METALS COMBUSTION IN NORMAL GRAVITY AND MICROGRAVITY

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Introduction and background

The study of the combustion characteristics of metallic materials has been an ongoing area of research at the NASA White Sands Test Facility (WSTF) (ref. 1 and ref. 2). This research has been in support of both government and industrial operations and deals not only with the combustion of specific metallic materials but also with the relative flammabilities of these materials under similar conditions. Since many of the metallic materials that are characterized at WSTF for aerospace applications are to be used in microgravity environments, it was apparent that the testing of these materials needed to proceed in a microgravity environment. It was believed that burning metallic materials in a microgravity environment would allow the evaluation of the validity of applying normal gravity combustion tests to characterize metallic materials to be used in microgravity environments. It was also anticipated that microgravity testing would provide insight into the general combustion process of metallic materials. The availability of the NASA Lewis Research Center's (LeRC) 2.2-second drop tower provided the necessary facility to accomplish the microgravity portion of the testing while the normal gravity testing was conducted at NASA WSTF. The tests, both at LeRC and WSTF, were conducted in the same instrumented system and utilized the standard metal flammability test of upward propagation burning of cylindrical rod samples.

Until this study, microgravity combustion tests did not exist for metals and alloys and there was uncertainty as to whether these materials would support combustion in the absence of gravity. However, nonmetals have been tested under microgravity conditions. Generally it has been found that in microgravity, nonmetals do not burn as well as similar experiments in normal gravity. Normally, the reduction in combustion rate for nonmetals in microgravity has been attributed to the vapor-phase diffusion flame these materials exhibit.

To study the microgravity combustion of metallic materials, a proposal was written and submitted to the director of Johnson Space Center (JSC). The JSC director funded this work through the JSC Director's Discretionary Fund in 1989 with a duration of two years. With this funding, an experimental program with appropriate instrumentation and facility usage commenced to study the combustion of metallic materials in microgravity. Three subsequent proposals were funded by the NASA WSTF Laboratories Office Chief to continue this work and two proposals are currently under consideration for funding. The results of these test programs and anticipated future work are summarized below.

The use of metallic particles as additives to rocket propellants is normally thought of as the impetus for understanding the combustion characteristics of metallic materials. Since this time, there have been several critical failures of metal components in high-pressure oxygen systems. For these reasons NASA was prompted to initiate programs to better understand the ignition, combustion, and flame spread of metallic materials as well as programs to contrast the similarities and differences of metallic materials combustion as a function of the gravity level.

Unlike nonmetallic materials which burn in a vapor-phase reaction, metallic materials can exhibit a liquid or condensed-phase combustion reaction (ref. 3). The majority of recent testing conducted by WSTF and others involved the combustion of cylindrical rods. In normal gravity, it has been shown that, an increase in rod diameter will be accompanied by a decrease in the regression rate of the melting interface (ref. 2). Experimentation in normal gravity has also shown that a decrease in the ambient oxygen pressure will also result in a decrease in the regression rate of the melting interface (ref. 2).

Experimental

Complete details of the experimental system design, equipment, certification, ignition event, and operation both in normal gravity at WSTF and microgravity at LeRC are given in ref. 4.

The oxygen used at both WSTF and LeRC was 99.5% pure (min.) and the oxygen environment was static at the beginning of a test except for the slight free-convective effects induced by the ignition event. The metals and alloys tested, to date, include rods of iron, 316 stainless steel, 2219 aluminum, titanium, nickel 200, Monel K-500, copper, and tungsten. Thin and thick sheets and meshes of 316 stainless steel were also tested.

Results and Discussion

Figure 1a shows a molten ball, just after detachment, that was formed on the end of a 0.32-cm-diameter cylindrical iron rod burning at 6.9 MPa in normal gravity. The melting interface is the contact area between the solid rod and the formed molten ball (while still attached to the rod). The molten ball grows as energy is transferred from the combustion process to the solid rod and the melting interface moves upward. This process proceeds, in normal gravity, until the molten ball detaches from the solid rod and a new molten ball is formed. The detachment of the molten ball occurs when the gravitational force exceeds the sum of the adhesion and surface tension forces which hold the molten ball to the solid rod.

As stated, at the beginning of testing it was unclear as to whether metallic materials would support combustion without gravity. It was quickly determined that the metallic materials tested do support combustion under microgravity conditions similar to conditions that support combustion in normal gravity. Figure 1b shows the microgravity combustion of the equivalent experiment shown in Fig. 1a. The 2.2 seconds of microgravity time would have been equivalent to approximately five growth-and-detachment cycles in normal gravity. Instead of detaching in microgravity, the molten ball continues to accumulate mass until impact at the bottom of the drop tower occurred. Upon impact, now in normal gravity, the rod would not extinguish but would continue to burn until completely consumed.

