Combustion Joining of Regolith Tiles for In-Situ Fabrication of Launch/Landing Pads on the Moon and Mars

Robert E. Ferguson,[1] and Evgeny Shafirovich[2]
The University of Texas at El Paso, El Paso, TX 79968

and

James G. Mantovani [3]
NASA Kennedy Space Center, FL 32899

To mitigate dust problems during launch/landing operations in lunar and Mars missions, it is desired to build solid pads on the surface. Recently, strong tiles have been fabricated from lunar regolith simulants using high-temperature sintering. The present work investigates combustion joining of these tiles through the use of exothermic intermetallic reactions. Specifically, nickel/aluminum (1:1 mole ratio) mixture was placed in a gap between the tiles sintered from JSC-1A lunar regolith simulant. Upon ignition by a laser, a self-sustained propagation of the combustion front over the mixture occurred. Joining was improved with increasing the tile thickness from 6.3 mm to 12.7 mm. The temperatures sufficient for melting the glass phase of JSC-1A were recorded for 12.7-mm tiles, which explains the observed better joining.

I. Introduction

RECENT interest in manned lunar and Martian landings has led to new research in the area of *in situ* resource utilization (ISRU) as a way of reducing transportation costs. It is hoped that native resources of the Moon and Mars could be used to provide propellants, life support, and construction materials for the missions. In particular, ISRU approaches could be useful for the construction of launch/landing pads.

Previous lunar missions have experienced notable and potentially dangerous rocket plume effects on surface regolith during landing and takeoff.[1] To mitigate the dust problems, it is desired to build a solid, flat pad in a location that has repeated launch and landings near any permanent infrastructure of an outpost.[2] Obviously, it would be attractive to use local regolith for this purpose. To consolidate lunar/Martian regolith simulants, various methods have been proposed and tested, including incorporation of regolith into thermoplastics, [2-5] high-temperature sintering, [6-8] and thermite-type reactions with aluminum[9-12] and magnesium.[13-17] Among them, sintering appears to be a robust, mature technology provided there is enough energy for heating the regolith to the required high temperature. Recently, the Granular Mechanics and Regolith Operations Lab at Kennedy Space Center has developed a sintering technique that converts lunar regolith simulants into ceramic tiles that are sufficiently strong and remain stable after being exposed to high-temperature gas flow in simulated thruster testing.[18,19]

To build reliable launch/landing pads from regolith tiles, connecting these tiles together is desirable. One promising approach is based on the use of self-propagating high temperature synthesis (SHS), which has been used for synthesis of numerous ceramic and other materials.[20,21] The SHS process may occur if the initial materials (e.g., powders) are able to interact exothermally and generate temperatures that are high enough for a self-sustained combustion, leading to the formation of the desired materials. The process is driven by the released chemical energy, with no external energy input needed, except for a small amount for the process initiation (ignition). One of various SHS techniques is the so-called combustion joining, where a mixture of reactive powders (usually, thermites or intermetallics) is placed in the gap between two parts and ignited, leading to the formation of a strong weld between the two parts.[21,22]

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[1] Graduate Research Assistant, Department of Mechanical Engineering, 500 W. University Ave.
[2] Associate Professor, Department of Mechanical Engineering, 500 W. University Ave., AIAA Associate Fellow.
[3] Physicist, Granular Mechanics and Regolith Operations Lab, Mailcode UB-R1.

The present work aims to apply the combustion joining technique for regolith tiles. This involves the use of reactive powders mixed and placed between the tiles to be joined. Upon ignition, the combustion front propagates over the mixture, also affecting the edges of the tiles so they will merge with the combustion product in the gap, forming a single piece of a solid material after cooling. Because regolith for the tiles, and potentially at least part of the joining powder, would be available *in situ* on the Moon or Mars, the mass of materials brought from Earth would be dramatically reduced, thus increasing the chance of mission success, both technologically and financially.

It is important to select a suitable reactive mixture for combustion joining of regolith tiles. The mixture should be sufficiently exothermic to generate combustion temperatures that will affect (e.g., melt) the tile edges so that they will easily merge with the formed combustion products. Lunar and Martian regolith simulants consist of mineral phases that melt at very high temperatures. However, it has been shown that JSC-1A lunar regolith simulant includes a glass phase that melts at 1120 °C.[23] Based on this, it has been hypothesized that reaching this temperature may be sufficient for joining the regolith tiles.

