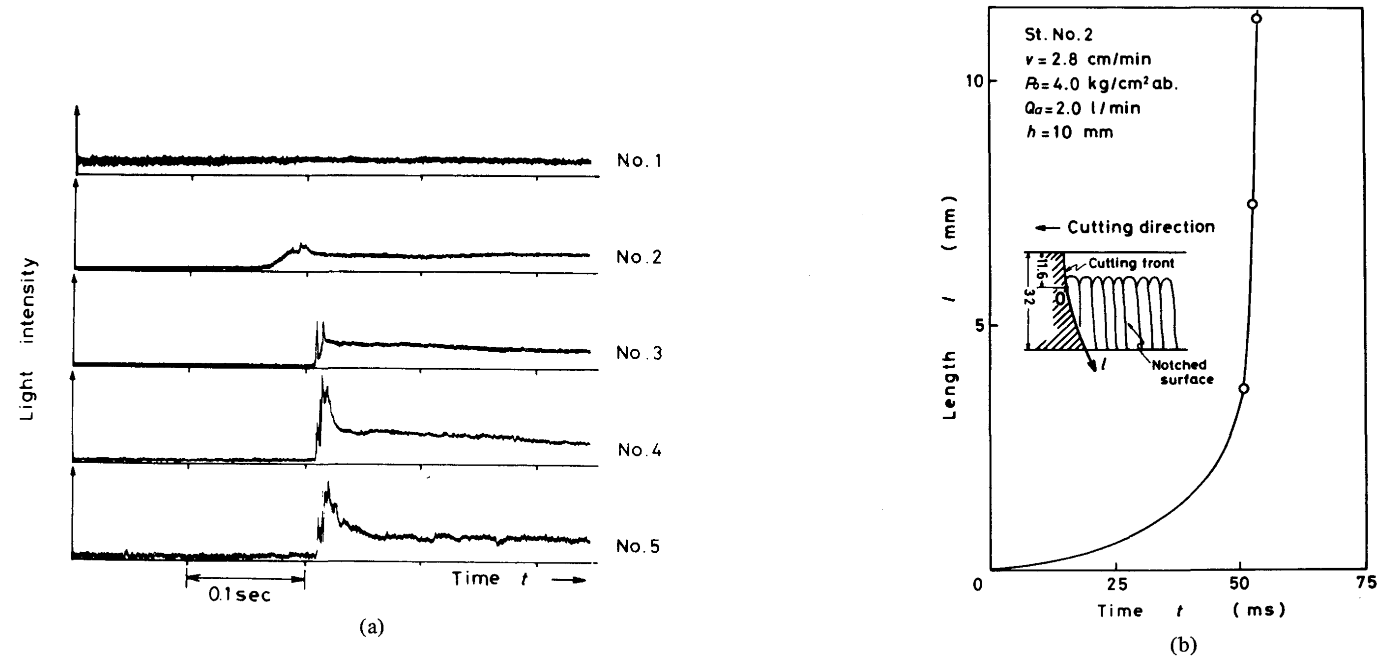


Fig. 15 Propagation of downward re-ignition

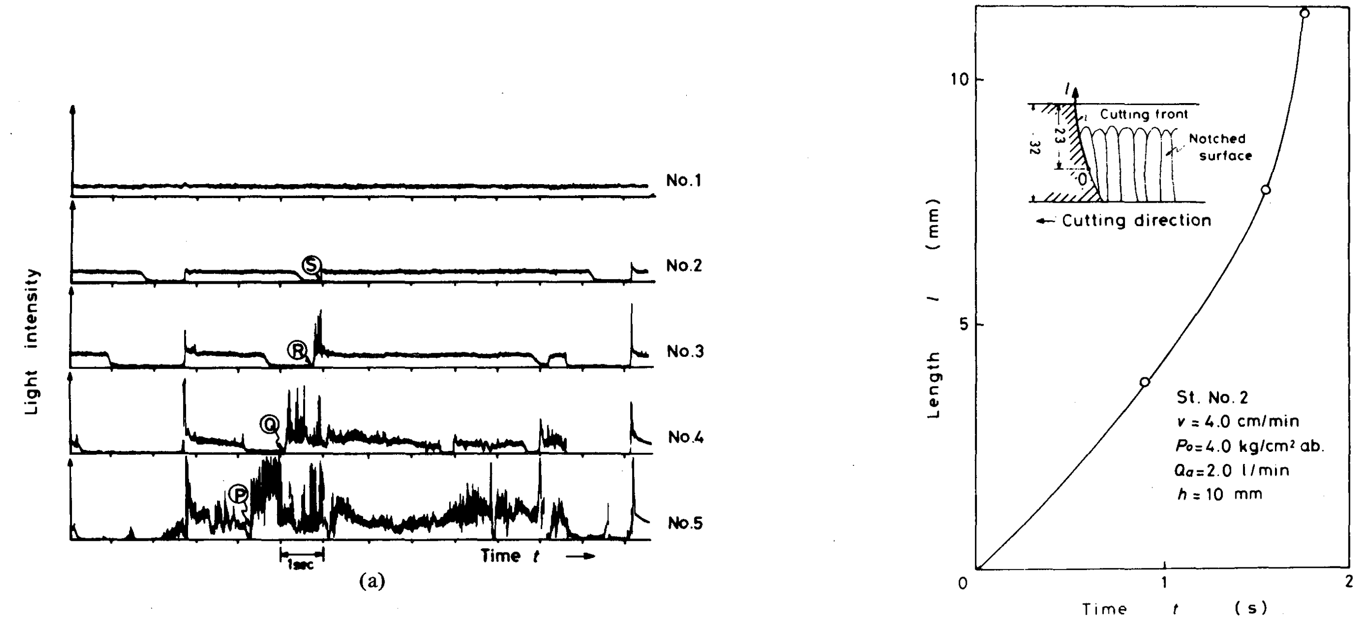


Fig. 16 Propagation of upward re-ignition

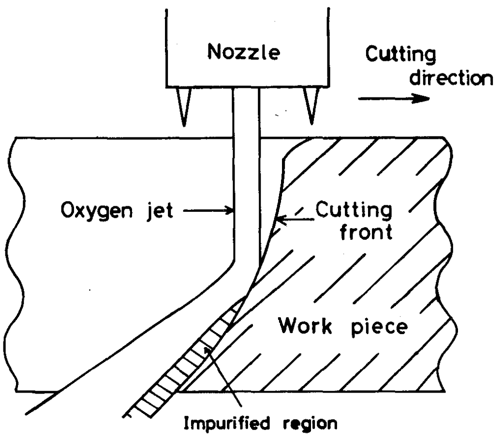


Fig. 17 Development of impurified boundary layer in down stream of impinging jet in low speed cutting

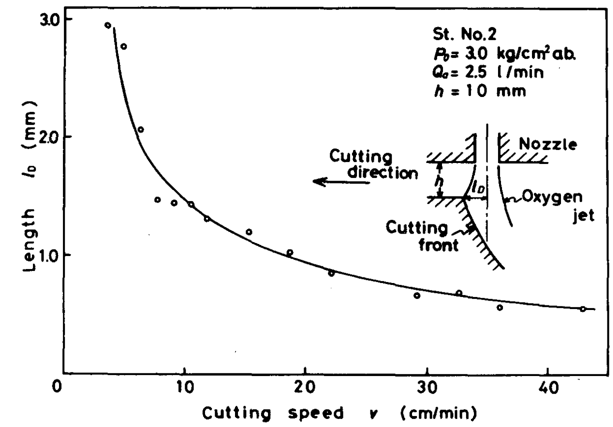


Fig. 18 Effect of cutting speed on distance between jet and cutting front

to clarify the correlation between the jet and front wall during cutting.

