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Citation	Transactions of JWRI. 1985, 14(1), p. 45-54
Version Type	VoR
URL	https://doi.org/10.18910/6047
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Interaction between Supersonic Jet and Burning Iron Wall in Oxygen Gas Cutting (Part I)†

—Shock Wave Behaviour and Combustion Phenomena—

Akira MATSUNAWA*, Tomoaki NAKAI** and Ikuo OKAMOTO***

Abstract

The paper describes an observation method of interaction phenomena between a supersonic jet and cutting front wall in oxygen gas cutting by a two dimensional experimental model in which a self sustaining combustion takes place at the end of continuously fed iron strip, and the obtained results of jet flow pattern and burning wall behaviours by Schlieren methods with high temporal resolution. It has been observed that a distinct oblique shock wave is generated when the combustion rate is increased and its behaviours are affected by the burning rate and position of jet impingement at the top edge of burning wall. There are three basic types of shock behaviours, i.e., one stationary mode and two periodic modes, and their appearing conditions and cross correlations with the burning wall parameters have been clarified. It has been also revealed that the two types of periodic motions of shock wave are closely related to the so called lose-cut phenomenon in flame cutting that is featured by a sudden interruption of combustion reaction in higher cutting speed.

KEY WORDS: (Oxygen Gas Cutting) (Flame Cutting) (Supersonic Jet) (Flow Pattern) (Oblique Shock Wave) (Jet Impingement) (Combustion) (Schlieren Photography)

1. Introduction

In oxygen gas cutting or flame cutting which utilizes the thermal energy generated by chemical reaction between oxygen and iron, it is known that two independent critical conditions exist beyond which the cutting is not possible at higher speed[1−4]. One is called the lose-cut phenomenon and another is gouging critical in which the plate of given thickness is not seperable. In particular, the lose-cut phenomenon that is featured by the sudden interruption of burning reaction during cutting restricts the higher speed of cutting. There are several works on the factors affecting lose-cut phenomenon[1−4], but its mechanism has not been fully understood.

Two different models have been proposed on the combustion mechanism of oxygen gas cutting. One is the Hofe's liquid model[5] where the diffusion of Fe and O atoms in the molten slag governs the reaction, and another is the Well's gaseous boundary layer model[6,7] in which the combustion is ruled by the diffusion of oxygen molecules in the gaseous impurity boundary layer. At the present time it has not been identified which theory is correct. However, by the recent works on lose-cut phenomenon, gouging phenomena and notching phenomena at low cutting speed, there are many experimental facts that can be reasonably interpreted if one takes into account the oxygen diffusion in the gaseous boundary layer[3,4,8]. Boschnakow[9] also has concluded that the gaseous boundary layer model is more probable than liquid model in actual oxygen gas cutting.

The present authors have noted a fact that the so called lose-cut phenomenon, i.e., a sudden distinction of burning reaction, always takes place at the top part of the cutting front when it is immersed deep into the central part of supersonic oxygen jet, and they assumed that the phenomenon would be associated with the interaction between the supersonic jet and burning wall, particularly with the behaviors of shock wave when a supersonic flow impinged on a blant edge. In order to clarify this assumption, observations of flow pattern and its correlation to combustion states of iron were examined in this paper using a two dimensional burning model.

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

2. Two Dimensional Experimental Model of Oxygen Gas Cutting and Flow Pattern Observation of High Speed Jet

2.1 Two dimensional experimental model of combustion and visualization of flow pattern

An oxygen jet used for flame cutting is a circular axisymmetric shape having the radial and axial components under the condition of free jet and thus it can be regarded as a two dimensional flow. But, the actual oxygen jet during cutting has principally three directional components, i.e., one component parallel to cutting direction

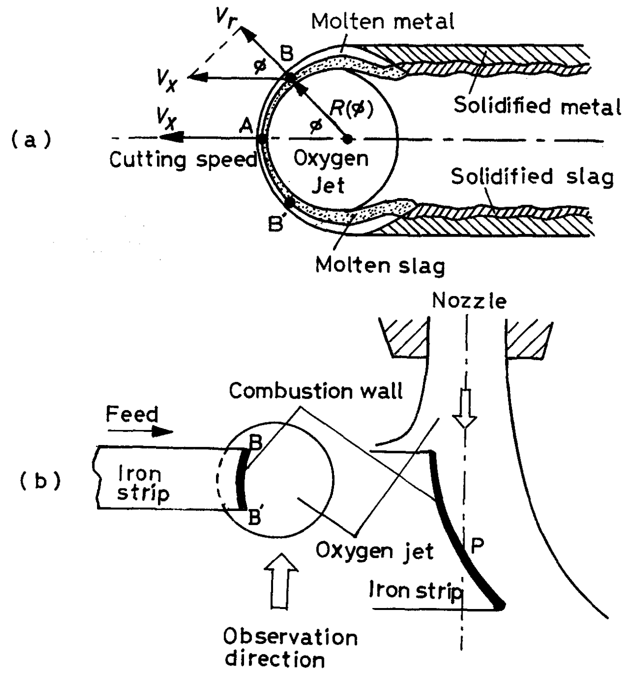


Fig. 1 Schematic illustration of Oxygen gas cutting and its two dimensional experimental modeling.

and two independent components parpendicular to the direction of cutting, and the reaction rate on the cutting front wall under the quasistationary state is different depending on the place along the curved surface of burning front as indicated in **Fig. 1**. Namely, as shown in Fig. 1(a), the quasi-stationary burning rate in the direction perpendicular to curved surface, v_r, is expressed as follows if the cutting speed parallel to x-direction and angle of the direction of curvature of curved surface at point B are taken v_x and ϕ respectively.

$$v_r = v_x \cos\phi \tag{1}$$

Therefore, if one considers a very narrow angle ϕ or short distance from the point A, the width B-A-B' in Fig. 1(a) for example, it can be reasonably assumed that the burning process is the one directional reaction with constant combustion rate of v_x. From this view point, the authors attempted to realize the two dimensional combustion model by burning the end of iron strip having less thickness than the diameter of oxygen jet as shown in Fig. 1(c). Thus, it could be possible to observe the flow pattern of oxygen jet along the burning wall as well as combustion mode by an optical method.

