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Thermal oxidation analysis of aerosol synthesized fuel particles composed of Al versus Al-Si

Neil G. Vaz, I. Shancita, Michelle L. Pantoya*

Mechanical Engineering Department, Texas Tech University, Lubbock, TX 79409, United States

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ABSTRACT

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Keywords: Metal combustion Alloys Composites Ignition Melting Oxidation We compared the reactivity of spherical particles composed of aluminum (Al) and silicon (Si) with spherical particles of Al with similar size (nominal diameter $1-2 \mu m$). Both particles were synthesized using a liquid atomization technique such that both particles were encapsulated in a native oxide passivation shell. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) in inert and oxidative environments were performed coupled with X-ray Diffraction (XRD) for species identification. The results showed that incorporation of Si in the Al particles lowered the melting temperature by 85 °C and resulted in lower apparent activation energy for the oxidation reactions and more complete combustion at lower temperatures compared with pure Al powder. Results show promise for engineering fuel particles with minor alterations in metal formulation that promote more complete combustion and energy conversion.

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1. Introduction

Powdered metals are well-known for their use as fuels due to their high heat of combustion, flame temperature, and self-propagating exothermic reactions [1,2]. Metal alloys and composites have been gaining attention for their potential to enhance or customize combustion behavior by manipulating thermal or physical properties. For example, aluminum (Al) when mechanically alloyed with magnesium (Mg) showed more complete combustion because magnesium oxide (MgO) does not form an oxide cap that passivates the combusting material as does aluminum oxide (Al₂O₃) [3]. Aerosolized spherical Al–Mg particles have also been studied but shown to produce lower flame temperatures when compared to pure Al particles owing to the reduced heat of combustion associated with Mg [4]. Other alloy examples include ballmilled Al and zirconium (Zr) composites that were designed to regulate ignition temperature depending on the ratio of metals and their milling method [5]. Also, composite mixtures of Al and Si powders showed enhanced combustion performance such as shorter ignition delay time and faster flame propagation compared to Al powder [6]. Given the chemical potential energy of Si [6] and its effect on lowering the melting temperature of Al [7], adding Si to Al to form a composite particle shows promise in regulating metal combustion towards a lower ignition temperature and more complete combustion, without the cost of reduced potential energy.

* Corresponding author. *E-mail address:* michelle.pantoya@ttu.edu (M.L. Pantoya). This study examines the reactivity of Al and Al–Si particles that were aerosol synthesized to form spherical particles with a native oxide passivation shell. Physically the two particles are similar in size, distribution, core-shell architecture, with the only difference being the addition of Si in one case but not the other. This isolation of chemical composition uniquely allows for an investigation of how lower melting temperature influences reactivity. This study was designed to investigate the thermal and reactive properties of both particles in an inert and an oxygen-rich environment. Results were analyzed using activation energy calculations [8–11] to understand the mechanisms favored between the two fuel particles.

2. Materials and methods

2.1. Materials

Aluminum, Al, (nominal size $1-2 \ \mu m$ diameter, Product Number 0230HJ) and Al–Si (nominal size $1-2 \ \mu m$ diameter, Product Number 0271DX) particles were procured from Skysprings Nanomaterials (Houston, TX, USA). Particle size distributions were analyzed using a NI Comp 3000 static particle size analyzer with distilled water as the scattering medium and found to be similar to the supplier's specifications. The size distributions for the two powders were comparable to each other and shown in Fig. 1. Particle size analysis was also conducted for the heated products post oxidation for comparison of the powders physical changes upon oxidation.









Fig. 1. Intensity-weighted size distributions showing similar sizes of Al–Si composite particles (nominal size $1-2 \mu m$) with open bars and Al particles (nominal size $1-2 \mu m$) with shaded bars. Picture Type: Color in online version, black and white in print, 1 column size.

The particles were synthesized by heating pure bulk materials to elevated temperatures such that liquid atomization formed solid particles that have an amorphous aluminum oxide passivation shell surrounding the metal core. Al-Si particles atomization was completed at 900 °C and the Al particles at 800 °C. The Al-Si particles were synthesized with a manufacturer reported purity of 11-13 wt% Si and 87-89 wt% Al. Also, from the phase diagram for Al and Si, the eutectic transition for Al-Si alloys occurs at 12.2 wt% Si and causes a reduction in melting temperature to 577 °C [7]. The melting temperature of our powder is 574 °C and suggests that the composition corresponds closely to the eutectic composition of 12.2.wt% under equilibrium conditions. X-Ray Diffraction (XRD) confirmed the presence of Al and Si in the Al-Si particles in a proportion of 92.7 wt% Al and 7.3 wt% Si. Given the Si concentration measured via XRD and the melting temperature reduction, the internal microstructure of the particles is expected to be of dendritic morphology, similar to a recent study on spherical Al-Si particles that were consolidated into projectiles and used for ballistic impact testing [12].

