On Cellular Pattern Formation in Detonation Propagation

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1 Introduction

In the study of detonation, smoked foil technique [1-3] is widely used to record variation of cellular patterns because of its simplicity and robustness in visualizing frontal structure of gaseous detonations. It is well known that size of the cellular patterns depends on the mixture type and its initial condition. Because of great success in the smoked foil technique no other visualization tools have been developed so that there is limitation in information obtained in the experiment. In terns of the mechanism of soot track formation several explanations have been proposed: (1) micro-vortices along a slip line behind the triple shock sweep loose soot particles off [4], (2) isochoric combustion and a spherical propagating blast wave having a circular flame are responsible for removal of soot [5], and (3) soot motion is due to variations in the direction and magnitude of the sheer stress generated by a flow in the boundary layer [6, 7]. However, the precise physical mechanism by which the soot tracks are created remains still unclear.

This paper aims to clarify the mechanism of cellular pattern formation on smoked foil records by applying other materials and to find alternative tools to visualize detonation characteristics.

2 Experimental apparatus

The detonation tube used in the present work is a stainless tube of 5350 mm in length and of 50.5 mm in inner diameter. A pair of stainless steel plates of 1500 mm in length were inserted into the detonation tube so that a narrow channel 40 mm wide and 3 mm high was formed in the test section. Propagation velocity of detonation in the test section was measured with the 15 combination probes [8] with which arrival of a shock and reaction front can be detected individually at one measurement point. Detailed description of the experimental set-up was given in Ref. 9

To clarify the mechanism of cellular pattern formation in detonation propagation several kinds of materials such as $CaCO_3$ particles, Al_2O_3 particles, fly ash were placed directly on the lower side of the plate. In addition, heat sensitive paper used for thermal facsimiles and pressure sensitive paper (Fuji film, "Prescale", LLWPS) were also tested for finding other methods of cellular pattern imprint. In all the experiment, at least one side of the plate forming the channel was coated with soot. As for the test gas, a stoichiometric hydrogen-oxygen-argon mixture was charged into the detonation tube under an initial pressure varying from 30 to 39 kPa.

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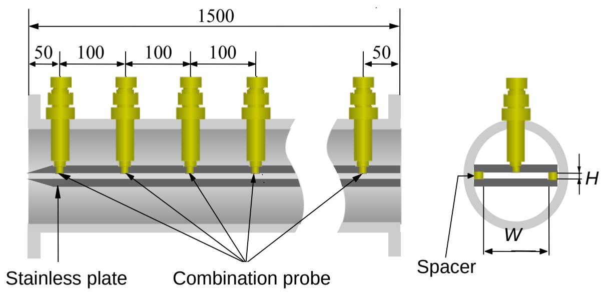
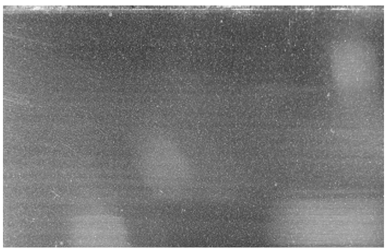


Figure 1. Schemtic of test section. W = 40 mm, H = 3 mm.