In this study, a straight nozzle of 2.3 mm exit diameter and a strip of 2 mm thickness and 25 mm width of commercially available pure iron (0.008 – 0.01 %C) were employed. The nozzle was fixed and the strip iron was continuously fed burning its end. For the observation of flow pattern, the above stated two dimensional model shown in **Fig. 2** was located in the observation area of a

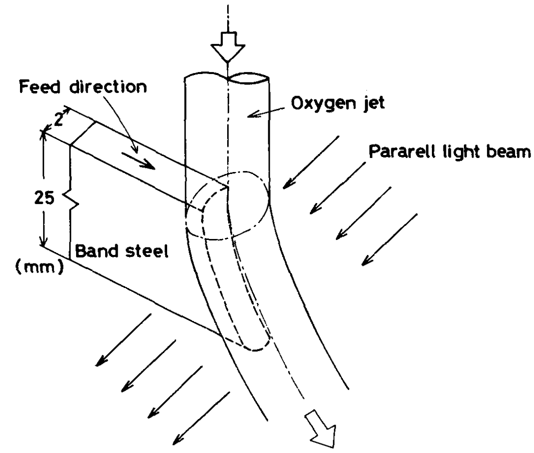


Fig. 2 Edge combustion of continuously fed iron strip

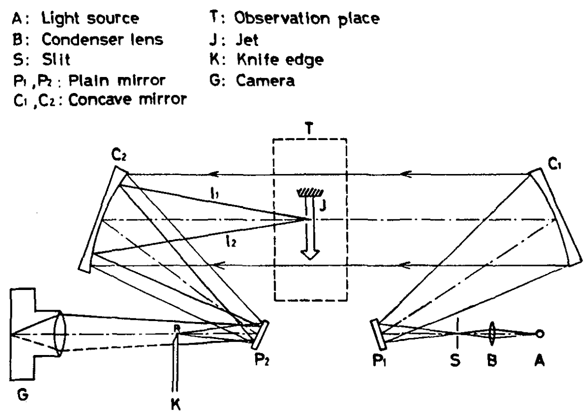


Fig. 3 Schlieren optical train

Schlieren photography optical system as shown in **Fig. 3**, and the still picture and high speed cinematography observations were conducted. As the light source of Shlieren optics, a continuous wave high pressure mercury lamp and a high voltage spark light source with very short emission time of 2 μs were employed depending on the observation purposes.

2.2 Comparison of two dimensional combustion model with actual oxygen gas cutting

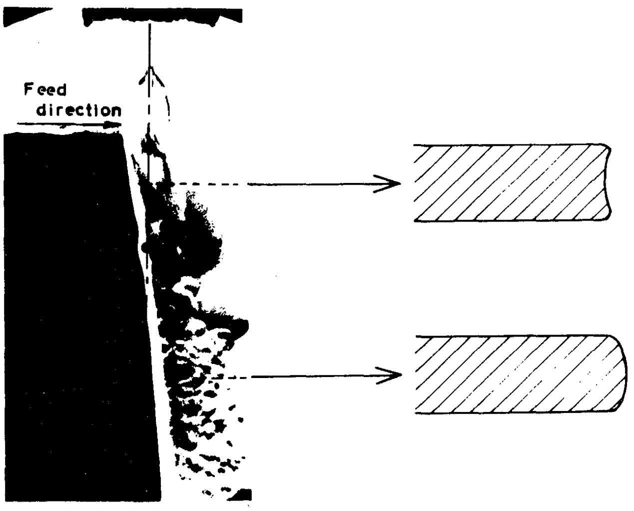


Fig. 4 Schlieren picture during edge combustion and shape of burning front

Figure 4 shows an example of Schlieren picture during burning in the two dimensional experimental model and its cross sectional shape of reaction surface which were obtained by the instantaneous distinction of combustion by immersing a copper plate into a jet during steady state burning. As seen in the picture, the reaction surface tails against the nozzle position in the lower part of strip which is just similar to that of conventional flame cutting, and the cross sectional shape of burning front shows different configulation depending on the position along the jet stream, adopting concave shape in the range above the point where the extended nozzle center line intersects with the combustion front and convex shape in the downstream range.

Nishiguchi and Matsuyama[1] classified the cutting front surface into three specific regions, i.e., Regions I, II and III, depending on the heat input characteristics on burning surface. From this view point, the above described shape of reacting surface in the region higher than the point of intersection of centerline of oxygen jet on the wall is quite similar to that of Region I in flame cutting, but considerably different in the down stream range. Namely, the experimental model employed in this study conforms to the actual oxygen gas cutting phenomena only in upper part of strip plate.

In flame cutting, it has been already clarified that the distance l_d between nozzle axis and the top edge of cutting front wall and its inclination angle change with cutting speed. **Figure 5** shows the relation between the above parameters and burning speed (feeding speed of a iron strip) in case of two dimensional model. Figure 5(a)

