On the Mechanism of Soot Track Formation: Experimental Study

Amy K.W. LAM†, Joanna AUSTIN†, Florian PINTGEN†, Eric WINTENBERGER†, Joseph E. SHEPHERD‡
Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA 91125, USA
†Graduate Student, ‡Professor: email jeshep@galcit.caltech.edu

Kazuaki INABA*, Akiko MATSUO**
Department of Mechanical Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, JAPAN
*Graduate Student, **Assistant Professor

Key Words: Mach reflection, Soot track, Detonation, Cellular structure, Shock tube

1. Introduction

The soot foil technique has been an important research tool in the study of detonations for many years [1]. It has been used extensively to measure the characteristic cell width of detonation waves and also to quantify the regularity of the structure. Urtiew and Oppenheim [2] used schlieren visualization through a sooted window to show that these cellular tracks are associated with the triple points in the detonation front. Shock wave triple points in unreactive gases have also been observed to produce tracks on sooted surfaces by Mach [3]. However, the physical mechanism by which the tracks are created, either in detonations or in unreactive flows, is unknown.

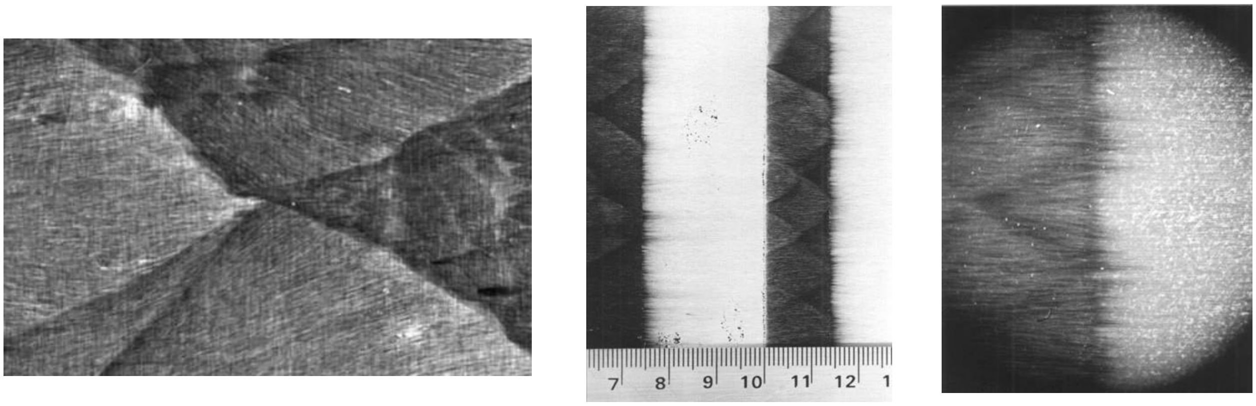
This work is an experimental study of the mechanism of soot track formation, combining results from three Mach reflection sources: detonation waves, shock propagation over a wedge in a shock tube, and shock propagation over a wedge in an open blast wave facility. The reactive flow (detonation) experiments show definitely that the soot is being transported along the surface of the foil, up to 10 mm in some cases. The unreactive flow experiments eliminate the role of combustion in soot track formation. We propose that the shear stress has a critical role in the local removal and accumulation of the soot. A companion paper [4] discusses this problem with a numerical approach.

2. Experiments

For soot foils, flat sheets of 3003 alloy aluminum, 241 mm by 114 mm by 1.0 mm thick were covered with soot by suspending them from the top of a make-shift chimney which was covered with a lid while at the bottom of the chimney a 40 mm by 60 mm piece of cotton rag soaked in waste fuel is burned. After a few minutes, the foil is covered with soot. For Mach 1.9 shots, some low viscosity fluid (Dow Corning 200 fluid - viscosity 20 cs) is rubbed onto the exposed side of the foil (one drop per 50 mm vertical strip) prior to adding the soot. The added viscosity fluid helps the soot to adhere to the surface and prevents all the soot from being wiped off the foil completely. After the soot track has been formed, the soot foil is fixed with a spray-on acrylic gloss.

2.1 Detonation Cells

A 280 mm diameter, 7.3 m long detonation tube [5] was used in this study. The foils were prepared with strips of soot removed in order to study the transport of the soot, Fig. 1. From this work we are able to conclude that the soot is being transported downstream along the surface by the forces induced on the soot. The portion of the cell behind the Mach stem appears darkest, and the amount of soot observed on the foil gradually decreases towards the end of the cell. It appears that the soot is being accumulated at the track due to the difference in direction of the shear stress behind the incident wave and the Mach stem. Recent preliminary experimental results have indicated



(a) (b) (c)

Fig. 1: Detonation tube experiment results. a) Detonation cells, image height 30mm, 4.5% N_2 diluted stoichiometric CH_4-O_2, 0.1 bar initial pressure, b) Soot foil prepared with strips of soot removed, units in cm, 40% N_2 diluted stoichiometric H_2-O_2, 0.2 bar initial pressure, c) Striped soot foil under microscope, 0.3 bar initial pressure. Flow is from left to right.