Several differences between the normal gravity and microgravity burning of the metal rods were apparent and include 1) the change in shape of the molten ball from a teardrop to a near perfect sphere, 2) the change in the shape of the melting interface from a circular section to an elliptical section which results in a larger attachment area, and 3) in microgravity the molten ball is often observed to precess around the rod as it burns (equivalent to the instability leading to spinning deflagration).

Calculation of regression rates of the melting interface in normal gravity is accomplished by monitoring the upward movement of the horizontal melting interface from a photographic record of the burning event. In microgravity, the regression rate of the melting interface is calculated by first representing the melting interface by a slanted line with start point and end point defined by the intersection of the molten ball and the solid rod. By monitoring the midpoint of this line as the melting interface progresses up the rod, a value of the regression rate can be obtained. As described in the background, in normal gravity, the regression rate of the melting interface increases with increasing oxygen pressure or decreasing rod diameter. This trend is also true during the microgravity combustion of metallic rods. Though a similar dependency of the regression rate as a function of rod diameter and oxygen pressure is shown between normal gravity and microgravity, there is a significant difference between the absolute regression rates. The regression rate of the melting interface greatly increases, for similar experimental conditions, during microgravity conditions. This increased regression rate, rod diameter dependency, and oxygen pressure dependency, as a function of gravity level, for the iron system, is shown in Fig. 2.

It has also been shown (ref. 5) that the molten ball formed on a burning iron rod (0.32-cm-diameter) at 6.9 MPa oxygen pressure, in normal gravity, contains excess oxygen above stoichiometric requirements (for the formation of FeO). This result is also true during the microgravity combustion of iron over a pressure range between 1.7 and 8.6 MPa.

The combustion of a 0.32-cm-diameter 2219 aluminum rod shows a combustion zone that is similar in shape, growth, and progression up the rod as seen with the iron rods. It is different with regards to total luminosity (more) and the quantity of volatile products surrounding the combustion zone.

During the microgravity combustion of 316 stainless steel (rods, sheets and meshes), which physically appears to burn identical to the iron, there was a fine olive green powder residue deposited throughout the chamber. This phenomena does not occur during similar experiments in normal gravity. This powder was collected, analyzed by x-ray diffraction, and shown to be chromium oxide (Cr_2O_3). This result suggests that the temperature of the molten ball during microgravity combustion is greater than for combustion in normal gravity and leads to the volatilization of chromium or chromium oxides. As the molten ball grows in microgravity, the molten ball retains more of the heat that is generated by combustion and results in a higher temperature. This increase in temperature is consistent with the increase in the regression rates also exhibited in microgravity.

Different shapes were burned in microgravity to compare configurational effects to similar normal gravity tests. One such test was a thin sheet of 316 stainless steel at 6.9 MPa oxygen pressure which, in normal gravity, extinguishes at this pressure. As the molten mass accumulates in normal gravity it detaches and residual thermal energy is lost at a faster rate than it is generated and so the burning extinguishes. In microgravity, this sample shape burns until the entire sample is consumed since the molten mass does not detach from the sheet. T'ien (ref. 6) has hypothesized the probability of a change in the flammability of a material when the burning event is moved from normal gravity to microgravity, but no experimental evidence, until this study, has verified this hypothesis.

Copper, nickel 200, and Monel K-500 are three materials that have been shown at WSTF to be nonflammable (0.32-cm-diameter rods) in normal gravity up to oxygen pressures of 69.5 MPa. In microgravity, these materials all appeared to burn at oxygen pressures as low as 6.9 MPa, but the test time of 2.2 seconds did not allow adequate time to allow propagation of the burning event for a significant distance along the sample rod. The burning copper rod is shown in Fig. 1c.

Conclusions and future work

Metals and alloys burn readily in microgravity environments which indicates adequate circulation in the formed molten mass to ensure fuel-oxidizer mixing. Under similar experimental conditions, rods that burn in normal gravity burn faster in microgravity. Sample shapes (sheets) that extinguish in normal gravity burned completely under similar microgravity conditions. Sample materials that do not burn in normal gravity at very high oxygen pressure burn in microgravity at substantially lower oxygen pressure for the 2.2 seconds of test time. A similar dependency between regression rate of the melting interface and oxygen pressure and rod diameter exists in normal gravity and microgravity. 316 stainless steel (rods, meshes, and sheets) produced volatile combustion products when burning in microgravity which does not occur in normal gravity. All of these observations are consistent with the implied observation that the temperature in the molten ball in microgravity is greater than in normal gravity. Excess oxygen, above stoichiometric requirements, is contained in the molten ball formed on iron rods both in normal gravity and microgravity.

There are several areas of emphasis for future work. More configuration testing and new material testing is also needed. The solution of a metals combustion model for iron (condensed-phase burning material) in microgravity is also proceeding which will result in determination of the activation energy, preexponential factor, and other parametric values needed for the characterization of the burning iron system. A stability analysis on the combustion phenomena at both the melting interface and the reaction zone is ongoing. The study of gravity effects on nonmetals which burn with surface flames (Teflon and graphite-filled polymers) is also anticipated future work.