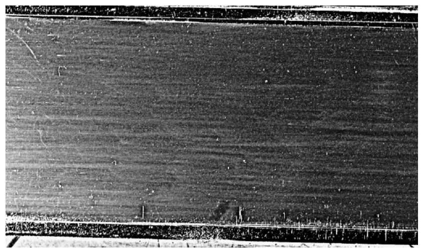
3 Experimental Results

Figure 2 shows the surface images of the plate on which various materials placed. Except for Al_2O_3, the cellular pattern could be observed in the most cases. Between $CaCO_3$ and fly ash, the former gave more distinct cellular pattern, although their particle diameters are in the same order of magnitude (a few micrometers). It was found that fly ash is easily blown away in passage of detonation wave because of its less adsorption force. As for Al_2O_3, three types of particle diameter of 1 μm, 10 ~ 20 μm, 50 ~ 75 μm were tested resulting in failure of visualizing cellular pattern. In Fig. 2 (d) the outline of the cell was shown as black lines on the heat sensitive paper, which indicates that trajectory of the region where the highest heat flux is provided forms the cellular pattern. However, the whole paper surface tends to be discolored as dilution rate of Ar decreases. In the case of the pressure sensitive paper, white regions form outlines of the cell, as shown in Fig. 2 (e). This paper contains micro-encapsulated color forming and developing material in the paper sheet. When it is pressurized, a red color impression appears and it is possible to measure pressure from intensity of red coloring when static load is applied. It must be noted that the image of Fig 2 (e) has been edited to emphasize the pattern by graphics software. The original image shows less distinct features and the whole paper tends to become red with decrease in dilution rate of Ar and increase in the initial pressure.

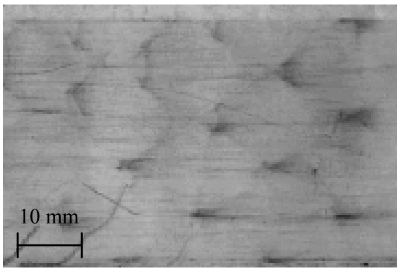
(a) $CaCO_3$



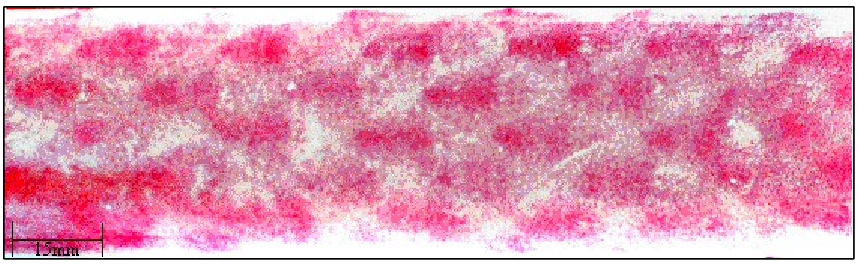
(b) Al_2O_3



(c) Fly ash



(d) Heat sensitive paper



(e) Pressure sensitive paper

Figure 2. Image of cellular pattern after detonation propagation. No cellular pattern can be obtained for Al_2O_3.

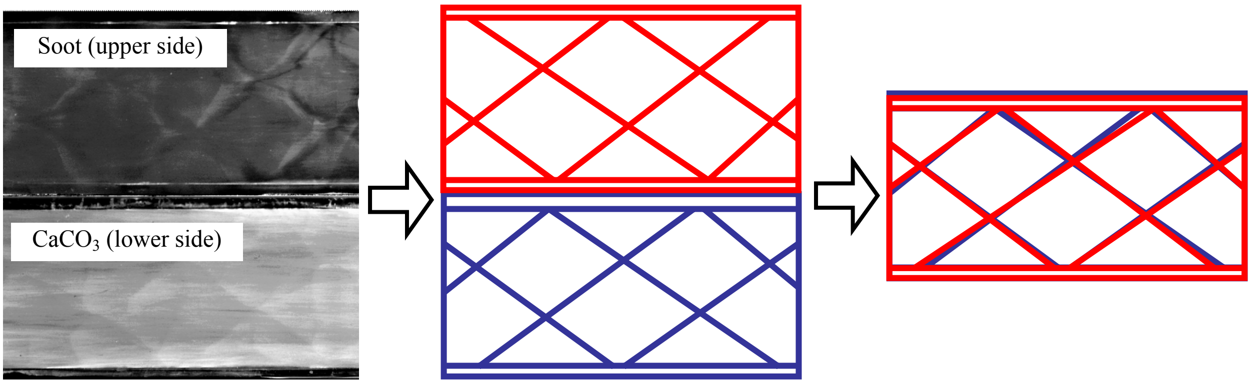


Figure 3. Cellular patterns showing symmetry on the upper and lower side of the plate.

