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SHOCK WAVES IN CONVERGING GEOMETRIES

J.L. Brown, G. Ravichandran

Division of Engineering and Applied Science, California Institute of Technology, Pasadena CA 91125

Abstract. Plate impact experiments are a powerful tool in equation of state (EOS) development, but are inherently limited by the range of impact velocities accessible to the gun. In an effort to dramatically increase the range of pressures which can be studied with available impact velocities, a new experimental technique is being developed. The possibility of using a confined converging target to focus shockwaves and produce a large amplitude pressure pulse is examined. When the planar shock resulting from impact enters the converging target the impedance mismatch at the boundary of the confinement produces reflected Mach waves and the subsequent wave interactions produce a diffraction cycle resulting in increases in the shock strength with each cycle. Since this configuration is limited to relatively low impedance targets, a second technique is proposed in which the target is two concentric cylinders designed such that the inner cylinder will have a lower shock velocity than the much larger shock velocity in the outer cylinder. The resulting dispersion in the wave front creates converging shocks, which will interact and eventually result in a steady Mach configuration with an increase in pressure in the Mach disk. Numerical simulations indicate a significant increase in pressure for both methods and show promise for the proposed concepts.

Keywords: Converging shocks, Mach reflection, EOS.
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INTRODUCTION

There has been a great deal of effort in researching ways to increase the velocity of an impactor in plate impact experiments including explosive lenses and liners, advances in smooth bore guns and magnetic loading techniques [1]. Rather than focusing on a way to increase the projectile velocity, here we examine two techniques to produce converging shock waves in the target in an attempt to obtain a useful high pressure region from which equation of state (EOS) data can be obtained. Numerical simulations are used for validation and experimental design, as future work will be conducted in validation using a powder gun facility. The powder gun has a 37 mm bore and can attain velocities of 400 to 2000 m/s, so the simulations will fall within these design parameters.

SHOCKS IN A CONVERGING TARGET

The first proposed technique is to impact a converging conical target geometry confined by a material of much higher impedance. This study will be limited to pressures much higher than the dynamic flow strength so the response is primarily

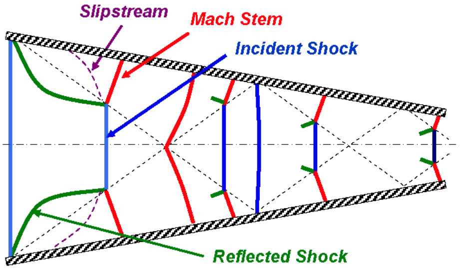

Figure 1. Diffraction of the incident shock wave in a converging target with rigid boundary conditions.

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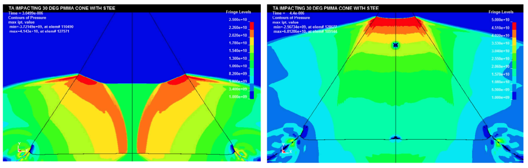
hydrodynamic, and a qualitative description of the wave interactions can be found from that expected in a fluid. In a typical fluid, a plane incident shock impinging on a wedge of modest angle will result in a Mach reflection [2]. As shown in Figure 1, the resulting Mach stems will eventually converge and another Mach reflection forms on the cone axis. This Mach disk will expand and interact with the target boundary, at which point a second diffraction cycle will begin. Each diffraction cycle will result in a subsequent increase in the shock strength [3].

Converging Target Numerical Simulations

Numerical simulations were performed using the commercial finite element code LS-DYNA to investigate the converging geometry technique. All of the simulations utilized axi-symmetric elements, an elastic-perfectly plastic strength model, and the Mie-Gruneisen EOS. Figure 2 shows the progression of the incident shock through its first diffraction cycle for a typical simulation.



a) t = 3.0 µs **b)** t = 4.4 µs

Figure 2. Pressure contours in a 30° PMMA cone with steel confinement and a tantalum projectile impacting from the bottom at 2 km/s. a) Mach reflections off of the cone interface prior to Mach stem convergence. b) High pressure state at the end of the target allows access to the principal Hugoniot.

Quantitative results for simulations consisting of tantalum impacting PMMA cones of 10, 20, or 30 degrees confined by steel at velocities of 1 or 2 km/s are shown in Figure 3. Pressure and particle velocities for elements along the center of the target are plotted along with the gain in pressure and equivalent plate impact velocity. The gain in pressure is the maximum achieved Hugoniot state relative to the incident shock pressure, while the equivalent plate impact velocity is the necessary impactor velocity to achieve this same maximum Hugoniot state in the conventional plate impact experiment.

