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Aluminum–nickel combustion for joining lunar regolith ceramic tiles

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A B S T R A C T

Combustion-based methods are attractive for space manufacturing because the use of chemical energy stored in reactants dramatically decreases the required external energy input. Recently, a sintering technique has been developed for converting lunar/Martian regolith into ceramic tiles, but it is unclear how to build a reliable launch/landing pad from these tiles with small amounts of energy and materials. Here we explored the feasibility of joining the regolith tiles using self-propagating high-temperature reactions between two metal powders. Combustion of an aluminum/nickel mixture placed in a gap between two tiles, made of JSC-1A lunar regolith simulant, was studied in an argon environment at 1 kPa pressure. Stable propagation of the combustion front was observed over the tested range of distances between the tiles, 2–8 mm. The front velocity increases with increasing the distance between the tiles. Joining of the tiles was achieved in several experiments and improvement with increasing the tile thickness was observed. Thermophysical properties of the tiles, the reactive mixture, and the reaction product were determined using differential scanning calorimetry and laser flash analysis. A model for steady propagation of the combustion wave over a condensed substance layer placed between two inert media was applied for analysis of the investigated system. Testing the model has resulted in reasonable agreement between the experimental and modeling dependencies. Both experimental and modeling results indicate a narrow quenching distance in the investigated system, which implies that a small amount of the reactive mixture would be required for sintering regolith tiles on the Moon.

1. Introduction

It is widely agreed that *in situ* resource utilization (ISRU) is an enabling technology for future space exploration. Efforts are focused on the development of effective and efficient methods for the production of propellants, oxygen, and structural materials on the surface of the Moon and Mars. It would be attractive to use combustion-based methods for space manufacturing because the use of chemical energy stored in reactants dramatically decreases the required external energy input. Combustion of lunar or Martian regolith simulants with aluminum [1–4] and magnesium [5–9] has been investigated with the goal of fabricating construction materials. In the present work, we investigate the use of combustion for joining ceramic tiles, made of regolith, to form launch/landing pads on the surface of the Moon.

Recently, researchers at NASA Kennedy Space Center have developed techniques for converting lunar or Martian regolith into ceramic tiles that are sufficiently strong, survive rocket plumes, and can be assembled into a pad [10,11]. It is unclear, however, how to build a reliable, strong pad from these tiles with relatively small amounts of energy and materials. The present work aims to apply the combustion joining technique (sometimes called SHS welding) [12–14] for this purpose. This involves the use of reactive powders mixed and placed between the tiles to be joined. Upon ignition, the exothermic reaction between the powders propagates over the mixture, also affecting the edges of the tiles so they will merge with the combustion products in the gap, forming a single piece of a solid material after cooling.

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 (see Table 1) that melts at 1120 °C [15]. Based on this, it has been hypothesized that reaching this temperature may be sufficient for joining the regolith tiles.

Many thermite and intermetallic mixture generate much higher temperatures. Thermites, however, produce at least two phases (metal and oxide), which usually separate from each other because of gravity [6]. This may worsen the properties of the weld. From this point of view, intermetallic mixtures appear to be more

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Table 1
Composition of JSC-1A lunar regolith simulant [5].

Mineral	Formula	Composition (wt%)
Anorthite	$CaAl_2Si_2O_8$	26.48
Albite	$NaAlSi_3O_8$	11.35
Orthoclase (K Feldspar)	$KAlSi_3O_8$	0.07
Wollastonite	$CaSiO_3$	7.77
Enstatite	$MgSiO_3$	7.38
Ferrosilite	$FeSiO_3$	4.28
Forsterite	Mg_2SiO_4	9.08
Fayalite	Fe_2SiO_4	3.36
Glass		26.67
MgFeAl silicate		3.06
Troilite	FeS	0.17
Ilmenite	$FeTiO_3$	0.11
Calcite	$CaCO_3$	0.11
Magnetite	Fe_3O_4	0.01
Quartz	SiO_2	0.01
Others		0.07
TOTAL		99.98

promising as they may form a single-phase product, thus eliminating the phase separation problem.

In the present work, a mixture of aluminum and nickel powders was selected for the experimental and modeling studies. Thermodynamic calculations with THERMO software [16] for Al/Ni mixture (1:1 mol ratio) over the pressure range 0.01 – 100 kPa predict 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 was expected that combustion of this mixture in the gap between the tiles would 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. An additional factor in favor of testing Al/Ni mixture was the availability of reliable kinetic information, particularly on the activation energy of the reaction between these metals, which is important for modeling.