In **Figure 18** is shown the relative distance between the jet and the top edge of cutting front and its dependence on cutting speed. The length l_D increases with reduction of speed, particularly the speed below 10 cm/min where notching appears. While, the effect of cutting speed on the angles of top edge and impingement point on the front wall is shown in **Figure 19**, which were measured from the transverse sections obtained by sudden oxygen shut off method. It should be noted here that the both angles in notching speed region fluctuate greatly with time and adopt larger angles than the values extrapolated from the curves in higher speed range. Especially, the fluctuation of angle at jet impingement part and its vicinity is very large.

It is clear from the above stated experimental results that the increase in relative distance between jet and cutting front in very low cutting speed is likely to bring about an inherent unstable phenomena, particularly the change of wall angle at the jet impingement point. Therefore, once the combustion is interupted at the down stream of impingement point due to the lack of oxygen purity, the jet impingement point can not but move upward since the jet itself moves continuously while solidified wall is fixed with larger angle. Thus, the impurified region of wall jet also climbs up and the solidified wall developes upward.

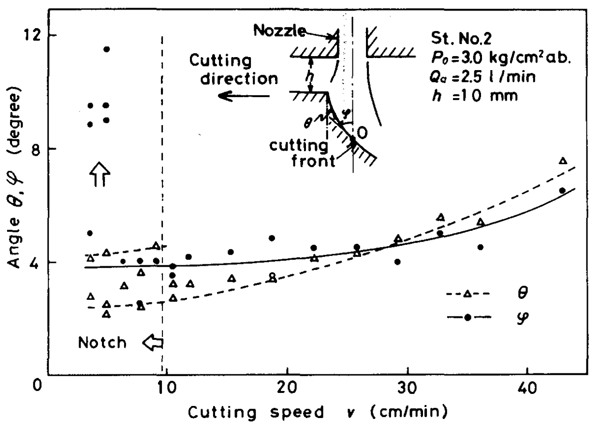


Fig. 19 Change in angles of cutting front with cutting speed

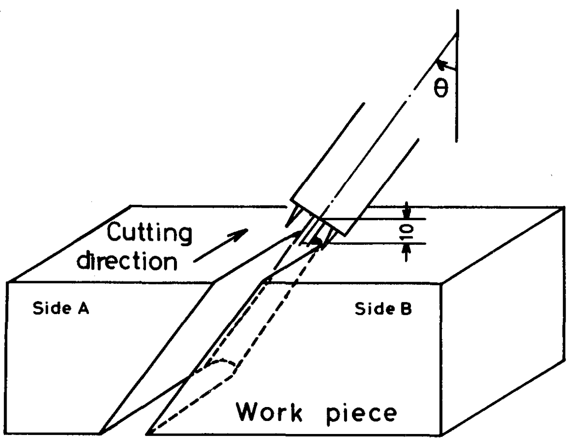


Fig. 20 Method of changing molten layer thickness at front wall

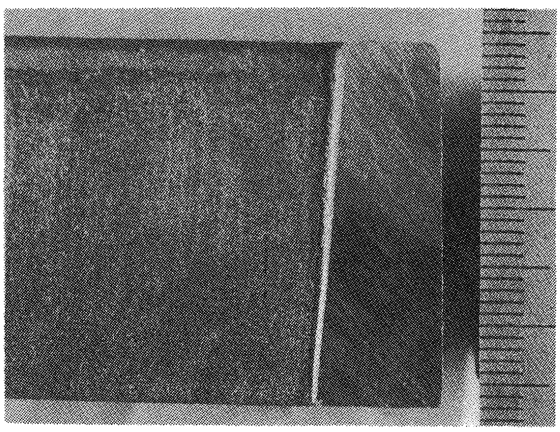
3.2. Effect of molten metal flow on notching phenomena

Molten metal or slag flow along the cutting front and its vicinity is also one of the important factors for cutting mechanism. It is estimated that the thickness of liquid phase becomes thinner in lower cutting speed, because the heat conduction loss to base metal is reduced with decrease in speed which leads to less heat generation density at the reaction surface. In general, a thin film flow is likely to be unstable fluid mechanically as well as thermally.