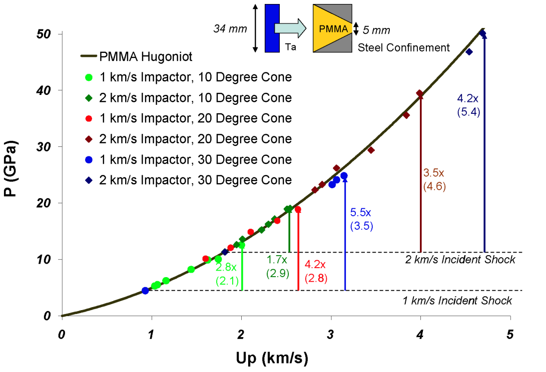


Figure 3. Hugoniot points obtained along the center of the converging target along with the gain in pressure. Velocities in the parenthesis are the equivalent plate impact velocities.

MACH LENS CONFIGURATION

The Mach lens configuration is an extension of a method used with explosives to generate extreme pressures [4]. Relating the same concepts to an inert plate impact configuration [5], the target consists simply of two concentric cylinders as shown in Figure 4. The target is designed such that the inner cylinder will have a lower shock velocity than that in the outer cylinder. This impedance mismatch generates a conically converging shock and a subsequent Mach reflection at the center of the inner cylinder upon convergence. The resulting Mach disk grows until a quasi steady state is reached, at which point the Mach configuration will propagate through the rest of the target.

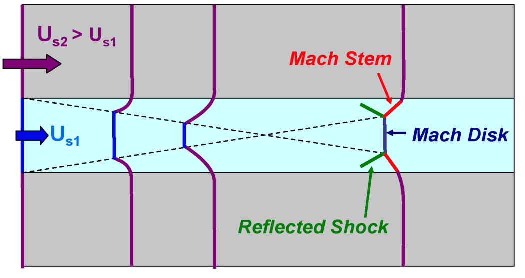


Figure 4. Mach lens target configuration. An initially plane shock is generated at impact on the left of the lens.

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Mach Lens Numerical Simulations

In an attempt to validate the Mach lens numerically, two configurations were examined. The first was a PMMA inner cylinder confined by aluminum. Impact conditions were varied by using aluminum and tantalum impactors at 1 and 2 km/s. The inner cylinder diameter is 4 mm, while the outer cylinder has a 34 mm diameter. The resulting evolution of the Mach wave and Hugoniot points are plotted in Figure 5. The pressure-time profile behind the Mach disk is qualitatively similar in nature to the shock produced by an explosive detonation or pulsed laser, so the simulated Mach state is the peak pressure and particle of an element within the Mach disk. The ideal Mach state is what would be expected if the wave speed in the inner cylinder is equal to that in the outer cylinder.

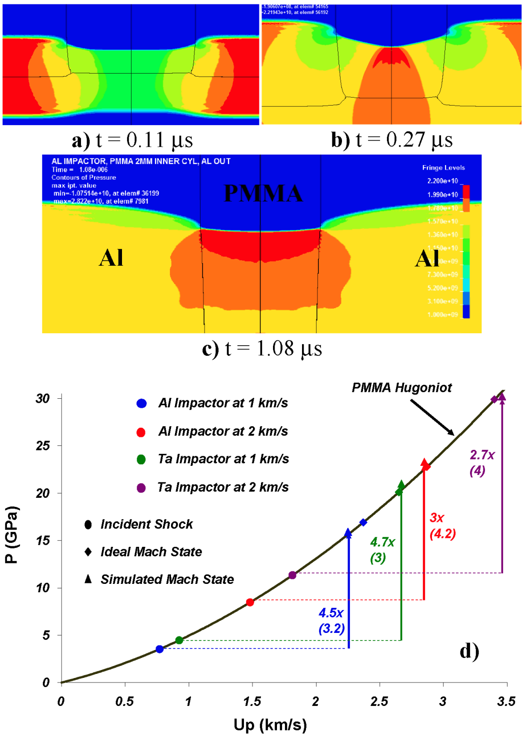

Figure 5. Results of aluminum (Al) and PMMA Mach lens simulations. Pressure contours in a typical simulation showing a) Reflected waves at interface, b) Mach reflection after reflected wave convergence, and c) the steady Mach configuration. d) Hugoniot points of the incident, ideal, and simulated shocked states.

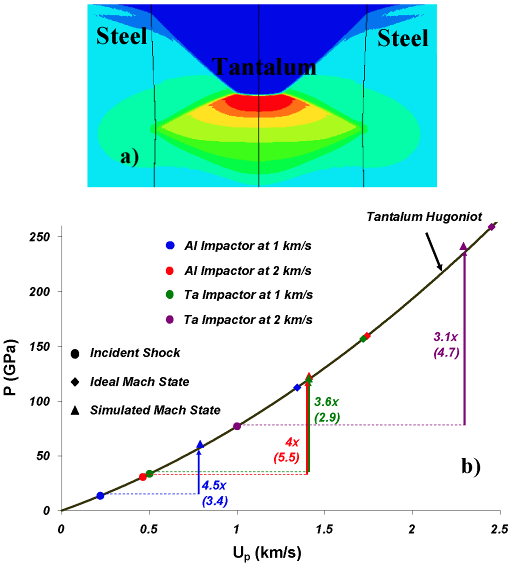

Figure 6. Results of 304 stainless steel and tantalum Mach lens simulations. a) Pressure contours showing the steady Mach configuration in a typical simulation (propagating up). b) Hugoniot points of the incident shock, ideal Mach state, and simulated Mach state for each simulation.

