

## In-Situ Production of Construction Materials by Combustion of Regolith/Aluminum and Regolith/Magnesium Mixtures

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### INTRODUCTION

Future exploration missions to the Moon and Mars will involve construction of radiation shielding, landing/launching pads, and other structures on the lunar/planetary surface. The construction materials could be produced *in situ* from regolith by sintering at high temperatures, *e.g.*, using microwave radiation [1]. Heating the regolith to the required high temperatures, however, would require significant energy input.

An alternative approach involves combustible mixtures of regolith with some additives. Upon ignition of such a mixture, exothermic reactions, either between the additives or between the additive and regolith, cause self-sustained propagation of the combustion wave. Such a process is usually called self-propagating high-temperature synthesis (SHS), and it has been used for synthesis of numerous ceramic and other compounds [2-6]. Owing to high temperatures during the process, SHS in regolith-based mixtures may produce materials that are sufficiently dense and strong for the construction applications. An important advantage of this method is that a relatively small amount of energy is required for ignition, while the high temperatures during the combustion process are generated by the reaction heat release.

Combustion of triple mixtures containing lunar regolith simulant JSC-1, titanium (Ti), and boron (B) has been investigated recently [7, 8]. Note that the highly exothermic reaction between Ti and B is widely used in

SHS and pyrotechnics. The authors [7, 8] reported that the triple JSC-1/T/B mixture containing 60 wt% regolith simulant is combustible. A major problem with the addition of Ti and B, however, is the lack of boron in lunar or Martian soil. Also, the mineral containing Ti is present to a relatively low extent and large energy is required to extract Ti from regolith. Other pairs of exothermally reacting elements could be used instead of Ti and B but they also have similar problems.

Another approach is to use metals such as aluminum (Al) and magnesium (Mg), which have the potential to react with regolith. Indeed, these metals form combustible mixtures (“thermites”) with some metal oxides. The mineral composition of lunar and Martian regoliths is based on oxides of silicon and metals. Some of these oxides, including silica, can be reduced by Al or Mg. Thus, adding Al or Mg to regoliths may produce thermites. Combustion of these mixtures may lead to the formation of materials that could be used for construction applications.

Aluminum and magnesium can be recovered either from lunar/Martian regolith, or from used structures and parts of the vehicles, landers, *etc.* An interesting possibility is the use of hydrides  $\text{AlH}_3$  and  $\text{MgH}_2$  for hydrogen storage with subsequent utilization of Al or Mg for the reactions with regolith.

Recently, the combustibility of regolith/Al mixtures has been demonstrated experimentally [9, 10]. The authors mixed

lunar regolith simulants JSC-1A and JSC-1AF with Al powder. The concentration of Al was varied from 19.44 wt% to 33.33 wt%. The mixture samples were placed as a loose powder in aluminum-foil crucibles and ignited using a U-shaped Nichrome wire located inside the sample. The experiments were conducted in air at atmospheric pressure and in vacuum. Upon ignition, a vigorous reaction occurred and continued after turning off the igniter.

As noted above, along with Al, magnesium could be used as a reacting metal. To our knowledge, combustion of Mg/regolith mixtures has not been studied. Note that due to the non-protective oxide layer on the surface of Mg and a relatively low boiling point of Mg (1363 K at 1 atm vs. 2792 K for Al), it is usually easier to ignite Mg than Al. More specifically, the ignition of Al particles may require higher temperatures [11] or use of expensive nanoscale particles [12]. The ignition problems may be important in the combustion of lean metal mixtures, which are of interest for *in situ* resource utilization (the metal additive should be minimal).

In this paper, we calculate the adiabatic combustion temperatures and equilibrium product compositions for mixtures of JSC-1A lunar regolith simulant with Al and Mg. For comparison, we also conduct thermodynamic analysis for the regolith/Ti/B system. Finally, we report the results of combustion experiments with mixtures of JSC-1A and Mg. Note that for a larger density (and strength) of SHS products, pressed samples rather than loose powders should be used. Also, a cylindrical pellet, compacted using a hydraulic

press and ignited from the top (a typical configuration in SHS) provides excellent conditions for studying and modeling the combustion process. Thus, the present paper focuses on the experiments with pressed pellets.