Many thermite and intermetallic mixtures generate much higher temperatures. Thermites, however, produce at least two phases (metal and oxide), which usually separate from each other because of gravity.[14] This may worsen the properties of the weld. From this point of view, intermetallic mixtures appear to be more promising as they may form a single-phase product, thus eliminating the phase separation problem.

In the present work, a mixture of nickel and aluminum powders was selected for the experiments. Thermodynamic calculations with THERMO software[24] for a stoichiometric (1:1 mole ratio) nickel/aluminum mixture at 1 atm pressure have predicted an adiabatic flame temperature of 1912 K (1639 °C) and formation of a single intermetallic phase NiAl, which is 42% liquid and 58% solid at this temperature. Based on these calculations, it is expected that combustion of this mixture in the gap between the tiles will melt the edges of JSC-1A tiles and form a strong bond between the formed nickel aluminide and the adjacent edges of the tiles. Note that aluminum could be recovered from lunar and Martian regolith.

The objective of the present work was to verify the feasibility of combustion joining of regolith tiles using nickel/aluminum mixture. Taking into account the lunar and Martian environments, the experiments were conducted at reduced pressure (10-60 mbar).

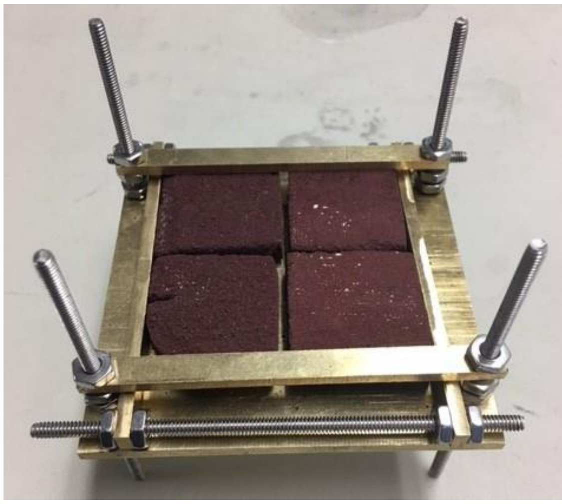
II. Experimental

The tiles were fabricated by sintering JSC-1A lunar regolith simulant in a furnace heated to 1125°C. They were approximately 10 cm x 10 cm squares, with thicknesses of 6.3 mm and 12.7 mm. For the experiments, the tiles were cut by a saw to 32 mm x 32 mm squares or 32 mm x 64 mm rectangles, while maintaining their original thicknesses.

A three-dimensional inversion kinematics tumbler mixer (Inversina 2L, Bioengineering) was used for mixing Al (3.0-4.5 µm, 97.5% pure, Alfa Aesar) and Ni powders (3-7 µm, 99.9% pure, Alfa Aesar). The powders were mixed in the stoichiometric proportion (1:1 mole ratio). Mixing was conducted in an argon environment for 60 min.

Either four square samples or two rectangular samples were placed into a special holder (Fig. 1), with stainless steel pins used to establish pre-determined experimental gaps of 2, 4, and 6 mm. The gaps were filled with the mixture of Al and Ni powders using a lab spatula. To ensure the same density of the powder layer in the gap, the holder was placed onto a vibrating shaker (Gilson SS-28 Vibra Pad) and the vibrations were used to uniformly settle the powder in the tile gaps.

The combustion experiments were conducted in a laser ignition facility (Fig. 2), previously used for studies of gas-generating mixtures.[25-27] This facility includes a windowed stainless steel chamber (volume: 11.35 L), equipped with a pressure transducer and connected to a compressed argon cylinder and a vacuum pump. An infrared beam of a CO_2 laser (Synrad Firestar ti-60) enters the chamber through a ZnSe window in the lid. The power of the CO_2 laser beam is controlled by a laser controller (Synrad UC-2000), while the duration of the laser pulse is set using LabVIEW (National Instruments) software connected to the laser controller. A custom-made electronic scheme based on a photoresistor turns off the laser pulse upon the ignition.



