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Interaction between Supersonic Jet and Burning Iron Wall in Oxygen Gas Cutting (Part II)†

– Combustion Stability and Flame Cutting Mechanism –

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Abstract

The paper describes the stability of combustion reaction in a two-dimensional model of oxygen gas cutting of iron which is obtained by the direct observation of flow pattern and burning wall configulation with high speed Schlieren photography. Combustion stability is closely related to the shock wave behaviours and necessary condition of stable burning is to satisfy a certain negative correlation between the shock wave angle and thickness of shock wave layer which is an appropriate index of the boundary layer thickness. If this relation is not held, two kinds of unstable reaction interruption which is the same phenomenon of lose-cut in actual flame cutting take place depending on the type of shock wave behaviour. A new boundary layer model of oxygen gas cutting is derived as a result of these investigations.

KEY WORDS: (Oxygen Gas Cutting) (Flame Cutting) (Thermal Cutting) (Supersonic Jet) (Shock Wave) (Boundary Layer) (Combustion) (Stability) (Jet/Wall Interaction)

1. Introduction

In the Part 1 of this article[1)] were described a method of visualization of the flow and burning wall patterns during flame cutting, shock wave behaviours and their correlation to combustion phenomena. It was clarified that a distinct oblique shock wave was formed near the upper edge of burning wall at higher burning speeds and the shock wave behaviour was classified into two typical types depending on the temporal change of shock angle as well as combustion phenomena.

The shock wave of Type I which took place in the medium range of burning rate was featured by the stable formation of an oblique shock wave with less fluctuation of shock angle and combustion phenomena. The Type II, on the contrary, was observed in the range of higher burning rate and characterized by the periodic change in shock angle and burning front wall configuration with considerable large amplitude. It was also confirmed that this Type II shock wave behaviour could be subdivided into two different modes depending on the shock wave formation and combustion phenomena. Namely, the Type IIA was featured by periodic fluctuation of oblique shock wave angle during combustion and the average angle of shock wave was larger than that of Type I. While, the Type IIB was characterized by the still larger fluctuation of shock angle than that of Type IIA and a specific shock wave of triangular shape was formed during a fluctuation period when the angle of an oblique shock wave reached to some critical value. Simultaneously, it was observed that the combustion reaction was interrupted at the top edge of burning wall during the formation of triangular shock wave. In the latter period of triangular shock wave formation, the main stream of oxygen jet detached from the iron wall in the down stream due to the formation of overhang and a strong reverse eddy appeared which assisted the reignition of top edge and again an oblique shock wave was generated.

As stated above, the characteristic behaviours of both types of shock wave were principally related to the combustion rate or feeding rate of iron strip. If the feeding rate was increased in the Type II range, a distinct phenomenon of sudden reaction interuption happened at the upper part of burning wall which was the same phenomenon of so called "lose-cut" which often took place in the conventional oxygen gas cutting in very high speed. It was, therefore, presumed that the lose-cut phenomenon was closely related to the shock wave behaviour and its effect on the formation of boundary layer along the burning wall.

In this paper will be described the static and dynamic stabilities of shock wave and their correlation to burning phenomena, their similarity to lose-cut phenomenon and a generalized mechanism of flame cutting based on gaseous

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boundary layer theory.

2. Stability of Shock Wave and Boundary Layer along Burning Wall

2.1 General relation between thicknesses of boundary and shock wave layers

There have been proposed two different models of oxygen-iron combustion mechanism in flame cutting. One is the Hofe's liquid model[2] in which the diffusion of Fe and O atoms in the molten slag rules the combustion reaction. Another is the Well's gaseous boundary layer model[3,4] where the combustion is governed by the diffusion of O_2 molecules in the gaseous impurity boundary layer. However, results obtained in the Part 1 of present study[1] on direct flow pattern observation and particularly on shock wave behaviours and their correlation to burning phenomena seem to support the gaseous boundary model.

Figure 1 shows the gaseous boundary layer model proposed by Wells[3,4]. The diffusion rate of oxygen molecules through the boundary layer of thickness of δ is given by the following equations.

$$N = \frac{Dp}{RT\delta} \, ln \frac{p_1}{p_2} = \frac{Dp}{RT\delta} \, ln \frac{1}{\eta} \qquad (1)$$

where,

N: Diffusion rate of O_2 through boundary layer [mol/s·cm²]
D: Diffusion coefficient of O_2 [cm²/s]
R: Gas constant [atm·cm²/mol·K)]
δ: Thickness of impurity boundary layer [cm]
p: Total pressure of boundary layer [atm]
p_1: Partial pressure of O_2 on burning wall [atm]
p_2: Partial pressure of impurity gas in main O_2 jet [atm]
η: Concentration of impurity in main O_2 jet