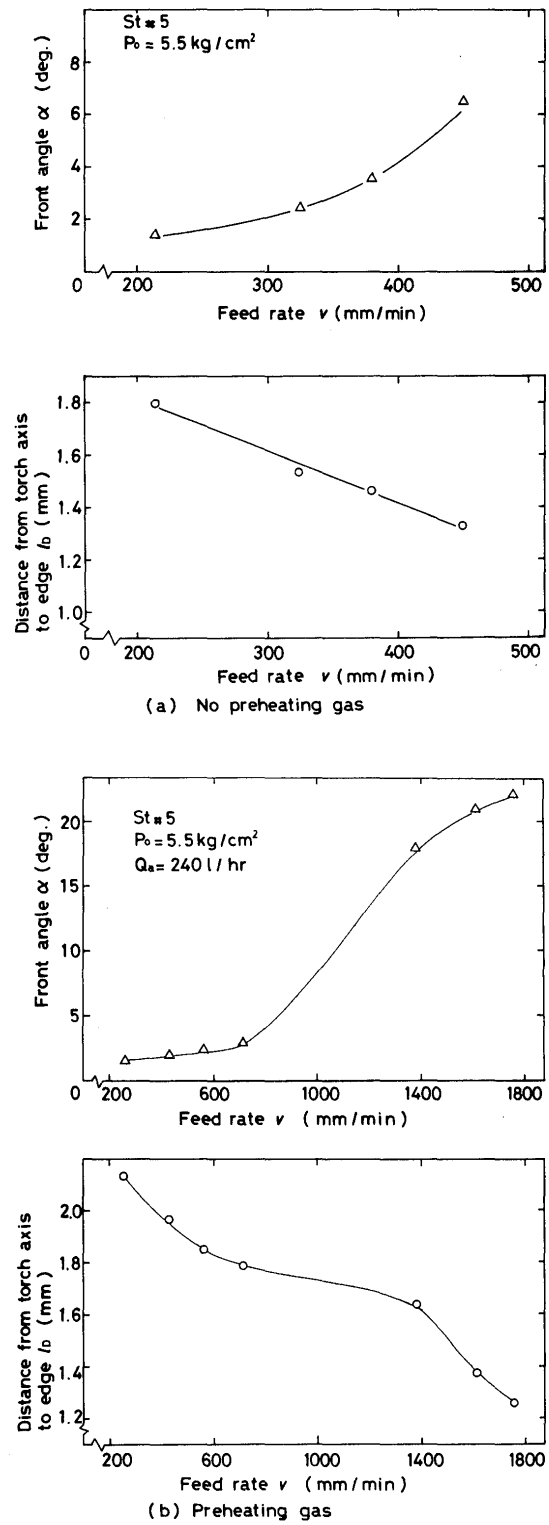


Fig. 5 Effect of feeding rate on distance between torch axis and burning edge and angle of combustion front (a) without preheating flame, (b) with preheating flame.

and (b) are the cases with and without preheating flame respectively. In spite of existence or nonexistence of outer flame, the top edge of burning surface invades deep into the jet and the angle of reacting wall increases as the feeding rate of strip iron is increased. The tendency is quite in good agreement with that in actual flame cutting.

By the preliminary studies described above, it was verified that the two dimensional experimental model could be an appropriate and reasonable assumption of actual flame cutting as far as the phenomena occuring in the region near top edge were concerned.

3. Generation of Shock Wave and Its Characteristic Behaviour

3.1 Shock wave generation during combustion

There are two types of supersonic Oxygen jets which is used for cutting[11]. As described in **Fig. 6**, one is a

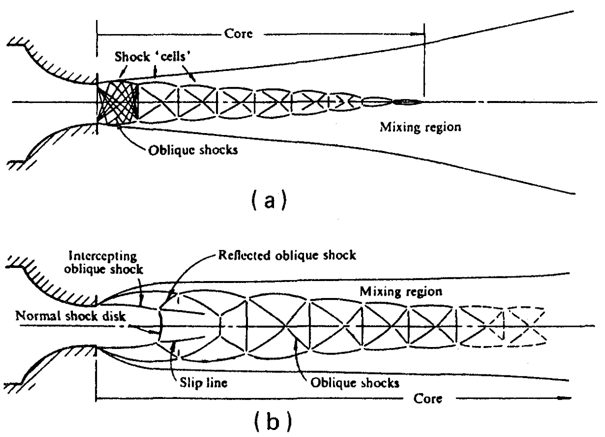


Fig. 6 Two types of Oxygen jet used for flame cutting[10]
(a) Moderately under-expanded jet,
(b) Highly under-expanded jet

moderately underexpanded jet and the other is a highly under-expanded one. The characteristic difference is whether a normal shock wave so called Mach disc is formed or not in the first cell, and the structure in downstream from the second cell is the same in either jet[10]. In this work a straight nozzle of 2.3 mm diameter was employed and Oxygen was jetted under the constant pressure of 0.55 MPa (5.5 kg/cm^2 ab.) inside the nozzle. **Figure 7** is a Schlieren photograph of the free jet under the above condition which obviously shows a highly under-expanded jet with a small Mach disc and slip lines in the first cell. Generally, the nozzle height z_h which is the distance between the nozzle exit and plate surface is selected so as it becomes 3 $\sim$ 4 times the nozzle diameter d_n in conventional flame cutting. Namely, in the case of present study, the torch height ranges from 7 to 10 mm, in which position the top edge of cutting kerf stays at the position of second cell of the jet. In this experiment, therefore, observations of the jet-wall interaction were done by feeding the top edge of iron strip into the second cell of oxygen jet. Here, in order to make an easy and