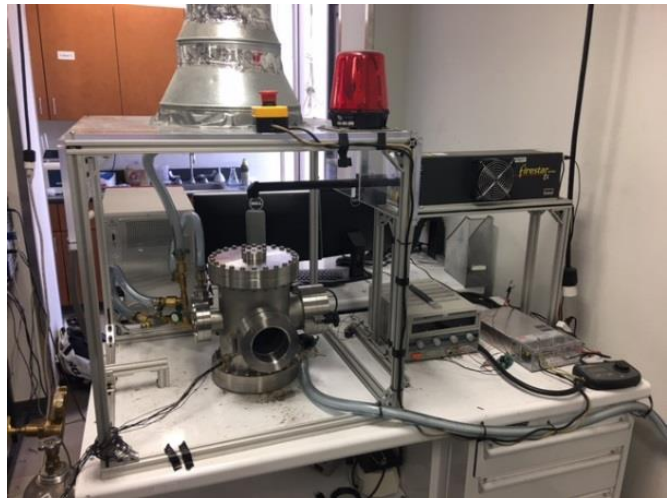


Fig. 1. Holder with tiles. **Fig. 2. Laser ignition facility.**

During the experiment, the holder with the tiles and the mixture was placed inside the chamber and the laser beam was aligned with the middle of the gap between the two tiles or with the center of the cross formed by the gaps if four tiles are tested (see Fig. 1). For this to be done, a red beam of a laser diode pointer (Synrad), pre-aligned with the infrared beam of the CO_2 laser, was used. The chamber was then evacuated and filled with ultra-high purity argon gas. The experiments were conducted at pressures 10 mbar and 60 mbar. Thermocouples (95%W/5%Re−74%W/26%Re, type C, wire diameter: 76.2 µm, Omega Engineering) were used to measure the temperature of the mixture during combustion.

III. Results and Discussion

In experiments with both two and four tiles, as well as with all tile thicknesses and experimental gaps, upon ignition, the combustion front propagated steadily over the mixture in the gap between the tiles.

Analysis of the products produced mixed results. In the test with four 6.3-mm thick titles, the formed solid product did not join the tiles. Although it retained its shape after separating from the tiles, only charring was observed on their edges (Fig. 2).

Better results were obtained with thicker tiles. Figure 3 shows that four 12.7-mm thick tiles remained joined after cooling (the light grey powder seen on the tile surfaces spread during shaking and remained intact during combustion of the mixture). The joint was strong enough to hold the weight of the tiles. Apparently, successful joining in the experiments with thicker tiles is explained by a relatively smaller effect of heat losses from the tile surfaces and hence a higher combustion temperature.

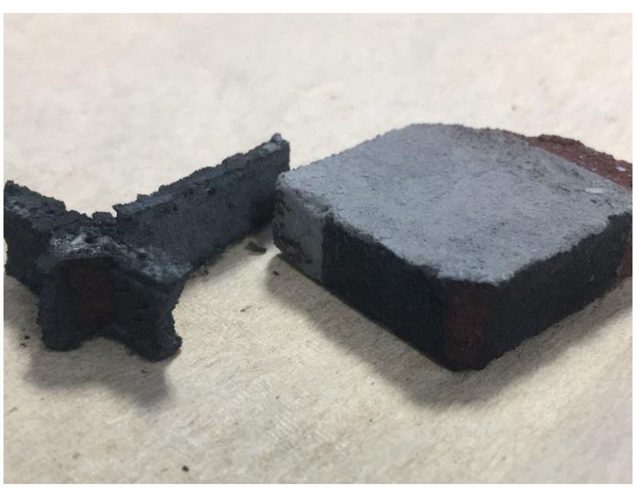


Fig. 2. Separation of 6.3-mm tiles after cooling. **Fig. 3. Joined 12.7-mm tiles.**

Thermocouple measurements were conducted for 12.7-mm tiles. The configuration with two tiles was used and the distance between them was 6 mm. In one test (conducted at 60 mbar pressure), two thermocouples were placed approximately in the center of the powder fill, away from the laser ignition point. They recorded the maximum temperatures 1384 °C and 1407°C. For illustration, Figure 4 shows the time variation of the electromotive force (emf), generated by one of these thermocouples. Since a Type C thermocouple has a highly non-linear temperature characteristic, the curve shows the measured emf of the hot junction relative to 0 °C, while the dashed gridlines correspond to the standard temperature-emf relationship for a Type C thermocouple (ASTM E-230).