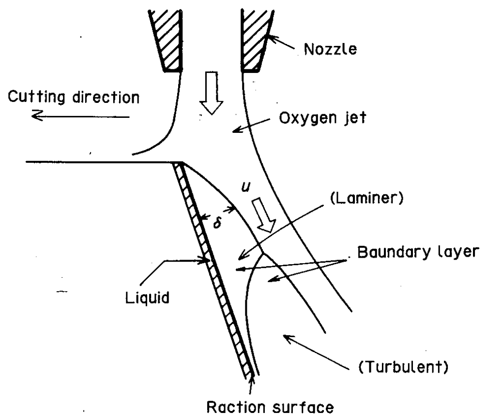


Fig. 1 Boundary layer model of oxygen gas cutting proposed by Wells[3]

T: Temperature in boundary layer [K]

The thickness of boundary layer is expressed as

$$\delta = k\sqrt{l} / \sqrt{\frac{u\rho}{\mu}} = kl / \sqrt{Re} \qquad (2)$$

where,

l: Distance along burning wall from top edge [cm]
u: Velocity of main O_2 jet [cm/s]
ρ: Density of O_2 [mol/cm³]
μ: Viscosity of O_2 [N·s/cm²]
k: Constant (given 5·2 by Wells[3,4])
Re: Reynolds number ($= ul\rho/\mu$).

The equation (2) was derived from the Prandti's boundary layer theory of two dimensional flow where the initial thickness of boundary layer at the edge was supposed zero.[5] If this relation is held in actual flame cutting, the oxygen molecules are sufficiently supplied at the top edge of burning wall where δ is zero and no reaction interruption like as lose-cut phenomenon can be expected at the upper corner of cutting wall.

The present authors revealed in the previous paper[1] that the one end of shock wave always initiated from a certain position in gaseous phase apart from the top edge of wall, which suggested that the thickness of boundary layer was not zero but finite at the top corner of burning wall.

It is known that there is some correlation between the thicknesses of shock wave layer and boundary layers as schematically shown in **Fig. 2.**[6] When a supersonic jet impinged on a wedge, the formation of oblique shock wave is different depending on the wedge angle. If the angle is small, the shock wave attaches to the top edge of wedge and consequently the thickness of boundary layer is zero at the initiation part. However, if a jet impinges on a wedge having large angle or on a blunt cone, the shock

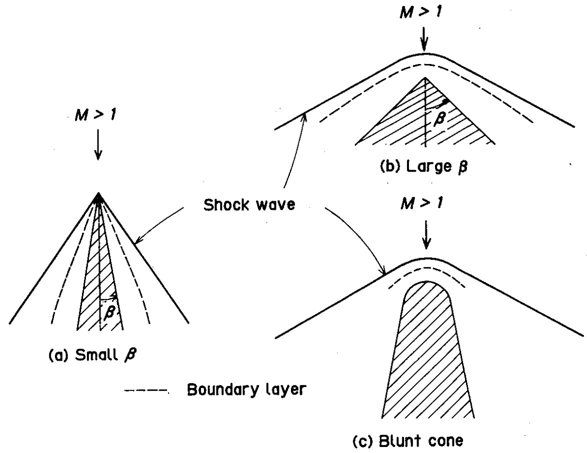


Fig. 2 Effect of wedge angle and blunt cone on detachment of shock wave and the development of boundary layer

wave is formed apart from the edge end and the thickness of boundary layer becomes finite at its origination. Here, the distance between the shock wave and top edge of solid is called the thickness of shock wave layer.

The shape of oblique shock wave and thickness of shock layer are affected by the main stream velocity even under the same wedge angle as illustrated in **Fig. 3**. Supposed an oblique shock wave being attached to the edge at the velocity of M_1 as seen in Fig. 3(a), the shock angle becomes large and represents arch shape in lower Mach number M_2 as illustrated in Fig. 3(b). If Mach number is reduced further to M_3 and M_4 as shown in Figs. 3(c) and (d), the shock wave shifts to upper stream detached from the solid and hence the boundary layer becomes finite at the end of wedge. Namely, the shock layer and boundary layer have some positive correlations each other.

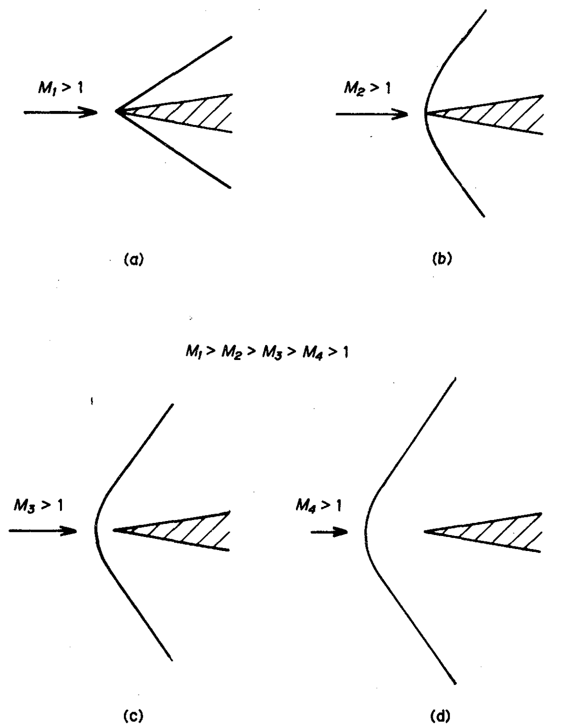


Fig. 3 Effect of jet velocity on detachment of shock wave[6)]