The overall goal of the present work was to verify the feasibility of joining regolith tiles using a combustible mixture of metal powders. The specific objectives included (1) experimental investigation of a self-sustained propagation of intermetallic reaction over the stoichiometric aluminum/nickel mixture placed in a gap between two regolith ceramic tiles, (2) measurements of thermophysical properties of the tiles, the reactive mixture, and the combustion products, and (3) analysis of the obtained results using the combustion theory.

2. Experimental procedure

The tiles were prepared from JSC-1A lunar regolith simulant. Ceramic molds with this powder were placed into an oven and held at 200 °C for several hours to remove residual moisture from both the regolith and the ceramics. The molds were then moved to a kiln, slowly (for 4–6 h) heated to 1125 °C, and held at that temperature for one hour. After that, the tiles were cooled naturally to ambient temperature. The final tiles were approximately 100 mm square with rounded corners (Fig. 1) and three different thicknesses of 9.2 ± 0.5, 17.2 ± 0.4, and 27.5 ± 0.6 mm. For the combustion experiments, the tiles were cut by a saw to 32 mm x 64 mm rectangles while maintaining their original thicknesses.

Aluminum (3.0–4.5 µm, 97.5% pure) and nickel (3–7 µm, 99.9% pure) powders were obtained from Alfa Aesar. The powders were mixed in the stoichiometric proportion (1:1 mol ratio) using a three-dimensional inversion kinematics tumbler mixer (Inversina 2 L, Bioengineering). Mixing was conducted in a nitrogen environment for 60 min.

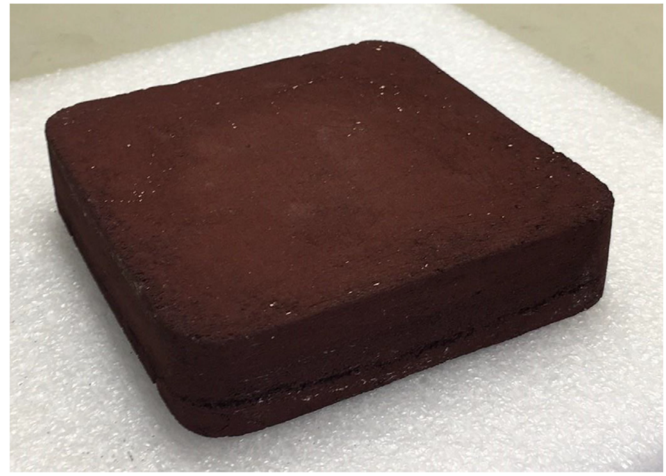

Fig. 1. Regolith tile.

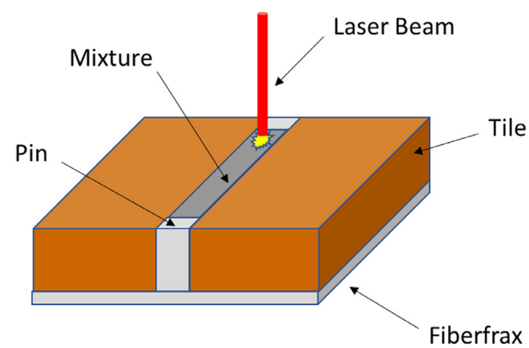

Fig. 2. Schematic of the experimental configuration.

For the combustion experiments, two rectangular tiles were placed in a special holder. More specifically, they were placed onto 3–6 mm thick thermal paper (Fiberfrax) located on a brass pedestal and secured using brass bars at the edges with bolts and nuts. Two stainless steel pins were used to establish the required gap between the tiles, which then was filled with the Al/Ni mixture using a lab spatula. To ensure the same density of the powder layer in the gap, the holder was subjected to vibrations using a shaker (Gilson SS-28 Vibra Pad). Additional powder was added until the powder level settled at the top of the tiles. The relative density of the mixture after the vibrating procedure was approximately 40%. Figure 2 shows a schematic of the experimental configuration. The length of the mixture layer was equal to about 50 mm.

The combustion experiments were conducted in a laser ignition facility, previously used for experiments with compacted powders and gels [17–19]. This facility includes a windowed stainless steel chamber (volume: 11.35 L), connected to a compressed argon cylinder and a vacuum pump. The pressure is recorded with a pressure transducer (Omegadyne PX-409-030AI). An infrared beam (wavelength: 10.55–10.68 µm, diameter: 2.0 ± 0.3 mm) of a CO_2 laser (Synrad Firestar ti-60) enters the chamber vertically through a zinc selenide 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.

During the experiment, the holder with the tiles and the mixture was placed inside the chamber. The infrared beam of the CO_2 laser was aligned with the mixture (see Fig. 2) using a red beam of a laser diode pointer (Synrad), pre-aligned with the infrared beam.