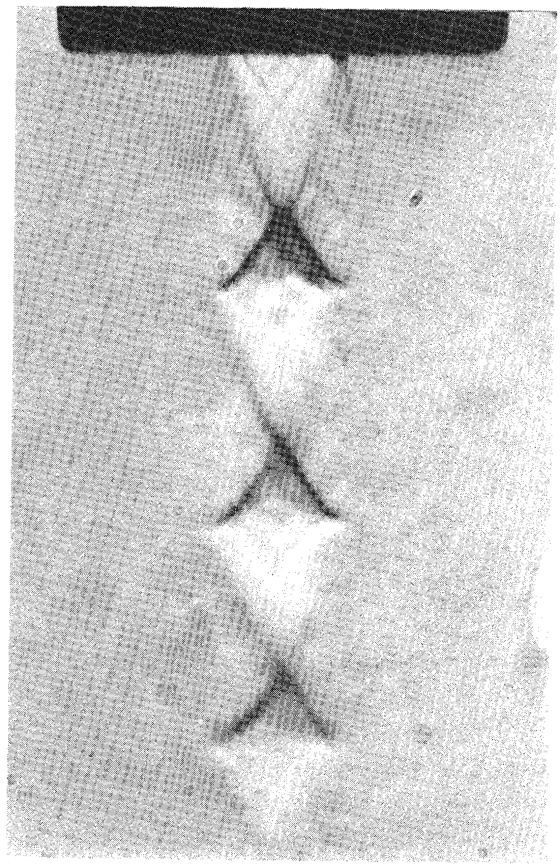
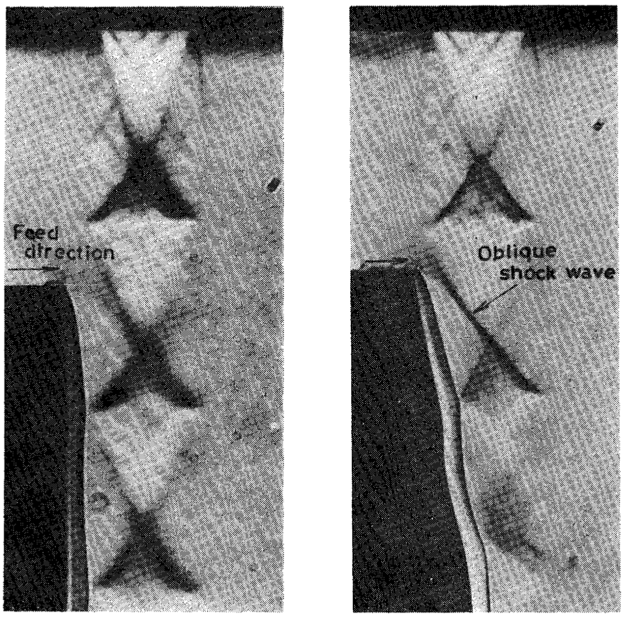


Fig. 7 Schlieren picture of Oxygen free jet used (p=0.55 MPa)

clear observation, the preheating flame was only used at the initiation of burning and self sustaining combustion was kept without preheating flame.

In **Fig. 8** are shown typical flow patterns along burning wall in different feeding rate (combustion rate) of iron strip. When the feeding rate is relatively small, the jet behaves just like a free jet attaching to the surface of burning surface as seen in Fig. 8(a). While in higher feeding rate, the top edge of combustion zone enters into the jet and a distinct oblique shock wave is formed a little far from the top corner of reacting wall as shown in Fig. 8(b). Beside this very characteristic phenomenon, the jet structure after the second cell is distorted by the inclined wall of burning surface. Thus, the flow pattern of jet during combustion at the strip end is divided into two types depending on the existence of oblique shock wave. Another interesting feature is noted if one sees the liquid surface profile during burning. Namely, the surface represents a wave or arch shape corresponding to the cell structure of jet, which comes from the fact that the side surface of each cell consists of a reflection plane of expansion and compression waves.

The generation of oblique shock wave is also affected by the nozzle height as shown in **Fig. 9** which represents the range of shock wave formation as the function of



(a) (b)

Fig. 8 Typical Schlieren photographs of self sustaining combustion of iron strip in different feeding rate
(a) Low feeding rate, (b) High feeding rate

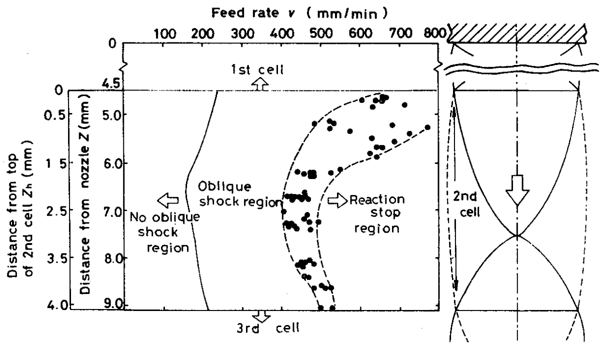
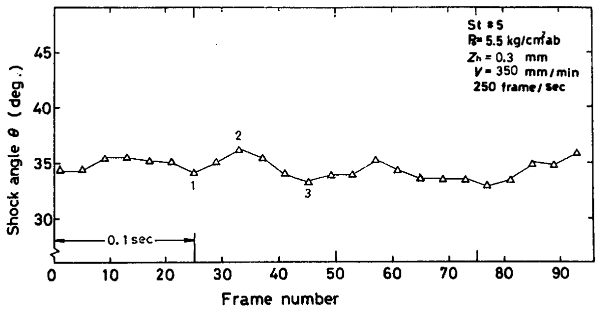


Fig. 9 Effect of burning rate (feeding rate) and jet impingiment position on shock wave formation and reaction limit

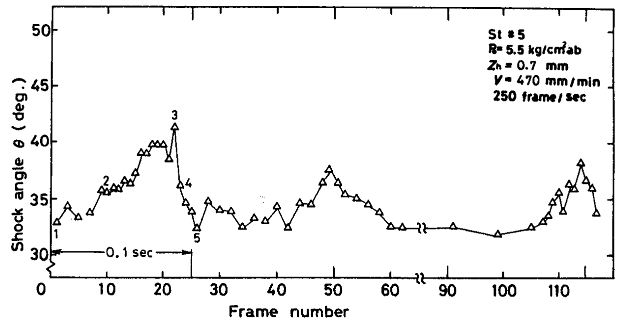
insert position of iron strip into the second cell and its feeding rate. When the feeding rate is very high, a phenomenon of sudden reaction interruption similar to the lose-cut phenomenon in conventional cutting takes place, but its initiation range is rather wide and erratic, and hence the range is indicated by its lower and upper limits by dashed curves in the figure.

