Combustion of Bulk Metals in Supersonic Flow

Ramzi El-Saadi, Vincent Tanguay, Andrew J. Higgins
McGill University, Montreal, Québec, H3A 2K6, CANADA
Corresponding author, A.J. Higgins, andrew.higgins@mcgill.ca

Introduction

While the combustion of metal in powdered form has been extensively studied for propellant and pyrotechnic applications, the ability of bulk metals to burn in high-speed flows has received relatively little attention. Typically, a burning metal particle in a propellant is treated as being at a uniform temperature and in mechanical equilibrium with the surrounding flow, which are justifiable assumptions for metal particles 100 μm and smaller and for flow velocities less than 100 m/s. Surface combustion of larger "bulk" samples of metal in quiescent flow is difficult to observe due to quenching of reaction by the large conductive heat losses to the rest of the metal. Bulk metal samples exposed to high-velocity flow of an oxidizing atmosphere, however, are capable of supporting surface reaction (combustion) while the interior of the sample remains cool. This phenomenon has been encountered with ram accelerators operating at high in-tube Mach numbers, where significant luminosity and even projectile acceleration have been observed with aluminum, magnesium, and titanium projectiles traveling in high-pressure oxidizing atmospheres (Knowlen et al. 1996, Seiler et al. 1998, Legendre & Giraud, 2000). Supersonic metal combustion also occurs in explosive dispersal of reactive particles (aluminum, magnesium, etc.). High explosives which have embedded particles of reactive metal can have significantly enhanced blast effect due to the explosive dispersal and reaction of these particles with the explosive products and surrounding air (Frost & Zhang 2003). The velocity of the particles can be in the range of 1-2 km/s and the particles can be as large to 100's of μm to several mm's in size, such that they burn in bulk form.

Aeroballistic experiments (Higgins et al. 2001) established that bulk samples (1.27-cm-diameter spheres) of reactive metals (aluminum, magnesium, and zirconium) can ignite and burn at supersonic speeds in pure oxygen. In these tests, the spherical projectiles were launched using a single-stage light gas gun to velocities between 1.2 and 2 km/s (Mach 3.6 to 6.0). By observing luminosity on the projectile, the envelope of projectile ignition in terms of projectile velocity and oxygen pressure were mapped. More recent (Batchelor & Higgins 2004) attempts to perform direct visualization of a supersonic burning projectiles (aluminum and zirconium) used smaller (3 mm diameter) flat-ended cylindrical projectiles launched from an explosive-driven light gas gun at velocities between 1 and 2 km/s. The photographs obtained strongly suggest that the observed reactions initiate on or near the surface of the projectile and continue as a long, luminous wake. The implication of this result is that reaction between the oxidizing atmosphere and the surface of the projectile can occur, while the interior of the projectile remains cold. This reaction can result in significant energy release and removal of projectile material that would not otherwise occur unless an oxidizing atmosphere was present.

Experimental Approach

The technique invoked in this investigation is to fix a sample of reactive material and accelerate a high-velocity flow of oxidizing atmosphere past the sample. The flow is accelerated by a normal shock wave driven by detonating a sample of high explosive (i.e., a blast wave). A