References

1) Stoltzfus, J.M., et. al., in *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Third Volume, ASTM STP 986*, D.W. Schroll, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 28-53.

2) Steinberg, T.A., et. al., in *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040* (J.M. Stoltzfus, F.J. Benz, and J.S. Stradling, Eds.), American Society for Testing and Materials, Philadelphia, 1989, pp. 54-75.

3) Steinberg, T.A., et. al., *Combust. Flame*, accepted.

4) Steinberg, T.A., Ph.D. dissertation, NMSU, Las Cruces, N.M., May, 1990; Univ. Micro., Inc., Ann Arbor, MI, 91-01023, 51-08B, *Dissertation Abstracts*, p. 4021.

5) Steinberg, T.A., et. al., *Combust. Flame*, 88:309-320 (1992).

6) T'ien, J.S., Presented at the International Microgravity 2Combustion Workshop, LeRC, Cleveland, OH, Jan. 25-26, 1989.

a) 0.45 s b) 1.16 s c) 1.15 s

Figure 1.—— Molten ball formed on a burning 0.32-cm-diameter rod in pure oxygen, a) iron in normal gravity (just after ball detachment-6.9 MPa), b) iron in microgravity (6.9 MPa) and, c) copper in microgravity (8.1 MPa). The white lines were added to the photographs to show the boundaries of the rods.

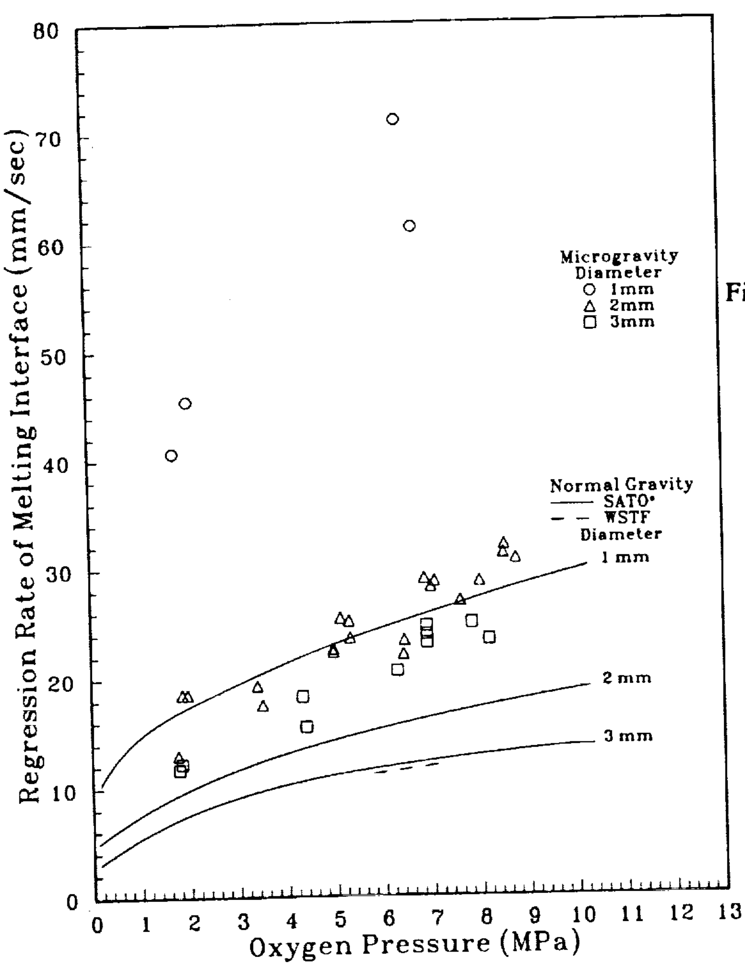

Figure 2.—— Comparison of regression rate of melting interface between normal gravity (mild steel and iron) and microgravity (iron) as a function of oxygen pressure and rod diameter. *From Sato, J. in *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume*, ASTM STP 1040 (J. Stoltzfus, F.J. Benz, and J. Stradling, Eds.), American Society for Testing and Materials, Philadelphia, 1989, pp. 162-167.

COMMENTS

Question (R. Friedman, Factory Mutual): What procedure did you use to ignite your sample?

Answer: The microgravity combustion test at LeRC had two different ignition procedures. In the first procedure, the ignition of the test samples occurred before the drop began, in order that the combustion could be observed during a transition from normal gravity to microgravity. The second initiation procedure ignited the test sample after free-fall (microgravity conditions) was established, in order to evaluate a rod's combustion in microgravity alone.

All experiments were ignited by small amounts of Pyrofuze wire wrapped around the bottom of the sample. The Pyrofuze wire was ignited by resistive heating and had a negligible effect on the surroundings.

SESSION G - DROPLET AND SPRAY COMBUSTION

(Chair, Forman Williams)