3.2 Classification of shock wave behaviour

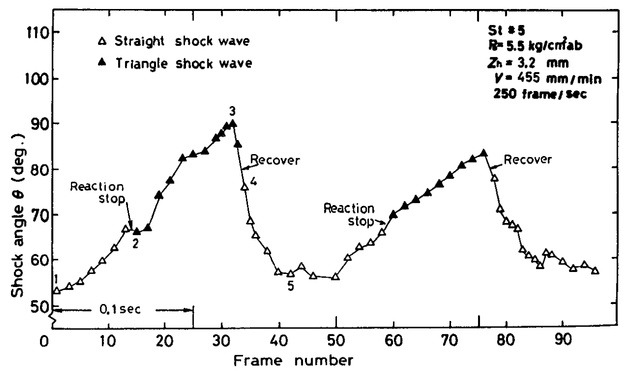
In the previous section was described the flow pattern of jet observed by a still Schlieren photography. In the range where an oblique shock wave was observed, it was found stationary when the feeding rate of iron strip was moderate. However, under the condition of high feeding rate where a reaction interruption was likely to occur, the abnormal sound was associated and the Shlieren picture showed different shape of shock waves depending on the time of exposure in spite of the same combustion situation. Presuming that this was caused by the temporal change of shock wave formation, high speed Schlieren pictures were taken using a 16 mm high speed camera at the filming rate of 250 frames per second. The result showed that two types of shock wave were identified during burning. Namely, one was the linear oblique shock wave (Type A) that was already described in the previous section and the another was a triangular shape shock wave (Type B). Furthermore, it was clarified after the film analyses that the temporal change of shock wave angle, i.e., the angle between the shock and center line of nozzle, was a good measure of characteristic change of shock wave angle, i.e., the angle between the shock and center line of nozzle, was a good measure of characteristic change of shock wave behaviour with time. **Figure 10**



(a)



(b)



(c)

Fig. 10 Three typical time dependent behaviours of shock wave shows the typical examples of temporal change of shock angle in different burning conditions, from which the behaviour of shock wave has been classified into two basic modes, i.e., Type I with almost no appreciable fluctuation and Type II with considerably large and periodic fluctuation of angle.

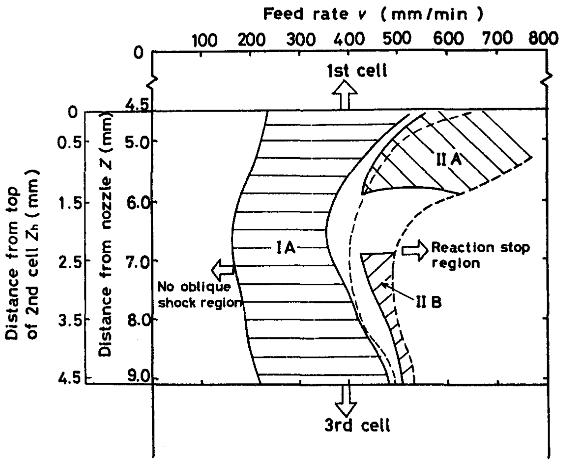


Fig. 11 Shock wave generation diagram of three different behaviours

Figure 11 represents the shock behaviour diagram based on the above classifications. As seen in the figure, the temporal and spacial behaviour of shock wave during burning could be basically divided into three types, i.e., Types IA, IIA and IIB, depending on the feeding rate and position in the second cell. Other blank area in the shock generation range is the transient region of above three types. Here, it is noted that Types IIA and IIB always appear in the same range where the combustion reaction is likely to interrupt suddenly as already described in Fig. 9. It is, therefore, presumed that the distinction of burning reaction is closely related to the shock wave behaviours. The precise feature of individual type is as follows.

(a) Shock wave behaviour of Type IA

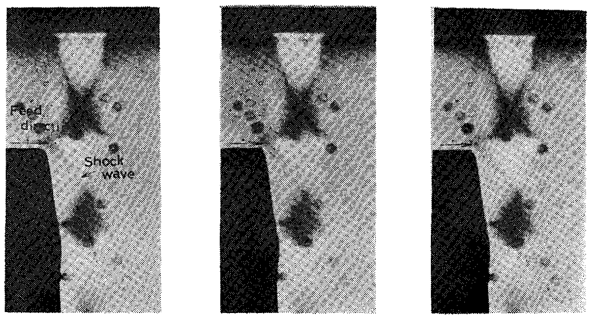
In **Fig. 12** is shown the high speed Schlieren pictures of Type IA, in which it is obvious that the temporal and spacial variations in shock angle as well as the burning front shape is minute and a stable oblique shock wave is formed.

(b) Shock wave behaviour of Type IIA

This type is featured by the fact that the oblique shock wave same as Type IA that is formed a little far from the top edge of reaction wall changes its angle greatly and in long periodic cycles as seen in **Fig. 13**. It is also characterized by the liquid surface of burning wall varying its shape in the same period corresponding to the spacial change of shock wave. This behaviour is specifically observed when the top edge of iron strip is located at the upper part of second cell of oxygen jet under the high feeding rate condition.

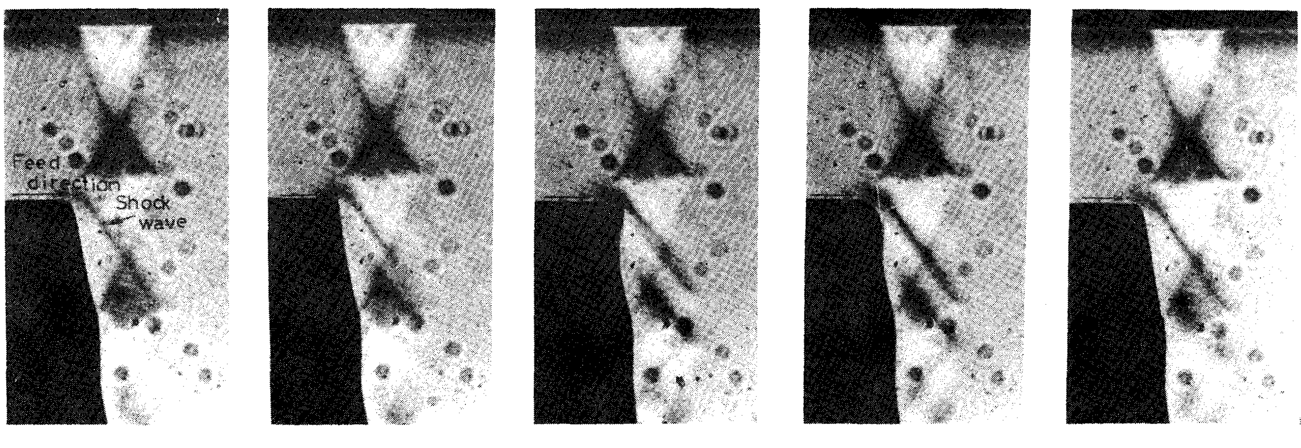
(c) Shock wavc behaviour of Type IIB

In this type, the spacial variation of shock wave becomes much greater than that of Type IIA and the shock shape exhibits a specific feature during a period of variation as illustrated in **Fig. 14**. Namely, a linear oblique