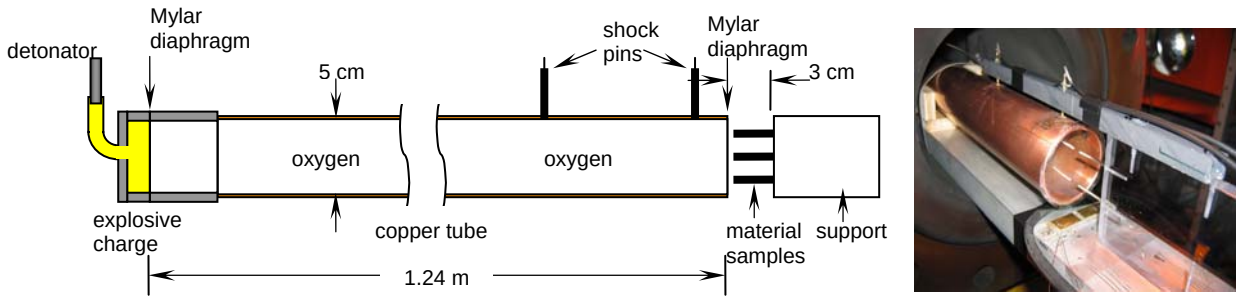

Figure 1. Schematic and photograph of experimental apparatus. Photograph shows two samples (Zr and Ti) and copper tube being loaded into blast chamber. Explosive charge not shown in photograph.

schematic of the charge is shown in Fig. 1. The length of the capsule containing the explosive charge was varied (5 mm-15 mm) in order to change the amount of explosive used and strength of generated shock. The shock was driven down a 1.24-m-long, 5-cm-diameter copper tube that had previously been flushed with pure oxygen. The shock-accelerated flow of oxygen generated then encountered the material samples (flat-end cylinders, 1.5-3 mm in diameter, 3 cm long), which were mounted at the exit of the tube.

The material samples were observed during an experiment using high-speed image-intensified CCD cameras (DiCam Pro and HSFC Pro) which observed the experiment via a window in the blast chamber. The cameras used shutter times between 20 and 80 ns. The pictures are of silhouettes of the material samples and self-luminous phenomena only.

An important consideration is the relative significance of the energy release of metal combustion as compared to the internal energy of the high-temperature flow (either stagnation temperature for an aeroballistic environment, or the post-shock temperature for the shock-accelerated flow experiments reported below). As the flow temperature approaches the adiabatic flame temperature, the additional increase in temperature due to combustion reactions may become negligible.

To quantify these considerations, the post-shock flow temperature is compared to the adiabatic flame temperature for varying the strength of shock wave used to generate the flow. In

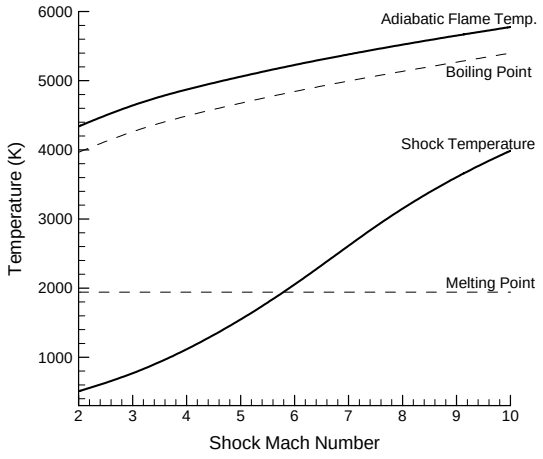

Figure 2. Combustion temperature (at constant pressure) for titanium with oxygen in post-shock flow as a function of shock Mach number.

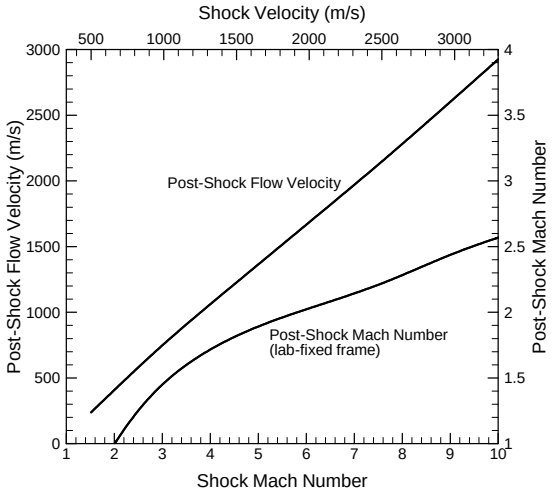

Figure 3. Post-shock flow velocity and Mach number as a function of shock Mach number.