The shock angle is also one of the important parameters which influences on the thickness of boundary layer. **Figure 4** shows the velocity change before and after an oblique shock wave and the shock polar diagram. Velocity components normal and parallel to the shock wave must satisfy the following relations.[6)]

$$u_{1s} = u_{2s}$$
$$u_{1n} \geqslant a \geqslant u_{2n} \tag{3}$$

where,
a: velocity of sound.

Taking the x-axis parallel to the main stream direction before the shock wave and the y-axis perpendicular to x, the relation between x and y components of velocity after the oblique shock wave is given by the equation (4).[6)]

$$v_y^2 = (u_1 - v_x)^2 \frac{u_1 v_x - u_c^2}{\frac{2}{\gamma+1} u_1^2 - u_1 v_x + u_c^2} \tag{4}$$

$$v_x = u_2 \cos\beta$$

$$v_y = u_2 \sin\beta$$

where,
u_c: Critical velocity
(= (2/(γ + 1) [(γ − 1) $u_1^2 + 2a_1^2$]
a_1: Velocity of sound in up-stream
γ: Ratio of specific heats (c_p/c_v)

Figure 4(b) shows the relation of Eq. (4), and it is obvious that the deflection angle β of main stream after the shock wave never exceeds the maximum value β_{max}. It is also

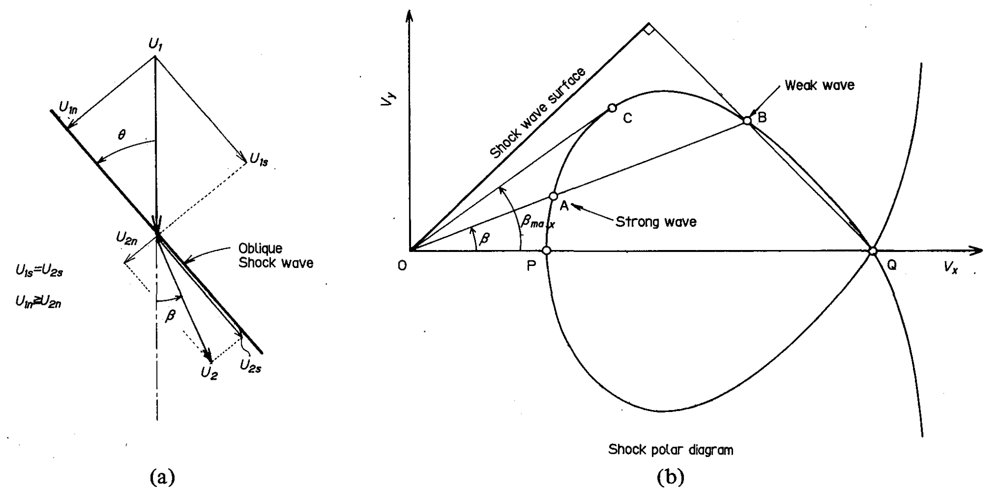


Fig. 4 Velocity change through shock wave and shock polar diagram[6)]

noted in the figure that there exists two solutions of down stream velocity under the condition of same β and M values. At the point B in Fig. 4(b), the flow velocity is supersonic even after the oblique shock wave and this is called a weak shock wave. While, the down stream velocity at the point A is subsonic and is called a stron shock wave.

In case of a weak shock wave, the shock angle increases and the down stream velocity u_2 decreases as the deflection angle of main stream increases as schematically represented in **Fig. 5**. If the Prandtl's theory is applied along the wedge wall, the thickness of boundary layer is reverse proportional to $u_2^{1/2}$ since

$$\delta \propto (l/u_2)^{1/2} \qquad (5).$$

Namely, the thickness of boundary layer becomes thicker as the shock angle is larger.

In case of a strong shock wave, on the contrary, the shock angle reduces as the deflection angle β is increased. At the same time, even under the constant deflection angle of main stream, the shock angle increases as the speed of impinging jet is increased. However, in the strong shock wave too, the stream velocity after the shock wave also becomes slower as the shock angle is larger, which means that larger shock angle corresponds to the thicker boundary layer.