## THERMODYNAMIC CALCULATIONS

The adiabatic flame temperature and combustion products for mixtures of JSC-1A lunar regolith simulant with Al and Mg at pressure of 1 atm were calculated using THERMO software, which is based on the minimization of the Gibbs free energy and includes thermochemical properties of approximately 3,000 compounds [13]. THERMO allows one to determine the equilibrium product composition for the given temperature and pressure as well as the adiabatic flame temperature and combustion product composition for the given pressure. This software has been used extensively in research on SHS and on the metal-CO<sub>2</sub> propulsion for Mars missions [11]. For the calculations, the mineral composition of JSC-1A lunar regolith simulant [14, 15] was slightly simplified. In particular, the glass composition was assumed to be identical to that of the crystalline part of the regolith and the concentrations of minor (<0.02 wt%) ingredients were neglected. The assumed composition is shown in Table 1. Since the database of THERMO software does not include albite and ferrosilite, the formation enthalpies of these compounds, -3,929.86 kJ/mol and -1,193.45 kJ/mol, respectively, were taken from Ref. 16.

Table 1. Mineral composition of the model regolith system used in thermodynamic calculations.

Mineral	Formula	Composition, wt%
Anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>	37.95
Albite	NaAlSi <sub>3</sub> O <sub>8</sub>	16.27
Orthoclase (K Feldspar)	KAlSi <sub>3</sub> O <sub>8</sub>	0.10
Wollastonite	CaSiO <sub>3</sub>	11.14
Enstatite	MgSiO <sub>3</sub>	10.58

Ferrosilite	FeSiO <sub>3</sub>	6.13
Forsterite	Mg <sub>2</sub> SiO <sub>4</sub>	13.02
Fayalite	Fe <sub>2</sub> SiO <sub>4</sub>	4.81
TOTAL		100.00

Figure 1 shows the obtained adiabatic flame temperatures ( $T_{ad}$ ) for the mixtures of the model regolith system with aluminum and magnesium. For Al, the maximum  $T_{ad}$ , 1566 K, is observed at 23 wt% metal. For Mg, the maximum  $T_{ad}$  is equal to the melting point of silicon, 1690 K, which is present in the combustion products. This temperature plateau is observed in the range from 26 wt% to 39 wt% Mg.

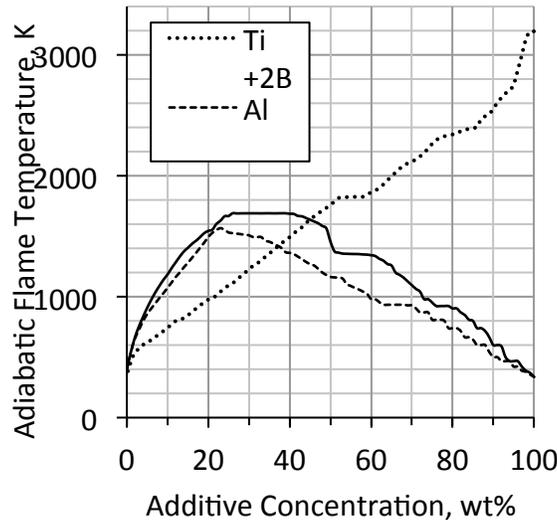


Fig. 1. Adiabatic flame temperature of the model regolith system with added Al, Mg, and Ti/B as a function of the additive concentration.

It is seen that Mg-based mixtures exhibit a higher  $T_{ad}$  than Al-based ones at all metal concentrations. Specifically, for lean metal mixtures,  $T_{ad}$  for Mg is higher by more than 100 K than that for Al in the range from 8 wt% to 17 wt% metal. The maximum  $T_{ad}$  for Mg is higher by 124 K than that for Al. These observations, as well as the aforementioned data on easier ignition of Mg particles [12], imply that Mg/regolith mixtures may burn better than Al-based ones.