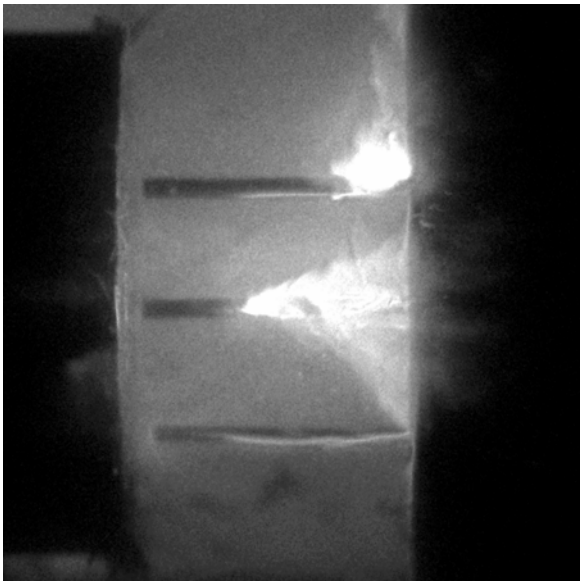

Figure 4. Photograph of zirconium, titanium, and magnesium (top to bottom) samples in a flow of oxygen accelerated by a Mach 6 shock wave. The flow is from left to right. Picture taken 30 μs after passage of shock.

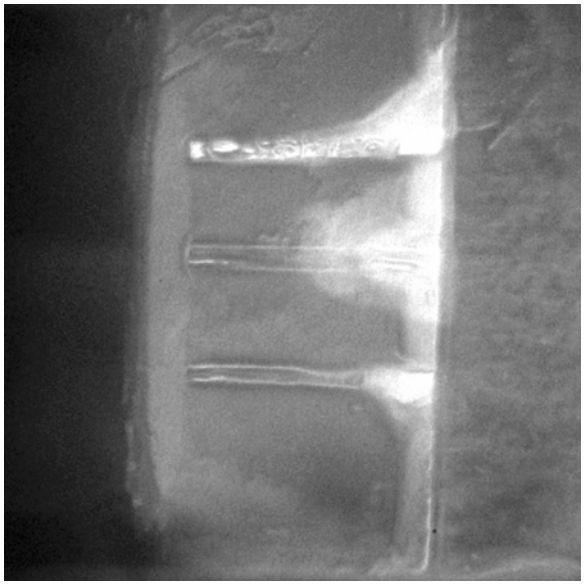

Figure 5. Photograph of zirconium, aluminum, and magnesium (top to bottom) samples in a flow of oxygen accelerated by a Mach 9.2 shock wave. The flow is from left to right. Picture taken 10 μs after passage of shock.

Figures 2, the adiabatic flame temperature as a function of the shock Mach number is plotted for titanium (the plots for aluminum, magnesium, zirconium are qualitatively similar). The adiabatic flame temperature calculation assumed constant pressure, stoichiometric combustion between the metal and oxygen, occurring at the static pressure and temperature of the post-shock flow. The shock temperature and the adiabatic flame temperature were both computed using the NASA CEA program (Gordon & McBride 1994). The post shock velocity and Mach number (viewed from lab-fixed frame) were also computed using CEA and are shown in Fig. 3. Note that the Mach number does not exceed Mach 2.5 due the extremely high temperatures (and sound speed) in the shocked flow.

Results

A photograph of samples of zirconium, titanium, and magnesium exposed to the flow generated by a Mach 6 shock wave in oxygen is shown in Fig. 4. This picture was taken approximately 20 μs after the arrival of the shock wave. Large regions of intense luminosity resulting from combustion are visible on the zirconium and titanium samples. The recovered samples showed local removal of surface material in the regions where luminosity is visible in the picture. Note that the magnesium sample shows no sign of combustion, and the sample was recovered without mass loss.

Results are shown in Fig. 5 from the strongest shock wave used (Mach 9.2). Note the "mottled" structure of the luminosity on the zirconium sample (no titanium sample was present in this experiment). The aluminum and magnesium projectiles exhibit boundary layer luminosity, and all of the recovered samples showed significant erosion and mass loss.