As described above, the thickness of shock layer as well as its angle is an important index that shows the thickness of boundary layer along the wall, though it is very qualitative concept.

2.2 Thickness of shock wave layer and its correlation to shock wave parameters during stable combustion

In order to estimate the change in boundary layer thickness against cutting variables, correlations between the shock wave layer, shock angle and wall angle (deflection angle of main jet) were examined from high speed camera observation as described in the previous report.[1)] Here, the thickness of shock wave layer and other parameters were defined in **Fig. 6**.

Figure 7 **(a)** and **(b)** show static correlations among four typical parameters as a function of feeding rate (stationary burning rate of strip iron). As stated in the previous paper, the shock angle fluctuates small in Type I range. But, in Type II, it changes periodically with very large amplitude. In the figure, the shock angle θ_m is the mean value in case of Type I shock wave and the average value of the minimum angles during fluctuation in case of Type II wave. (Refer to Fig. 8) The front angle and the thickness of shock wave layer are the measured value that correspond to the above θ_m. As seen in Fig. 7, the sets of the shock angle and front angle and the thickness of shock layer and distance l_d have positive correlation each other, but negative correlation are seen between these two sets. Here, it should be noted in Fig. 7(a) that the correlation between the average shock wave angle and wall angle is positive which indicates the shock wave is a weak wave as a whole. However, as described in the previous paper the correlation is negative during large fluctuation in Type II shock wave behaviour (Figs. 17 and 18 in the Part I), and this means that the shock wave is a strong wave during this period. Namely, in Type II shock wave, a repetition of

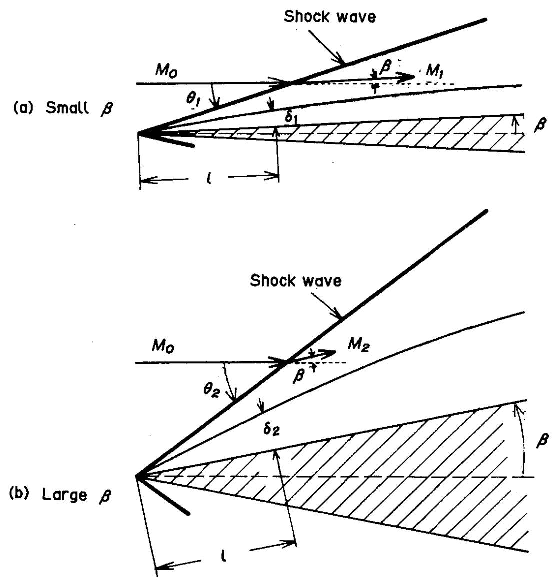


Fig. 5 Effect of wedge angle on shock wave angle and boundary layer thickness along wall

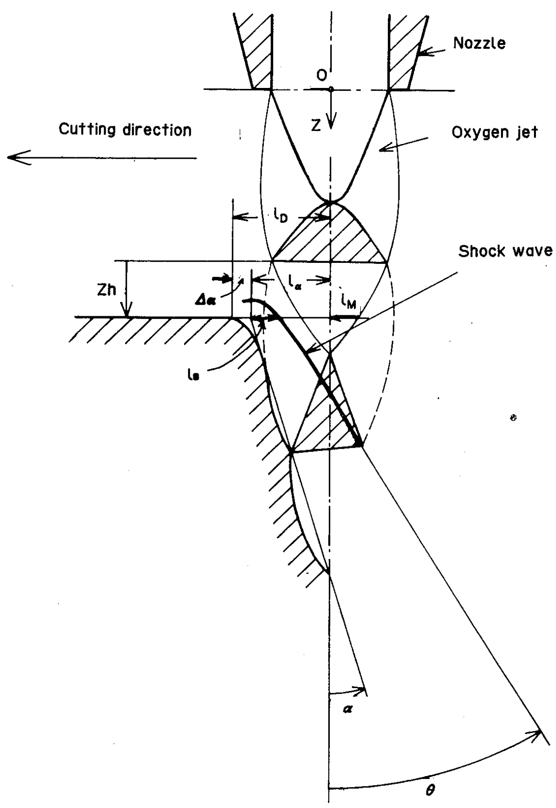
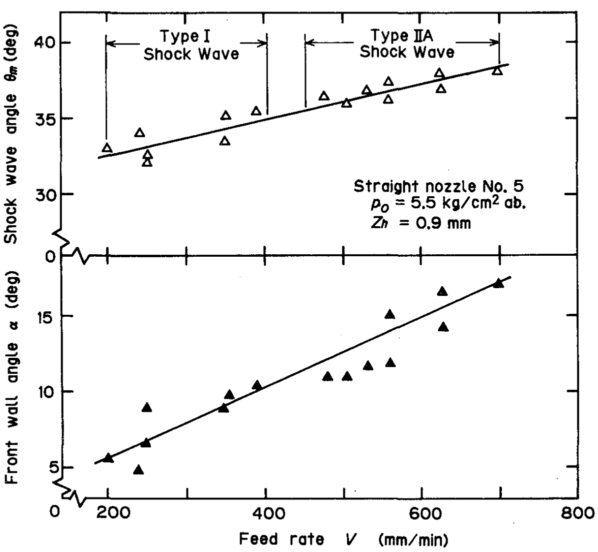
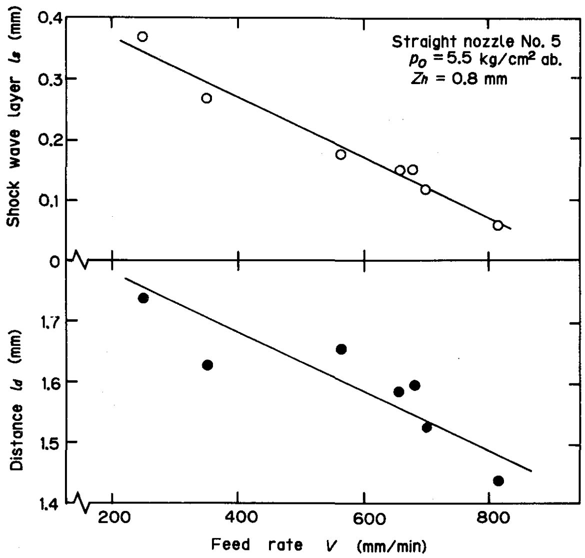