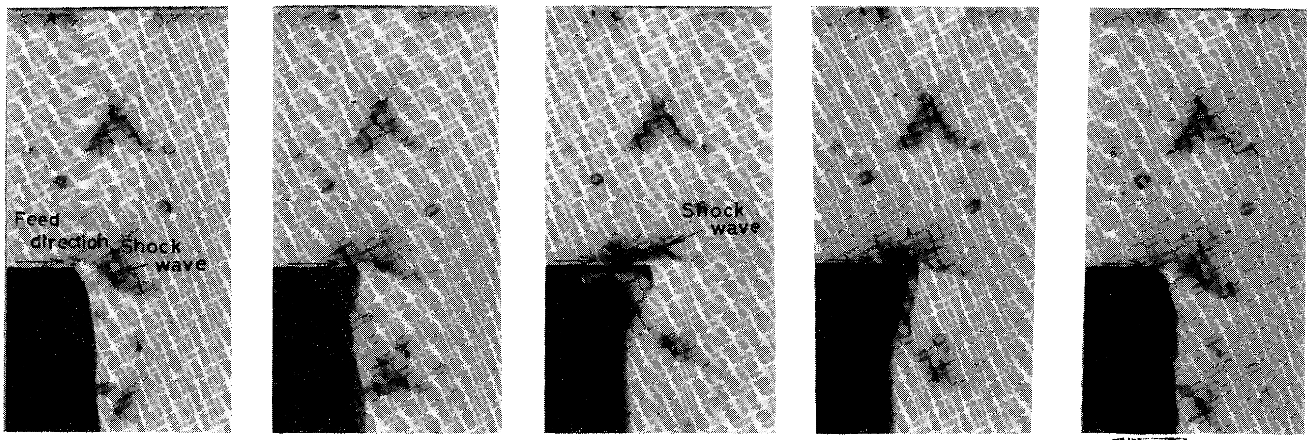
(1) (2) (3)

Fig. 12 Shock behaviour in Type IA (Moderate burning rate)



(1) (2) (3) (4) (5)

Fig. 13 Shock behaviour in Type IIA (High burning rate)



(1) (2) (3) (4) (5)

Fig. 14 Shock behaviour in Type IIB (High burning rate)

shock which originates from a certain distance from the top edge increases its angle gradually as the time elapses (state 1 in the figure), and turns into a triangular shape at the state 2. The angle of this triangle shock increases further reaching to about 90 degree at the state of 3. Then after the stage 3 the angle is reduced in the reverse and the triangle shape changes into the linear shape again at the stage 4. At the stage 5, the shock wave returns to its original state of 1. Corresponding to the above variation of shock front, the burning surface also varies its shape periodically in characteristic manner. Namely, the liquid surface of combustion in the stage 1 exhibits a similar manner as described in the previous Fig. 13, but at the stage 3 the reaction is suddenly interrupted only at the top corner of edge in spite of continuous burning still being kept in lower part. Since the iron strip is continuously fed, an overhung shape is thus formed as the time elapses up to the stage 3. In the stage 3 where a large overhung shape is formed, it is observed that the high temperature liquid at the lower burning part is pushed upward by a strong eddy formed in reverse direction to the main stream and reignition of interrupted part takes place again at the stage 4. As described above, the shock wave behaviour in Type IIB is closely related to the periodic phenomena of ignition and interruption of combustion reaction. The phenomenon is a specific one when the top edge of reaction wall is located at the lower part of second cell of jet.

3.3 Correlations between shock wave behaviour and burning surface shape

In this section will be described the precise temporal behaviour of shock wave and its corelation to the burning wall shape as well as its relative position to the oxygen jet which were measured from the high speed Schlieren pictures. The definition of measured parameters are graphically shown in **Fig. 15**. Here, a parameter defined as

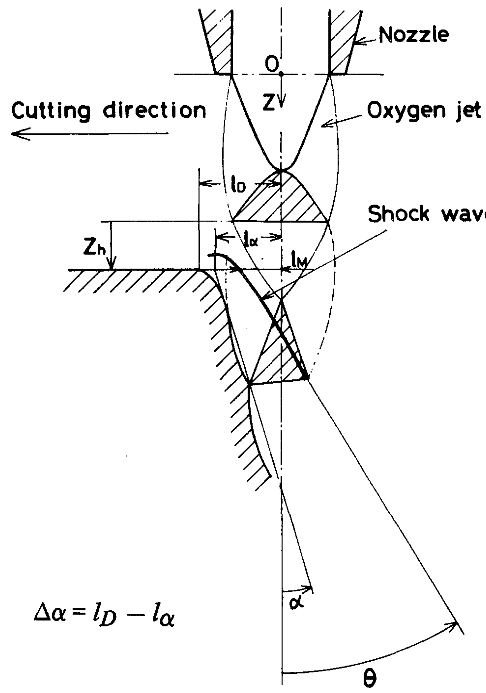


Fig. 15 Difinition of shock and front wall parameters measured

edge roundness is an apparent index showing the corner radius at the top edge of burning wall and shows that the smaller value represents the sharper corner.