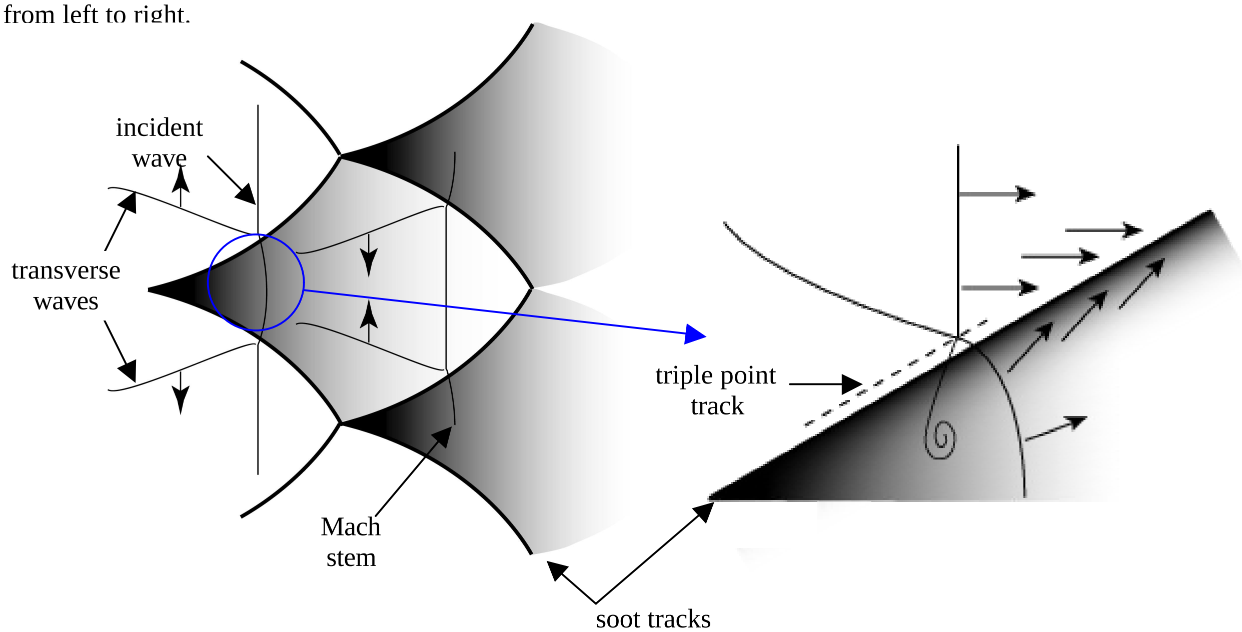


Fig. 2a: Detonation cells

Fig. 2b: Schematic of soot build-up

that the soot track and triple point track are not coincident [6]. A schematic illustrating these observations is shown in Fig. 2b.

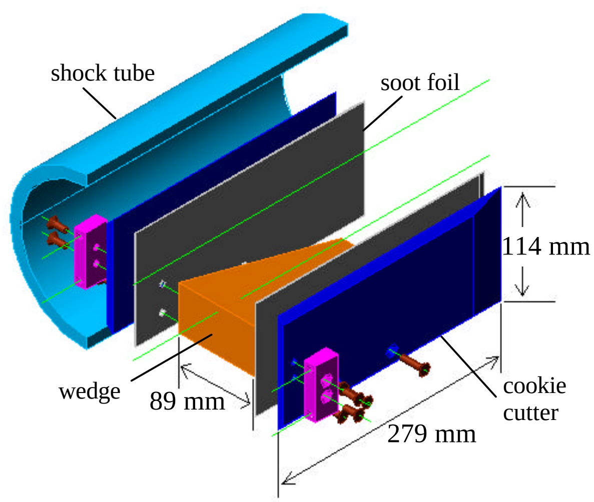


Fig. 3: Schematic diagram of the test section.

2.2. Shock Wave Propagation over a Wedge

A 152 mm diameter, 17.5 m long shock tube was used. The soot foils are held at the end of the shock tube by parallel plates with sharp leading edges. The top and bottom edges of these plates have 45º chamfers to conform to the circular cross section of the shock tube. The plates are attached to a wedge such that the soot foils are directly in contact with either side of the wedge. Wedges of different angles (15º – 45º) can be accommodated. In the present study wedges, 89 mm wide and 51 mm high, with an wedge angle of 15º and 25º were used.