Fig. 6 Definition of related parameters



(a) Correlation between average shock wave angle and front wall angle



(b) Correlation between thickness of shock wave layer and distance from jet axis to wall edge

Fig. 7 Effect of burning rate on measured parameters

weak and strong waves occurs during periodic fluctuation.

Figure 8 exhibits the relation between shock angle θ_m and shock layer thickness when the feeding rate of iron strip is changed under the constant torch height or the torch height is varied under the constant feeding rate. Obviously there exists a negative correlation between shock angle and shock layer thickness in each series of experiment.

Generally, the increase in burning rate requires thinner boundary layer in order to acquire sufficient oxygen diffusion. There are two posibilities to form a thin boundary layer. One is to increase the velocity of main stream along a wall, and another is to reduce the initial thickness of boundary layer at its initiation if the a boundary layer has finite thickness at the wedge end. In case of constant stream velocity before the shock wave, the increase in wall angle or deflection angle of main stream brings the reduction of speed, which results in the development of thicker boundary layer. As stated in previous figures, the shock

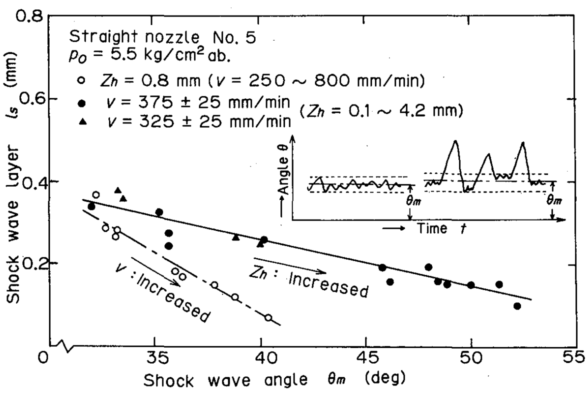


Fig. 8 Correlation between thickness of shock layer and shock wave angle

and wall angles increase as the feeding rate or torch height are increased, and this fact means the reduction of stream velocity after the shock wave. However, in an oxygen jet used in this study has not uniform velocity distribution but has rather complex velocity profile. Roughly speaking, the velocity is higher in the center part of jet than that of periphery. Fig. 7 showed that the distance between the jet axis and top edge of wall l_d became smaller when the shock angle was larger. This means that the top edge of wall is deeply immersed into the higher velocity region of jet, and consequently the reduction of flow speed along the wall seems to be suppressed effectively in spite of large shock and wall angles. Another important fact is that the shock wave is detached from the wall edge and its distance becomes smaller when the shock angle is larger. Detachment of shock wave from wall shows that the boundary layer has finite thickness at its origination, and thinner shock layer means thinner boundary layer. It seems, therefore, that, in the self sustained combustion model of present study, the necessary thickness of boundary layer for oxygen diffusion is self adjusted by immersing the top corner of burning wall into the high speed region in oxygen jet.