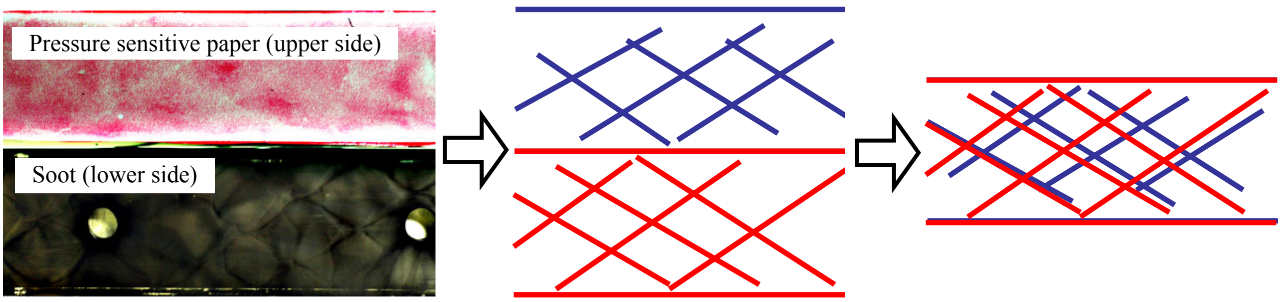


Figure 4. Asymmetrical cellular patterns for soot coating and pressure sensitive paper.

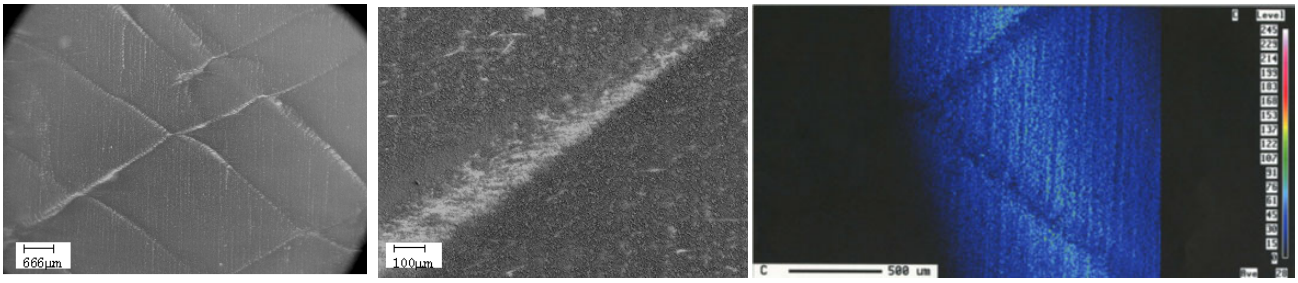
From the previous experiment it was found that the symmetrical cellular pattern is obtained on the upper and lower side of the smoked plate for detonation propagation in a narrow channel [10]. As mentioned before, at least one side of the plate is coated with soot so that the symmetry of the celluar pattern can be checked, as shown in Fig. 3. $CaCO_3$ particles, fly ash, and the heat sensitive paper demonstrated the good symmetry pattern, whereas the sensitive paper gave the asymmetrical pattern together with the smoked foil recode as shown in Fig. 4. This asymmetry is discussed in the next section. The experimental results were summarized in Table 1.

Table 1: Availability of cellular pattern and symmetry to that on the smokd foil for various materials placed on the plate. Open circle denotes that cellular pattern can be obtained in most cases. Open triangle means that quality of the pattern is strongly dependent on the initial mixture condition.

Material	$CaCO_3$	Al_2O_3	Fly ash	Heat sensitive paper	Pressure sensitive paper
Cellular pattern	○	NA	△	○	△
Symmetry to smoked foil	○	NA	○	○	NA

4 Discussion

Since the symmetrical cellular pattern appears in the case of $CaCO_3$ particles, which is essentially incombustible, it is deduced that removal of soot is achieved by hydrodynamic effects, not by combustion. To observe detailed conditions of the smoked foil surface, it was analyzed by SEM (Scanning Electron Microscope) and EPMA (Electron Probe Micro Analyzer). Figure 5 shows typical results of magnified images around the soot track by SEM and EPMA. These images apparently indicate less deposit of soot at the outlines of the cellular pattern and suggest that removal of soot is likely to be caused by a very local event such like micro-vortices, as proposed in Ref. 4.