The product compositions of the mixtures with 23 wt% Al and 26 wt% Mg are shown in Tables 2 and 3, respectively. The results for the Al-based mixture are in a qualitative agreement with the experiments [9], where Si, CaAl<sub>4</sub>O<sub>7</sub>, Ca<sub>2</sub>Al<sub>2</sub>SiO<sub>7</sub>, MgAl<sub>2</sub>O<sub>4</sub>, Al<sub>2</sub>O<sub>3</sub>, and FeSi were identified by X-ray diffraction analysis in the combustion products of JSC-1AF lunar regolith simulant mixed with 24.45 wt% Al.

Table 2. Combustion products of the mixture with 23 wt% Al.

Formula	Phase	Composition, wt%
MgAl <sub>2</sub> O <sub>4</sub>	Solid	31.81
CaAl <sub>4</sub> O <sub>7</sub>	Solid	30.24
Si	Solid	14.91

$\text{Ca}_2\text{Al}_2\text{SiO}_7$	Solid	8.58
FeSi	Solid	6.05
$\text{Al}_2\text{O}_3$	Solid	4.49
$\text{NaAlO}_2$	Solid	3.89
K	Gas	0.01
Na	Gas	0.01

Table 3. Combustion products of the mixture with 26 wt% Mg.

<b>Formula</b>	<b>Phase</b>	<b>Composition, wt%</b>
MgO	Solid	43.61
$\text{MgAl}_2\text{O}_4$	Solid	17.65
$\text{Ca}_3\text{MgSi}_2\text{O}_8$	Solid	16.04
Si	Solid	10.56
FeSi	Solid	5.82
$\text{CaMgSiO}_4$	Solid	3.99
Si	Liquid	1.16
Na	Gas	1.03
Mg	Gas	0.10
$\text{Na}_2$	Gas	0.02
K	Gas	0.01

We have also conducted thermodynamic calculations for the regolith mixed with the stoichiometric Ti/B mixture (Ti/B mole ratio is 1:2). Unfortunately, in the THERMO database, the number of compounds that contain Al, B, Ca, Fe, K, Mg, Na, O, Si, and Ti was so large that calculations were not possible. To select the compounds that can actually be present in the combustion products, we used HSC Chemistry 7 software [17]. This software includes properties of 25,000 compounds and can calculate the equilibrium composition for the given temperature and pressure. The adiabatic flame temperature, however, can be determined only if the product composition is known. Thus we used this software to identify the compounds that can be present in the combustion products and to decrease the number of selected compounds in THERMO database. The

equilibrium product compositions were determined for the regolith concentrations of 10 wt%, 60 wt%, and 90 wt% over the temperature range from 1173 K to 2173 K. The observed compounds were selected as possible combustion products in THERMO database. Then, the adiabatic flame temperature and product composition were calculated with THERMO. The obtained values of the adiabatic flame temperature are shown in Fig. 1. It is seen that at the additive concentrations of 23-26 wt%, which provide the maximum temperatures in the mixtures with Al and Mg, the temperature of the mixture with Ti and B is less by 500-600 K than the temperatures achieved with Al or Mg. Note that it is difficult to achieve self-sustained combustion in mixtures where the adiabatic flame temperature is as low as 1000-1300 K. To reach the temperature of 1566 K

(achievable with 23 wt% Al) or 1690 K (achievable with 26 wt% Mg), the regolith/Ti/B mixture should include 43 wt% or 47 wt% Ti/B pair, respectively. This comparison, along with the unavailability of B and Ti in space exploration missions, clearly indicates that research efforts should be focused on Al and Mg.

An additional advantage of using Al and Mg is the formation of silicon as a byproduct (see Tables 2 and 3). Silicon could be separated from the combustion products using its relatively low melting point (1690 K) and used for the fabrication of solar cells.

## EXPERIMENTS

The combustion experiments with Mg/JSC-1A mixtures were conducted in a windowed steel chamber. During the experiment, a pellet of

the tested mixture was installed on a brass pedestal and ignited at the top by an electrically heated Nichrome wire. The combustion process was observed using video recording. The experiments were conducted in argon at pressure about 90 kPa.