RESULTS AND DISCUSSION

The results from Figures 3, 5 and 6 are summarized in TABLE 1. Both techniques produce significant increases in pressure, but the Mach lens configuration is particularly attractive for further study. Not only does the Mach lens produce similar gains, but it also has several advantages over the converging geometry. First, is the obvious ability to study high impedance materials such as tantalum. Second, the Mach lens produces a steady state wave configuration which makes any experimental measurement much easier. Third, inside the Mach disk, a condition of uniaxial strain exists which makes the experiments much more in line with the classic 1D hydrodynamic treatment of shock waves. Finally, there is the added feature of the ease of fabrication and assembly. These significant advantages will limit further discussion to the Mach lens configuration.

As shown in Figures 5 and 6, the resulting steady Mach configuration depends greatly on the materials chosen, and the PMMA configuration seems to be an ideal candidate for experimental

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TABLE 1. Results from numerical simulations using converging geometry and Mach lens configurations.

Impactor Material	Impact Velocity (km/s)	Target Configuration	Pressure Increase	Equivalent Plate Impact Velocity (km/s)
Ta	1	10° / 20° / 30° PMMA cone	2.8 / 4.2 / 5.5	2.1 / 2.8 / 3.5
Ta	2	10° / 20° / 30° PMMA cone	1.7 / 3.5 / 4.2	2.9 / 4.6 / 5.4
Al	1 / 2	PMMA Mach Lens	4.5 / 3	3.2 / 4.2
Ta	1 / 2	PMMA Mach Lens	4.7 / 2.7	3 / 4
Al	1 / 2	Ta Mach Lens	4.5 / 4	3.4 / 5.5
Ta	1 / 2	Ta Mach Lens	3.6 / 3.1	2.9 / 4.7

validation of this technique. The simulations suggest there is a negligible Mach stem in this configuration for impact velocities above 1 km/s. Since the Mach stem serves as a continuity condition between the two wave speeds, there is a negligible velocity gradient, and the velocity of the Mach disk in this case should be the same as the shock velocity in the outer aluminum cylinder. If this proves to be true in the experiments, configurations such as these become very valuable as the wave speed is essentially obtained for free from the impact velocity as long as the impactor and outer cylinder materials are well characterized.

CONCLUSIONS

Results from numerical simulations on two experimental techniques have been examined. While both the converging geometry and Mach lens techniques show promise, the Mach lens has many significant advantages. The lens consists simply of two concentric cylinders and forces the convergence of reflected shocks from the material mismatch. When the reflected shocks converge, the result is the subsequent growth of a transient Mach reflection. After a length of roughly the diameter of the inner cylinder, the Mach reflection becomes steady and propagates unchanging through the rest of the target. Gains in pressure of up to 4.7 times, and equivalent plate impact velocities to 5.5 km/s from a 2 km/s gun are simulated using this configuration.

FUTURE WORK

The simulations suggest the PMMA lens setup is ideal for experimental validation. PMMA is a well characterized transparent material and can be constructed with an in-situ reflecting surface. Velocity interferometry and stress gauges can then be used to obtain a measurement of the material state behind the Mach disk. These experimental results are expected to give further insight into the nature of Mach reflections in solids. It will be interesting to see if a principal Hugoniot state is achieved, as is suggested by the simulations. If the technique can be validated using PMMA, experiments will then be conducted on tantalum to further study the Mach reflection phenomena.

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REFERENCES

1. L. C. Chhabildas and M. D. Knudsen, "Techniques to Launch Projectile Plates to Very High Velocities," in *High-Pressure Shock Compression of Solids VIII*, L. C. Chhabildas, L. Davison, and Y. Horie, Eds.: Springer-Verlag, Berlin, 2005.
2. G. Ben-Dor, "Shock Wave Reflection Phenomena," Springer-Verlag, New York, 1992.
3. R. E. Setchell, E. Storm, and B. Sturtevant, "An investigation of shock strengthening in a conical convergent channel," *J. Fluid Mech.*, vol. 56, pp. 505-522, 1972.
4. G. R. Fowles and W. M. Isbell, "Method for Hugoniot Equation-of-State Measurements at Extreme Pressures," *J. Appl. Phys.*, vol. 36, pp. 1377-1379, 1964.
5. Y. Syono, T. Goto, and T. Sato, "Pressure enhancement by conically convergent shocks in composite cylinders and its application to shock recovery experiments," *J. Appl. Phys.*, vol. 53, pp. 7131-7135, 1982.

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