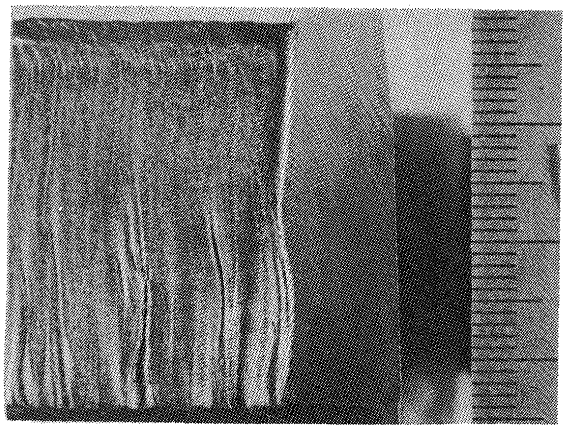
It has been, therefore, suspected that the unstable liquid flow might give a considerable effect on notching mechanism. But, there were no appropriate measures to grasp the objective and quantitative behavior of hot molten slag flow. Then, the authors conducted some qualitative experiment to know the effect of liquid phase on notch formation.

In order to change intentionally the thickness of molten layer at both side of a kerf, a slanted cutting method was adopted as described in **Figure 20.** The results were as seen in **Figure 21**, where the cutting speed was selected in the region that notching phenomena did not appear in the case of zero inclination angle. When the angle was small enough, the molten layer was thick and smooth cut surface was obtained. On the other hand, when the angle became large, the thickness at the both side of cutting front was not symmetric but became thinner at the Side A in Fig. 20 and the notch was formed as shown in Fig. 21 (b).

It is evident that the behavior of molten layer is also important factor of notching phenomena, but the detailed understanding is still subjected in future.



(a)



(b)

Fig. 21 Effect of molten layer thickness on notch formation
(v = 11.9 cm/min, P_O = 3.0 kg/cm² ab., Q_a = 2.0 min N.T.P., t = 32 mm)
(a) θ = 3° (Thick molten layer)
(b) θ = 21° (Thick molten layer)

3.3. Stoppage of upward propagation of solidified wall

In 3.1. was discussed on the appearance of soldified wall and its upward development during notching, but there still left the reason unknown why the upward propagation stopped at the upper part, not at the top surface. On this matter will be discussed here from the view points of molten slag or metal flow as well as thermal stability at the upper part of the cutting front.

In regard to molten layer, its thickness should increase as the solidification develops upward, because the path of molten metal or slag continuously flowing from the upper part is greatly restricted by the appearance of solid wall. Therefore, the heat capacity of molten layer and its fluid mechanical stabilities increase, thus it is reasonably estimated that the further propagation of solidification is obstructed.

Another important factor is the effect of preheating flame. As was reported by Wells,[6] the amount of heat input from the acetylene flame is considerably large at the upper part of plate, which effectively contributes to improve the thermal stability. This fact has been experimentally verified by changing the flow rate of acetylene. Namely, the notch height became low if the heat generation of preheating flame was increased.

As described in the above, the thermal and fluid mechanical stabilities are the primary cause of stopping the solidification propagation, but the further quantitative analysis is difficult at the present stage.

3.4. Flow characteristic of jet at notching and self sustaining condition of periodic combustion

In the previous sections were stated the detailed measurements and possible mechanisms at each stage of notching. Here will be described the self sustaining condition of periodic repetition, considering the flow characteristic of an impinging jet.

A model experiment was conducted in order to clarify the violent combustion just after the appearance of solid wall and its correlation with flow behavior of oxygen jet. **Figure 22** shows the experimantal method, in which a pulsed gas blow was applied to the cutting oxygen jet from the front side in order to seperate the main stream artificially from the cutting front. By the method, one could easily reproduce the appearance of solid wall at the reacting surface even under the condition of sound cutting.