(a)SEM 15X (b) SEM 100X (c) EPMA

Figure 5. Magnified image of smoked foil by SEM (Scanning Electron Microscope) and EPMA (Electron Probe Micro Analyzer).

The asymmetry on the cellular pattern for the pressure sensitive paper is related to its characteristics. As for temporal response of the pressure sensitive paper, it can response to impact loading whose duration is several hundred microseconds, although its sensitivity is significantly reduced for varying temporal loading as compared to static loading [11]. Consequently, it can be assumed that intensity of color impression is dependent on impulse rather than the value of peak pressure when a blast wave is applied to the pressure sensitive paper. Figure 6 shows pressure histories at two different positions in a detonation cell. The position 1 corresponds to an apex of the cell and a higher peak pressure is observed than at the position 2 located inside the cell. However, the impulse per unit area I, defined by the following equation, gives 57 and 66 Pa·s for the position 1and 2, respectively

$$I = \int_0^\tau p(t)dt \,,$$

where integration period τ is set as 300 µs. This calculation implies that impulse inside the cell is

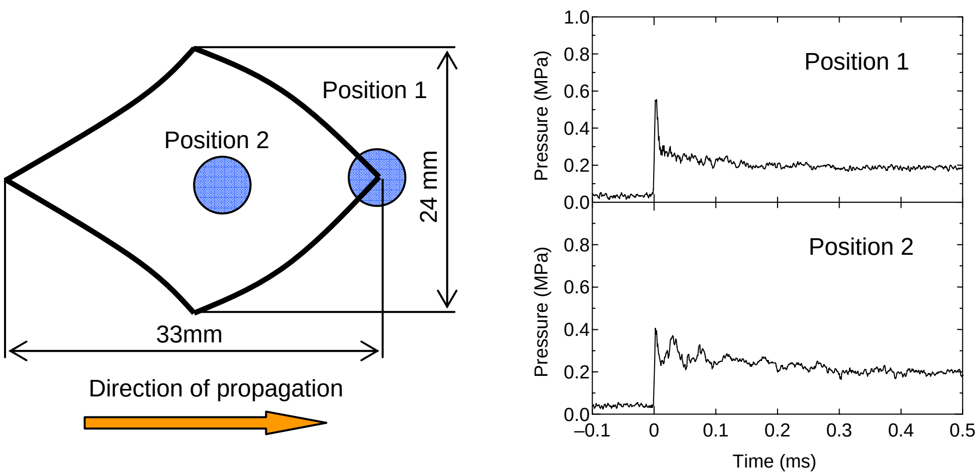


Figure 6. Pressure histories for different positions in cellular pattern. Solid circles in the left figure denote size and relative position of pressure transducer. $2H_2 + O_2 + 7Ar$, $p_0 = 32$ kPa.

larger than that at the outline of the cell and explains well the asymmetry of the cellular pattern shown in Fig. 4. Since structural damage is generally dependent of impulse per unit area, not the peak pressure, the pressure sensitive paper can be a candidate for estimation of damage given by detonation.

5 Summary

It is possible to obtain cellular patterns in detonation propagation using $CaCO_3$ particles, fly ash, heat sensitive paper, and pressure sensitive paper instead of smoked foil. The symmetrical cellular pattern with the smoked foil is demonstrated for $CaCO_3$ particles, fly ash, and the heat sensitive paper. The asymmetry of the cellular pattern for the pressure sensitive paper is explained from its temporal response to varying temporal loading. The magnified images around the soot track by SEM and EPMA indicate local removal of soot deposit along the outline of the cell.

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