3. Combustion Interruption in High Burning Rate

3.1 Instability of shock wave behaviour and its relation to combustion interruption

In an oxygen gas cutting of thin plate there is a critical cutting speed that the burning reaction is suddenly interrupted at the upper part of front kerf and this restricts the high speed cutting of thin plate. This is usually called

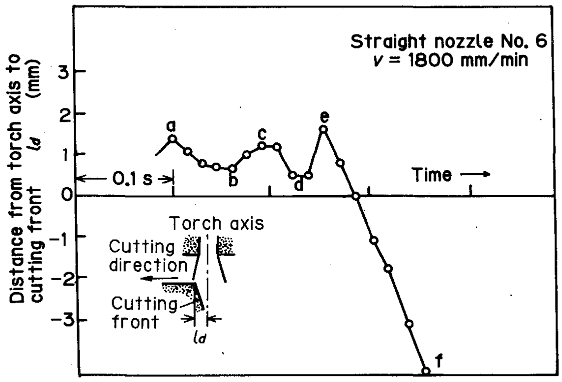
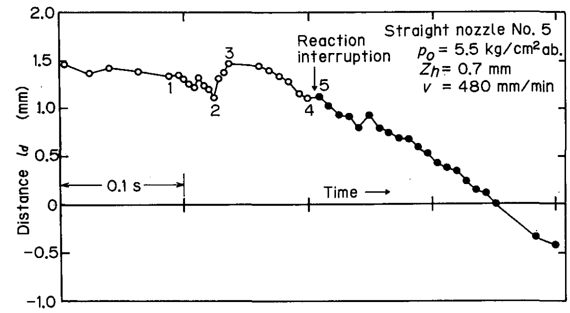


Fig. 9 Change in cutting front edge position at vicinity of critical speed of lose-cut initiation[7)]

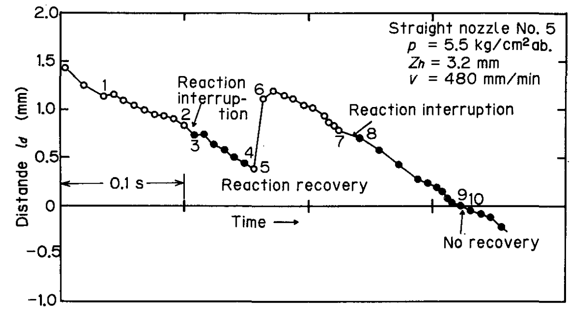
"lose-cut phenomenon" and some experimental studies were conducted to clarify the related phenomena. Nishiguchi and Matsuyama[7)] took high speed pictures of lose-cut phenomena. **Figure 9** shows their measured results indicating the relative position of cutting front wall from the oxygen jet axis at the vicinity of critical speed that a lose-cut phenomenon occurs. The distance l_d between the jet axis and wall edge repeats shortening and lengthening as the curve a~d and interruption of chemical reaction happens (at point e) at the upper edge of cutting front. The phenomenon was interpreted that the thickness of molten metal on the front wall became thinner which led unstable chemical reaction and finally self-adjustment of l_d could not be sustained. However, this does not explain the mechanism of lose-cut occurance, though it gives the unstable tendency.

The present authors made precise observation of reaction interruption by high speed Schlieren photography method. The experiment was done that the feeding rate of iron strip was slowly increased from a steady state burning ($v = 480$ mm/min) until the complete reaction interruption took place. The filming rate was 250 frames per second. Consequently, two distinct phenomena were revealed in the mode of reaction distinction and the difference in mode was directly related to the shock wave behaviour. Namely, under the condition of Type IIA shock wave behaviour, the combustion was suddenly interrupted at the top corner of wall and overall chemical reaction stopped after that. Under the shock wave condition of Type IIB, on the other hand, the reaction was interrupted similarly to the above but reignition took place again, and the process of distinction and reignition repeated before the final reaction interruption took place. The precise sequence of these phenomena were already shown in the Figures 13 and 14 in the previous report.[1)]

Figure 10 shows temporal viriation of distance from torch axis to edge of burning wall for both types of shock wave behaviour. In the Model A reaction distinction, some instability of edge position is observed as indicated by 1, 2 and 3 during combustion, but once the reaction is interrupted at 5 the distance l_d is kept reducing as seen by solid marks in the figure. While, in Mode B interruption, the distance is continuously reduced as shown by curve 1 to 2 in Fig. 10(b) and it still reduces along the curve 3 to 4 after the distinction of burning reaction which outbreaks at 3. However, the reignition of top corner happens at 5 and the distance is quickly increased to 6 and the same phenomena repeats. The recovery of burning reaction is the greatest feature of this mode, but this unstable phenomena do not continue and complete reaction interruption takes place at the point 8. As stated above, the distinction of burning reaction is likely to occur when the distance l_d is too small, but this fact does not give any reasonable explanation. Therefore, dynamic change of shock wave angle and its correlation to shock layer was investigated to grasp the change of boundary layer at the time of combustion interruption.