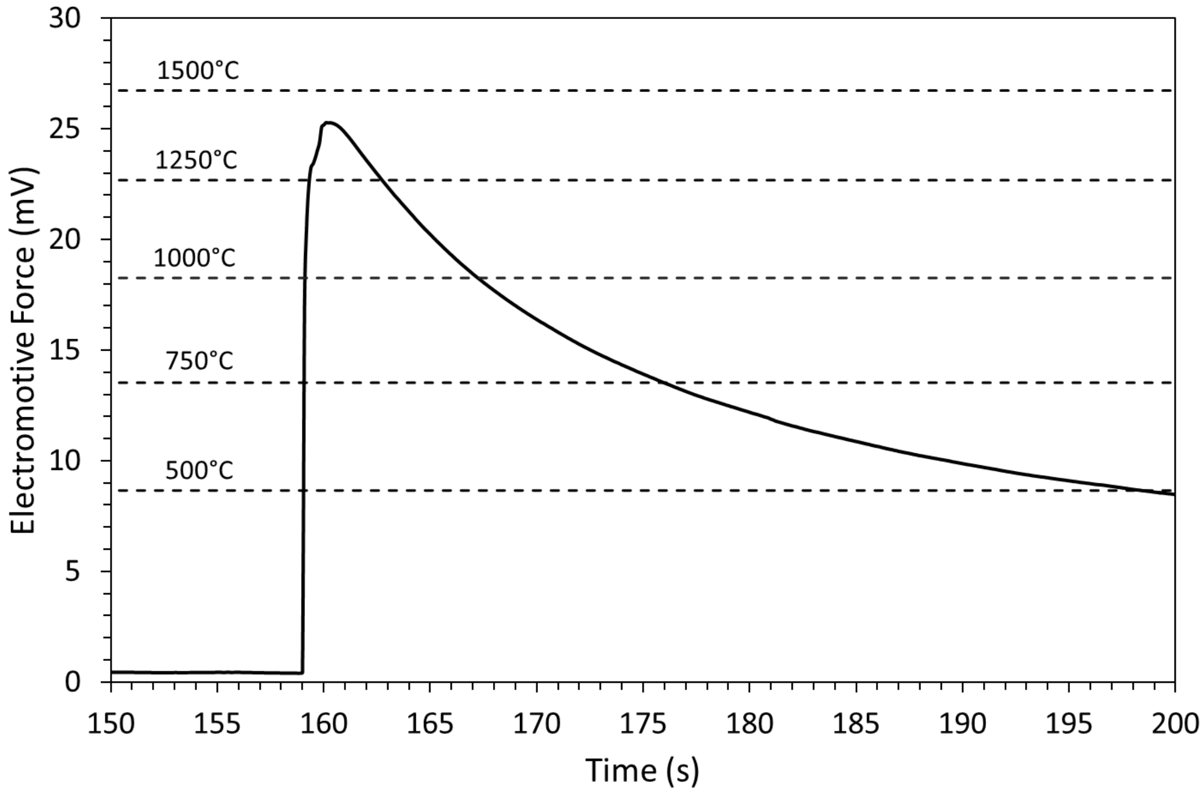


Fig. 4. Thermocouple record during combustion with temperature correlations.

In another experiment (conducted at 10 mbar pressure), the thermocouple was placed on the edge of the powder, next to the tile. The maximum recorded temperature was 1235 °C in this case. It is seen that in the case of 12.7-mm tiles, the achieved temperatures were higher than 1120 °C, the melting point of the glass phase in JSC-1A composition, which explains the observed joining of the tiles.

IV. Conclusions and Future Work

Combustion joining of ceramic tiles sintered from JSC-1A lunar regolith simulant has been demonstrated. It has been shown that Ni/Al mixture (1:1 mole ratio) placed in a gap between two regolith tiles, upon ignition by a laser, exhibits a self-sustained propagation of the combustion front. Joining was improved with increasing the tile thickness from 6.3 mm to 12.7 mm, apparently because of decreased heat losses and higher temperatures. The measured maximum temperature was close to 1400 °C in the center of the gap and less by about 150 °C near the tile edge, i.e., higher than the melting point of the glass phase in JSC-1A composition.

The future work includes studies on the effects of the gap thickness on the combustion stability, the front velocity, and the strength of the joint. Video recording and thermocouple measurements will be used for the front velocity measurements. To simulate the Martian environments, experiments will also be conducted in CO_2. The obtained joints will be characterized using X-ray diffraction analysis (Bruker D8 Discover XRD) as well as scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM, Hitachi S-4800). Mechanical properties of the joint will also be examined using available facilities.

Also, the specific heats and thermal diffusivities of the tiles will be measured using a differential scanning calorimeter (Netzsch DSC 404 F1 Pegasus) and a laser flash apparatus (Netzsch LFA 457 MicroFlash), respectively. These thermophysical properties will be used for modeling the combustion wave propagation over the reactive mixture in the gap between the regolith tiles.

Acknowledgments

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