In **Figure 23** are shown the light signal patterns and the obtained cut surface when a pulsed jet of carbon-dioxide was blown for 0.4 second. As seen in Fig. 23 (a), during the CO_2 blowing, combustion is clearly intercepted and solid wall appears due to the oxygen jet seperation by the fluid switching principle. Soon after shutting off the CO_2 blow, the oxygen jet reattaches on the cutting front and re-ignition takes place again. But the combustion rate at this stage is higher than that in stationary state and the cutting front proceeds quickly as in the same manner with the previous Figure 12, and the reaction stops again even

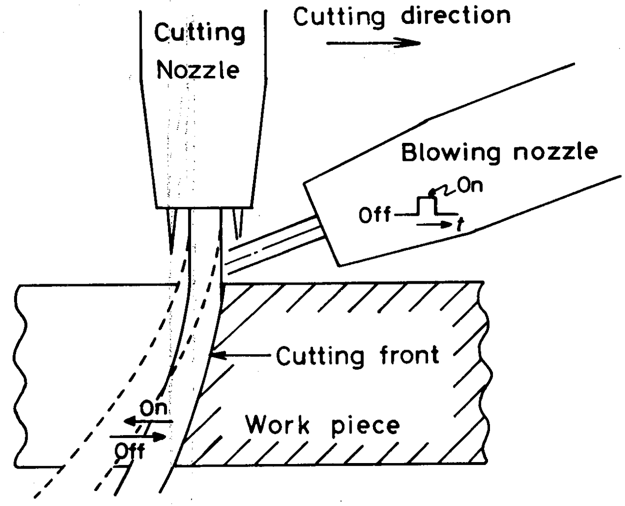


Fig. 22 Artificial notching generation by fluid switching

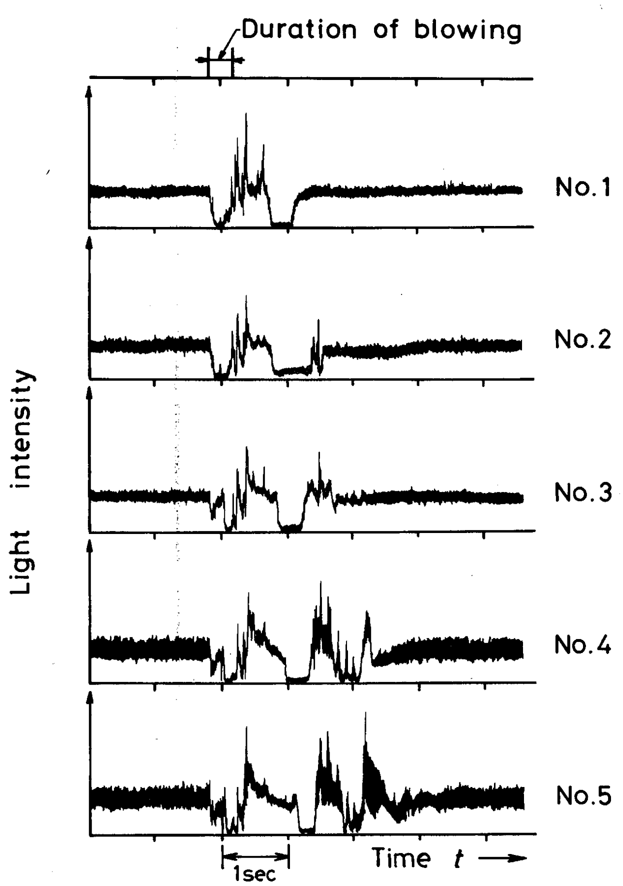


Fig. 23 Change in light signals at artificial notching by CO_2 blowing and its shape (v = 15.4 cm/min, p_o = 3.0 kg/cm² ab., Q_a = 3.0 l/min N.T.P., t = 32 mm)

though any external perturbation is not applied at this stage. This process of stoppage and re-ignition damps quickly after repeating several times and returns back to the steady state. Considering this phenomena from fluid mechanical aspect, it is reasonably concluded that the extinction of combustion is caused by the seperation of flow from the burning front due to its overhanged shape which is made by rapid burning and that the re-ignition begins by the reattachment of fresh oxygen jet. The shape of artificially formed notch is quite similar with those in low speed cutting, as seen in Fig. 23 (b).