(a) Mode A



(b) Mode B

Fig. 10 Temporal change of distance from torch axis to top edge in Type II shock wave behaviour at combustion interruption

Figure 11 exhibits the measured thickness of shock wave layer and shock wave angle at the time of Mode A combustion distinction and **Fig. 12** is its correlation. In these figures, the open marks represent burning state and solid marks indicate the distinction of combustion. As seen in Fig. 8, the thickness of shock wave layer has a negative correlation to the shock wave angle as far as the combustion reaction is kept and open circles stay in the band expressed by dashed curves. However, if an acting point is deviated from this zone due to some reason as shown by points from 4 to 5, the combustion is interrupted and the correlation between two parameters show positive as

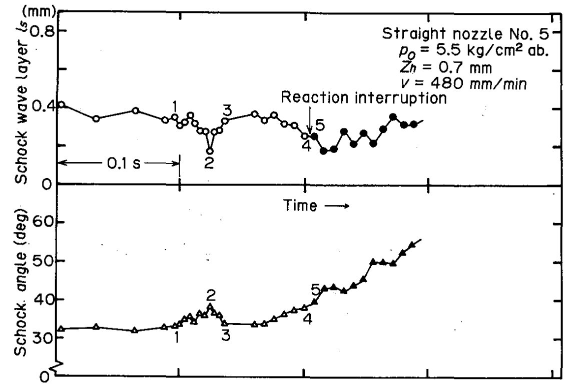


Fig. 11 Temporal change of shock wave layer and shock wave angle at combustion interruption of Mode A

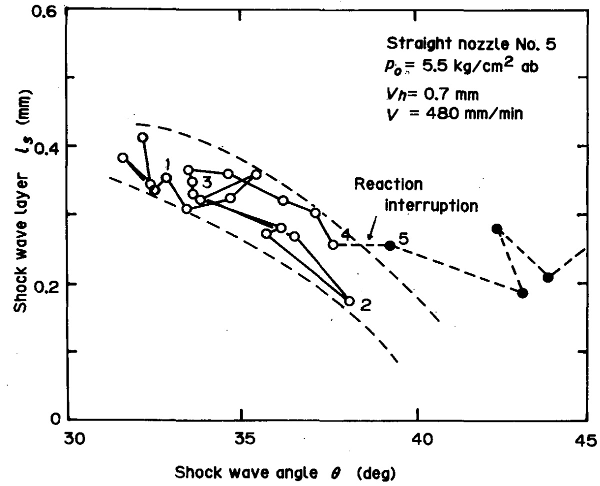


Fig. 12 Correlation between thickness of shock wave layer and shock wave angle before and after Mode A combustion interruption

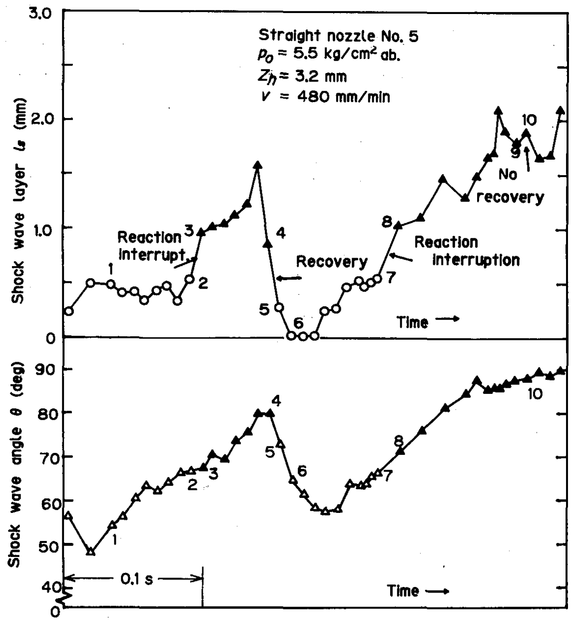


Fig. 13 Temporal change of shock wave layer and shock wave angle at combustion interruption of Mode B

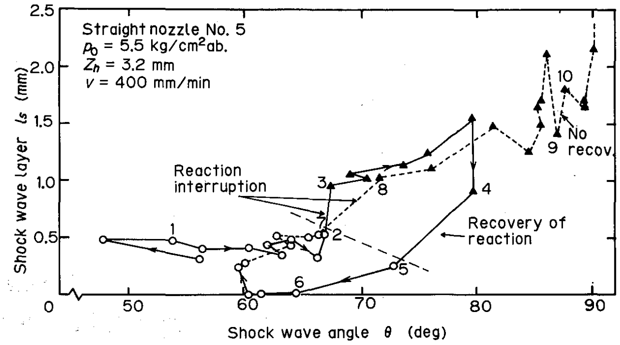


Fig. 14 Correlation between thickness of shock wave layer and shock wave angle before and after Mode B combustion interruption

shown by solid circles. This fact shows that even an unstable reaction can be recovered if the thickness of shock layer, i.e., thickness of boundary layer, is quickly reduced to necessary value for oxygen diffusion against external perturbation.