Figures 16 to **18** show the corelations among parameters in three typical types of shock wave generation. Numerals in each figure correspond to sequence or numbers in Figs. 12 to 14. In case of Type IA shock wave formation (Fig. 16), temporal fluctuation of every parameter was little and thus the phenomena was almost stationary. However, it was found that small periodic fluctuation of each parameter was almost synchronized as a whole. And the shock angle and front angle of burning surface had a positive cross-correlation each other. Namely, the shock angle became large when the front angle increased, and vice versa. The same positive cross-correlation was

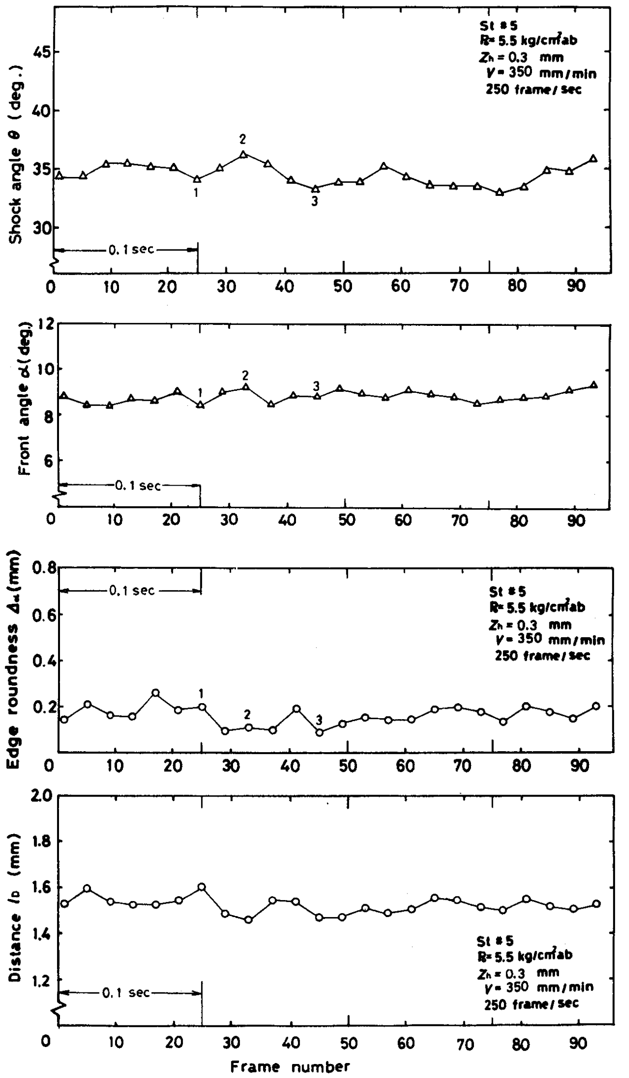


Fig. 16 Correlations among shock and front wall parameters in Type IA shock behaviour

observed between the roundness index of top corner edge and the relative distance between the jet and top edge of combustion front. There was, however, a negative cross-correlation between the two sets of parameters.

Figure 17 represents the correlations among four parameters in case of the Type IIA shock wave behaviour. Contrary to the case of Type IA, each parameter fluctuated greatly with time but there was a distinct negative correlation between the shock angle and other three parameters. Namely, when the relative distance between burning front and jet became smaller, which was equivalent to the deep invasion of front wall into jet, the front angle and corner roundness of burning wall became smaller simultaniously but the shock angle increased reversely. Numerals in the figure correspond to those of previous Fig. 13 and it is obvious that the parameters at the original stage 1 are similar in values to those of Type IA behaviour if one carefully sees the Fig. 16. However, as

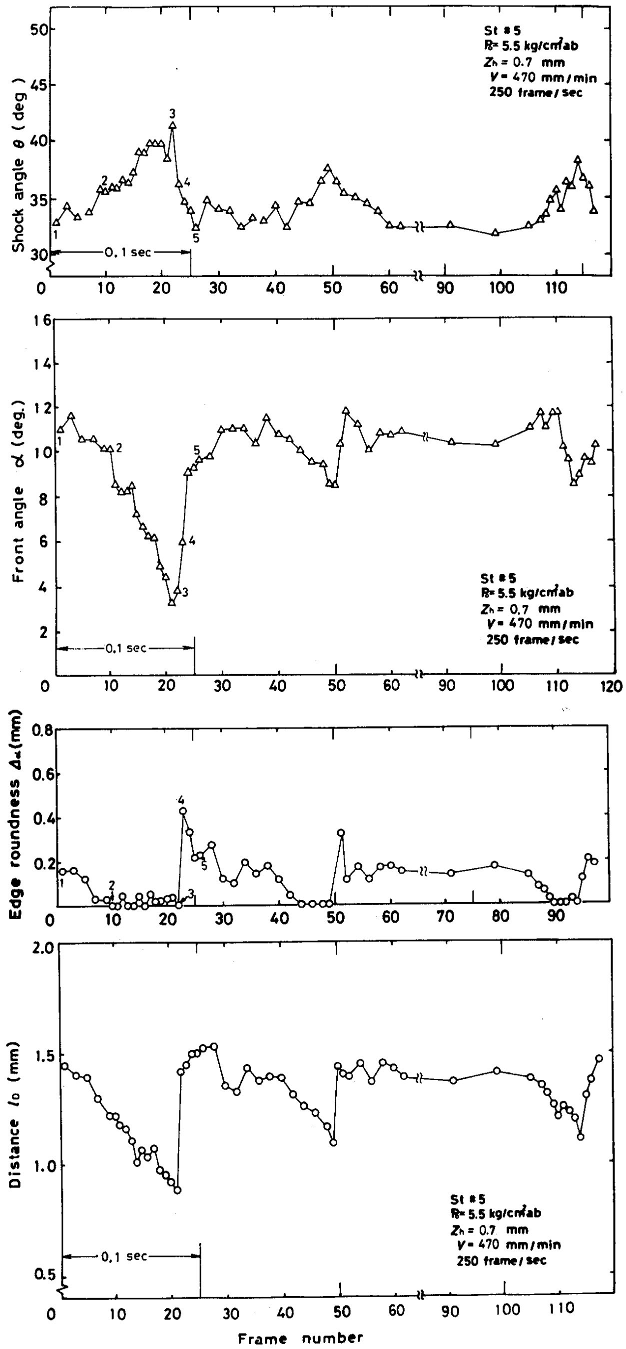


Fig. 17 Correlations among shock and front wall parameters in Type IIA shock behaviour

the time proceeds as stages 2 to 3, all parameters change their values considerably apart from those of Type IA and reach to the utmost state at the stage of 3. Then, they again return to the former values along the stages 3 to 5 and completely recover to original condition around the stage of 5. This recovering process takes place very rapidly compared with the previous process of deviating from the original situation. For example, the 0.5 mm change in distance l_d at the stages 3 and 4 takes place within 1/250 second, from which the transient rate of combustion is