The same phenomena can be even achieved by using pure oxygen as the blowing jet as is seen **Figure 24**. Only the difference is that the upper part does not extinguish but burns more violently by the sufficient addition of fresh oxygen.

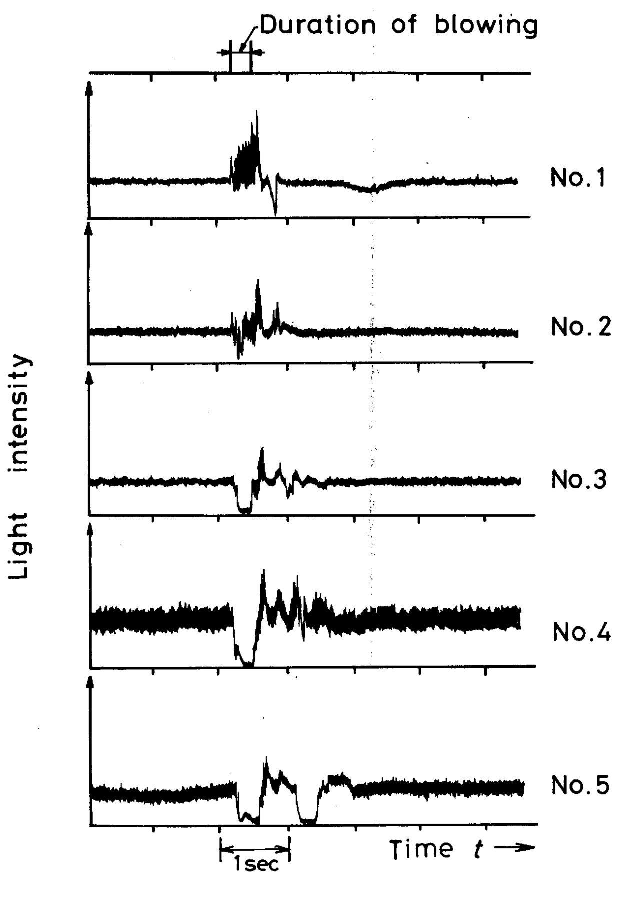


Fig. 24 Change in light signals at artificial notching by O_2 blowing and its shape (Experimental conditions are the same with Fig. 23.)

4. Conclusion

1) Notching is an inherent phenomenon in very low speed cutting and is characterized by the periodic repetition of the "extinction -- re-ignition and combustion -- extinction" process at the lower part of cutting front, in spite of being continuously burning at the upper front wall. The combustion rate is different with the position and the instantaneous speed is higher at the lower part. Notched kerf is the result of violent combustion at the front wall in each cycle.
2) The primary cause of notching is the extinction of burning at the bottom part of front wall due to the lack of necessary oxygen diffusion in the impurified boundary layer in a wall jet which develops after the impingement point of free jet on the cutting front. The upward development of extinction is explained by the climbing up this jet impingement point along the front wall which accompanies with the upward movement of impurity layer. The stoppage of this upward development is greatly influenced by the behavior of thin liquid film as well as the effect of the preheating flame.
3) The re-ignition is initiated from the boundary of molten layer and solidified wall and its propagation speed is very high. Since the lower part of front wall elapses longer time after solidification and its temperature becomes lower, the intensity of heat generated at the recombustion becomes high, which leads to higher burning rate. Therefore, the lower part proceeds forward very quickly and flow separation takes place which results in distinguishing the burning reaction.

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