The blast wave facility consists of an initiator (13mm diameter tube) reaching into the center of a 1.5 l balloon, both filled with premixed propane-oxygen. The setup is placed in the center of a 27 m^3 room at normal conditions and the soot foil - wedge assembly is located 600 mm from the center of the balloon, so that the spherical blast wave created is assumed to be unconfined. The Mach number of the shock is determined to be approximately 1.2 from the pressure history obtained by a pencil gauge. Six configurations of Mach number and wedge angle have been studied (Table 1).

Table 1: Test matrix

Case	Facility	Mach number	Wedge angle	Shot number
1	Shock tube	1.9	15 deg	Shot 2002-101
2	Shock tube	1.2	15 deg	Shot 2002-119
3	Shock tube	1.9	25 deg	Shot 2002-121
4	Shock tube	1.2	25 deg	Shot 2002-120
5	Blast wave	1.2	15 deg	Shot 90
6	Blast wave	1.2	25 deg	Shot 92

3. Results and Discussion

Soot tracks appear as a dividing line between lighter and darker regions on the soot foil. In cases 1 and 3, two tracks, T_1 and T_2, emerging from the wedge tip are observed, creating regions I, II and III of different brightness between each other and the edge surface, Fig. 4. Soot track T_1 appears as a straight line. Soot track T_2 is located between track T_1 and the wedge, and reveals in contrast to track T_1 discontinuities and is corrugated. Region II is observed to be darker than regions I and region III lighter than region I. The measured track angles are shown in Table 2 along with their corresponding theoretical and numerically calculated angles.

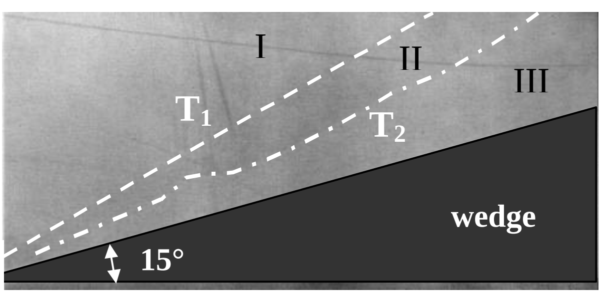


Fig. 4: Soot track for case 1, image height 80 mm.

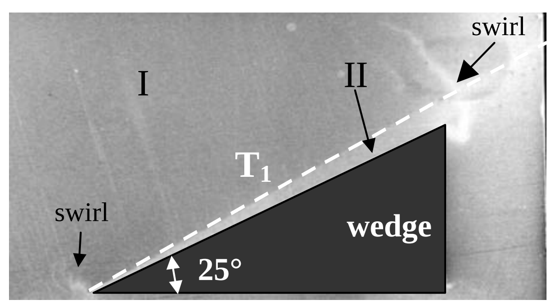


Fig. 5: Soot track for case 5 , image height 80 mm.

In cases 5 and 6 only a single soot track, T_1, was be observed, Fig. 5. Region II appeared in this case brighter than region I. Similarly, in cases 2 and 4, only a single soot track can be seen, showing the same brightness level in regions I and II as in cases 5 and 6. For a larger wedge angle the contrast was observed to be stronger. In the blast wave facility (i.e. cases 5 and 6), the soot tracks appeared most strikingly, since the contrast between region I and II was observed to be strongest. We believe this is due to the absence of a strong reflected shock wave in the unconfined blast wave facility in contrast to the shock tube.

Experiments conducted with a Mach number of 1.2 (cases 2, 4, 5, 6) exhibited swirls on the soot prints near the wedge vertices, Fig. 5. It is possible that the swirls do not appear in experiments with a Mach number of 1.9 due to the low viscosity fluid used in preparing the soot foils.

Table 2: Summary of triple point track angles.

Case	Mach number	Wedge angle	Experiment	Three-shock theory	Simulation
A	1.9	15 deg	F: 16 deg, S: 8 deg	17 deg	16 deg
B	1.2	15 deg	8-9 deg	-	11 deg
C	1.9	25 deg	F: 9 deg, S: 4 deg	11 deg	11 deg
D	1.2	25 deg	4-5 deg	-	6 deg

(F: First track angle, S: Second track angle).

Conclusions

Experiment investigating the soot track creation by Mach reflections in reacting and non-reacting flows have been conducted. Preliminary results indicate, that the soot redistribution can be attributed to variations in the surface shear stress. Further investigation of the boundary layer behavior, experimental measurements, and numerical computations of the shear stress are needed to clarify the mechanism of soot track formation.

Acknowledgments

K. Inaba was supported by the Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists. The authors acknowledge several discussions with Prof. H. Hornung.

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