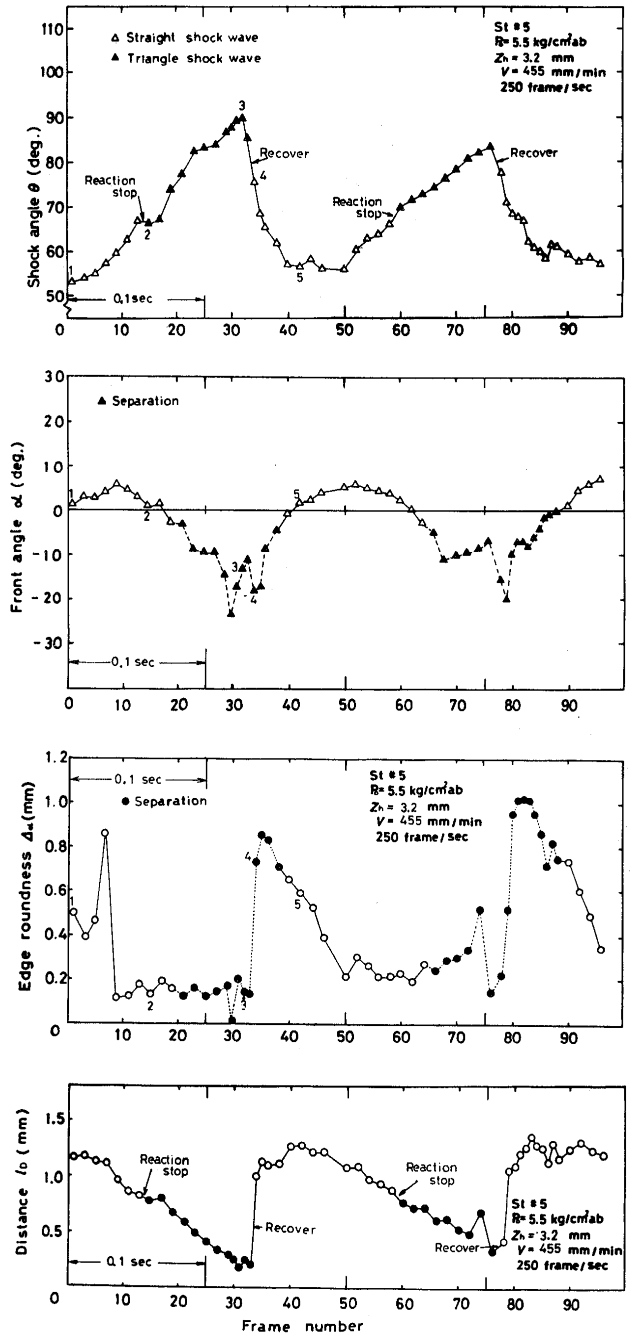


Fig. 18 Correlations among shock and front wall parameters in Type IIB shock behaviour

estimated to be about 75 m/min which is great deal higher, more than hundred times, than the apparent critical reaction stop speed shown in Fig. 9.

In Fig. 18 is shown the correlations among four parameters in case of Type IIB shock wave behaviour and their cross correlations are mostly the same with those of Type IIA mode but larger amplitude of fluctuations. Here, the front angle of burning wall adopts negative value for a duration of periodic cycle and this means the formation of overhung shape shown in Fig. 14. The most important feature of this type is that a triangular shape oblique shock wave is formed during the increasing stage of shock angle (stages 2 and 3 in the figure) and simultaneously the combustion reaction is interrupted only at the top corner edge. Soon after the shock angle comes to its maximum value or the distance is minimum at the stage of 3, reignition takes place and a linear oblique shock wave appears again. Another important phenomenon observed is that an overhung shape of burning front is brought just after the initiation of triangular shock wave and the separation of main jet from the burning surface takes place in the overhung region resulting in a strong reverse eddy flow. As explained in the previous Fig. 14, this eddy plays an important part on reignition of the reaction stop region. As descrived above, the interruption of chemical reaction and recovering process in a cycle is a distinct feature of this type which is different from the Type IIA behaviour.

4. Conclusion

Direct observations of the jet-wall interaction in flame cutting were made and the following phenomena were revealed. The precise mechanism of burning based on study will be described in the second part of this article.

1) Two dimensional experimental combustion model employed in this study was a reasonable assumption of actual oxygen gas cutting phenomena as far as the phenomena of upper part of kerf were concerned. The model enabled to conduct direct optical measurements and the flow pattern of oxygen jet as well as related burning phenomena were observed by Schlieren photography techniques with high resolution of time.
2) The most distinct and important feature of jet flow pattern was the generation of oblique shock waves in higher rate of burning. The shock wave behaviours were classified into three basic types depending on their shapes and temporal changes. Type IA shock wave which was initiated in moderate combustion rate was stable and stationary, while Types IIA and IIB which were observed in higher rate of burning accompanied periodic change in position with large amplitude. These shock wave behaviours were closely dependent on the burning wall phenomena and their cross-correlations were revealed.
3) The Types IIA and IIB shock waves were observed in the range where sudden interruption of combustion was likely to take place. Particularly in the Type IIB shock region, a specific phenomenon of repeating interruption of combustion and reignition was clearly found, and thus it was concluded that the sudden interruption of burning in high speed cutting was closely related with dynamic behaviour of shock wave.

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