Figures 13 and **14** shows the case of Mode B reaction interruption. It is noted from figures that relation between the thickness of shock layer and shock wave angle is not a negative correlation but almost independent during combustion, which is quite different from the Mode A. Namely, from points 1 to 2 the shock layer depth remains almost constant sustaining combustion in spite of shock angle increase, but the thickness increases rather abruptly at the point 3 and burning reaction is suddenly interrupted. After the distinction, two parameters show characteristic loop as the curve 3~4~5 in Fig.14 and reignition takes place at the point 5. However, when the acting point comes again to the critical point 7, which is almost the same acting point of 2, distinction of burning reaction initiates, but in this case the shock layer thickness continues to increase as the shock angle becomes large and no recovery of reignition occurs any more. As described before, the recovery of burning reaction is due to the strong reverse eddy formed just beneath the overhang of wall but precise observation of eddy as well as its parametric relations to the recovery of combustion have not been well clarified yet.

3.2 Boundary layer model of oxygen gas cutting

It was apparent from the direct observation of flow pattern in oxygen-iron combustion that the interaction between the oxygen jet and burning wall plays the most important role for the mechanism of thermal cutting. In particular the formation of shock wave near the top edge of burning wall and its behaviour give vital effect on stability of combustion. Therefore, the present authors have concluded that the oxygen diffusion through gaseous boundary layer along the burning wall is the essential mechanism of flame cutting. However the gaseous boundary model of oxygen gas cutting proposed by Wells[2,3] can not explain the unstable burning phenomena described in this paper because he supposed the zero thickness of boundary layer at the top corner of cutting front where the oxygen jet impinges, though Wells's model can be reasonably applied to the combustion in down stream region.

In order to establish a more general mechanism of flame cutting, the present authors has developed the following model of boundary layer and flow structures as shown in **Fig. 15**. Key points of the model are that the thickness of boundary layer is not zero but finite at the top edge of burning wall and an oblique shock wave is formed detached from the edge. And initail thickness of boundary layer is very much affected by the shock wave

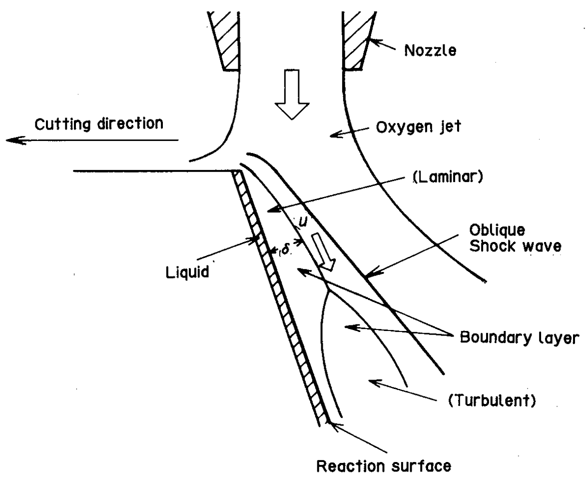


Fig. 15 Boundary layer model of oxygen gas cutting with supersonic jet

behaviour, particularly by the thickness of shock wave layer which is formed when a supersonic jet impinges on a blunt corner edge. Presently, there is no theoretical approach on the relation between the boundary layer thickness and shock wave characteristics in the non-uniform and asymmetric flow model like in this study, and hence there is no perfect explanation on the mechanism of self regulation of boundary layer thickness against the change in shock wave angle. However, the above combustion model seems to well explain the actual phenomena in oxygen gas cutting.

4. Conclusion

From the direct observation of shock wave behaviours and their relations to combustion phenomena, the following conclusions were derived about the stability and mechanism of oxygen gas cutting of iron:

1) Stability of combustion reaction was closely related to the correlation between the shock wave parameters and relative position and configulation of burning wall to the jet axis. In particular, the stable self-sustained combustion was achieved when the shock wave angle and the thickness of shock wave layer satisfied a certain negative correlation, and it was presumed that a kind of self regulation of boundary layer thickness took place when the shock angle became large, i.e., when the flow velocity reduces after the shock wave.
2) Two kinds of unstable burning reaction at higher combustion rate were found depending on the impinging position of cell of oxygen jet. One mode was that the reaction was suddenly interrupted when the upper part of second cell impinged on the burning wall (Type IIA shock wave). The another mode was that the combustion distinction and reignition took place periodically when the lower part of second cell interacted with the top edge (Type IIB shock wave). These phenomena were the same ones of loss-cut in actual cutting and were associated when the thickness of shock wave layer exceeded some critical value for given shock wave angle.
3) A new boundary layer model of flame cutting was proposed that has a finite thickness of boundary layer at its initiation which is related to the formation of a detached oblique shock wave from the top corner of cutting front.

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