A control experiment was also performed with pure nitrogen in place of pure oxygen. The test conditions from Fig. 5 (Mach 9 shock) were reproduced for this experiment: no luminosity was observed on the samples. The samples from this experiment were recovered in pristine

condition, no mass loss was measured. This result conclusively demonstrates that the intense luminosity and significant mass removal observed with oxygen experiments was due to exothermic reactions (i.e., combustion) occurring between the flow of oxidizer and the material samples.

A summary of the mass removed from the samples as a function of the shock Mach number is shown in Fig. 6. From this figure, it is apparent that zirconium and titanium are significantly more reactive than aluminum and magnesium in a supersonic, oxidizing atmosphere. Zirconium and titanium react with shocks as low as Mach 5, and exhibit significant mass loss at Mach 6 and above. Aluminum and magnesium show no signs of reaction until the shock Mach number exceeds Mach 8, and the mass loss is never as significant as that observed with zirconium and titanium.

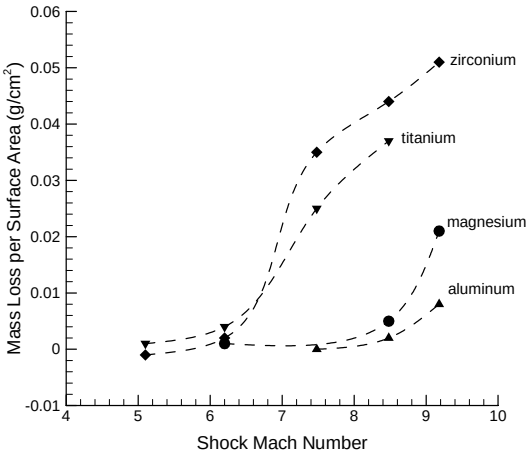

Figure 6. Measured mass loss from material samples exposed to blast waves of oxygen at various Mach numbers.

Conclusions

The experimental results reported here demonstrate that bulk metal ignition and combustion of reactive metals is possible in high-speed flows for shock-accelerated oxygen. It is interesting to note that zirconium and titanium appear to be much more reactive in a supersonic oxidizing environment than aluminum and magnesium. The amount of mass removed from the zirconium and titanium samples was also much larger, even though zirconium and titanium are refractory metals with melting points nearly twice as large as aluminum and magnesium.

References

Batchelor, P., and Higgins, A.J., 2004 "Ignition of Reactive Metal Particles in Supersonic Flow," Combustion Institute / Canadian Section Spring Technical Meeting, Kingston, Ontario.

Frost, D. L. and Zhang, F., 2003 "Effect of Scale on the Blast Wave Generated by a Metallized Heterogeneous Explosive," *Energetic Materials: Reactions of Propellants, Explosives and Pyrotechnics*, Proc. 34th Int. Annual Conference of ICT, Karlsruhe, Germany, 7.1-7.14.

Gordon, S. and McBride, B.J. 1994 "Computer Program for Calculation of Complex Equilibrium Compositions and Applications." NASA RP-1311.

Higgins, A.J., Frost, D.L., Knowlen, C., Zhang, F., and Murray, S.B., 2001 "Combustion of Supersonic Metallic Spheres," *18th International Colloquium on the Dynamics of Explosions and Reactive Systems*, Seattle, Washington, July 29 - August 3.

Knowlen, C., Higgins, A.J., Bruckner, A.P., and Bauer, P., 1996 "Ram Accelerator Operation in the Superdetonative Velocity Regime," AIAA Paper 96-0098.

Legendre, J.F., and Giraud, M., 2000 "Enhanced RAMAC Performance in Subdetonative Propulsion Mode with Semi-Combustible Projectile," *Journal de Physique IV*, Vol. 10, No. 11, pp. 23-30.

Seiler, F., Patz, G., Smeets, G., and Srulijes, J., 1998 "Influence of Projectile Material and Gas Composition on Superdetonative Combustion in ISL's RAMAC 30," AIAA 98-3445.