JSC-1A lunar regolith simulant was obtained from Orbitec. In the combustion experiments conducted with original JSC-1A powder, ignition was not achieved, apparently due to a large particle size of JSC-1A. To increase the specific surface area of this powder and thus increase the reaction rate between the regolith simulant and the metal, the former was ground in a ball mill. Figure 2 shows the influence of the milling time on the mean particle size, determined using a sieve shaker (Octagon 2000).

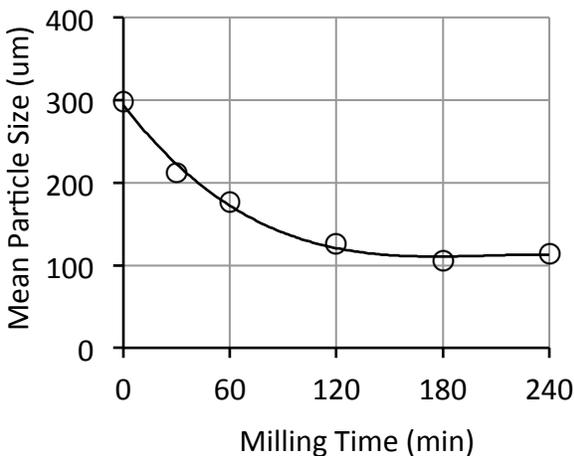


Fig. 2. The mean particle size of JSC-1A as a function of milling time.

Magnesium (-325 mesh, 99.8% pure) powder was obtained from AlfaAesar and used as received. The original and milled JSC-1A powders were mixed with Mg using the ball mill. The Mg concentration was 26 wt% in all tests. The mixture samples were compacted into pellets (diameter 1.3 cm, height 2.9-3.7 cm) using a hydraulic press.

The mixtures based on JSC-1A that was milled for two or more hours exhibited stable combustion. Figure 3 shows typical images of combustion front propagation over the Mg/JSC-1A mixture pellet. A relatively

uniform propagation of the combustion front is observed.

## CONCLUSIONS

Thermodynamic calculations of the adiabatic flame temperature and combustion products for the mixtures of JSC-1A lunar regolith simulant with Al, Mg, and Ti/B show that (1) at the additive concentrations of 20-30 wt%, Ti/B provides much lower adiabatic flame temperatures than Al or Mg and (2) Mg exhibits higher temperatures than Al. The maximum temperatures for Al and Mg are reached at 23 wt% and 26 wt%, respectively.

Stable combustion of Mg/JSC-1A mixture pellets in argon environment has been demonstrated experimentally.

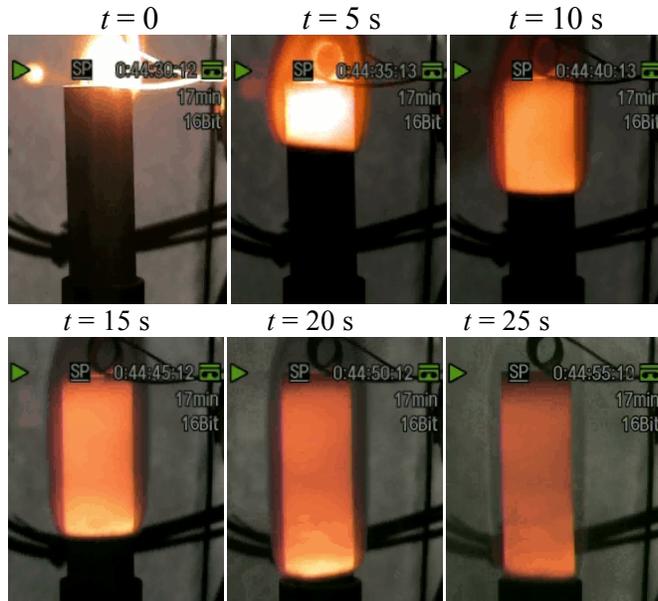


Fig. 3. Images of combustion front propagation over Mg/JSC-1A mixture (26 wt% Mg) in Ar atmosphere at 90 kPa. The milling time of JSC-1A: 240 min.

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