Powder X-Ray Diffraction (XRD) data was collected using a Rigaku MiniFlex II powder diffractometer operating in continuous θ -2 θ mode from 3°/5°- 70° with Bragg-Brentano beam geometry. The step size was 0.02° with a collection time of $1-3^{\circ}$ /min. Powder samples were mounted on zero-background holders. The X-ray source was Cu K α radiation ($\lambda = 1.5418$ Å) with a current of 15 mA and an anode voltage of 30 kV. Diffraction intensities were captured on a position sensitive D/ teX Ultra 1D silicon strip detector. Data were analyzed for Whole Pattern Fitting/Rietveld refinements with MDI Jade-X v7.7 software and the ICDD PDF 4+ database to produce both a qualitative and semiquantitative analysis of crystalline species. Powder XRD patterns of Al and Al-Si powders in Fig. 2 show Al powder had 100 wt% Al purity and Al-Si powder had 92.7 wt% Al and 7.3 wt% Si, but the manufacturer reported purity for Al-Si powder was 87-89 wt% Al and 11-13 wt% Si. The XRD data files with Rietveld refinement analysis for as-received Al and Al-Si powders are provided in Supplementary Information Figs. A.1-A.2. Powder XRD was also performed on heated products recovered from DSC-TGA experiments. The XRD data files for the product residue are included in Supplementary Information Figs. A.3-A.8.

Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) were conducted on Al and Al–Si powders to analyze their morphology and microstructure. The SEM images of as-received particles were captured at 10 kV with a Phenom Pro Desktop SEM (ThermoFisher Scientific) to illustrate their size and morphology. The TEM images were captured to resolve the shell thickness of as-received Al and Al–Si particles using a Hitachi H-9500 at 300 kV accelerating voltage. Both powders appeared to have similar shell thickness and structures. Heated products recovered from DSC-TGA



Fig. 2. Diffraction patterns and wt% composition from XRD analysis of Al and Al–Si asreceived powders. Peaks are labeled using the database provided in MDI Jade-X v7.7 software. Details of peak fitting using whole pattern Rietveld refinement are included in *Supplementary Information* Figs. A1-A2. Picture Type: Color in online version, black and white in print, 1 column size.

experiments were imaged using a Zeiss Crossbeam 540 at 10 kV to analyze particle morphology and surface features.

2.2. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA)

The DSC and TGA experiments were conducted on Al and Al–Si particles using a NETZSCH STA 449 F3 Jupiter which simultaneously measured heat flow (DSC) and mass change (TGA). The DSC calibration was done with indium, tin, bismuth, zinc, aluminum, silver and gold. The TG calibration was done with calcium oxalate. Melting point and sensitivity of the DSC and weight loss in TG matched the literature values within \pm 1%. Enthalpy values were determined per mass of powder sample.

Heating of approximately 10 mg powder samples in open alumina crucibles was examined in inert and oxidative environments. The first series of experiments examined melting behavior of the two powders in an inert argon environment. In the melting experiments, initially the chamber was flushed with argon for 30 min at a constant temperature of 25 °C followed by heating at 10 °C/min up to 800 °C, then a cooling cycle at 10 °C/min to 25 °C followed by another heating cycle. The initial flushing and repeated heating cycle allowed time for removal of residual gases and subsequent reactions with the particles.

The second series of experiments examined oxidation of the two powders in an oxygen-rich environment consisting of 80 vol% O_2 and 20 vol% Ar at a heating rate of 10 °C/min for a temperature range of 25–1400 °C, and experiments were performed in triplicate. All data were processed with Netzsch Proteus software to determine onset temperatures and enthalpy. The difference in mass gain and thus in rate of oxidation is statistically significant with a *p*-value less than 0.05 in the temperature ranges 584 °C – 1003 °C and above 1023 °C -1288.5 °C. The heated products from these experiments were examined using XRD and the diffraction patterns were further analyzed with whole pattern fitting Rietveld refinement to ascertain weight composition of these products.

To examine the stages of oxidation and resolve kinetics more carefully, two additional heating experiments in the same oxidative environment were programmed for a single heating cycle of 10 °C/min from 25 °C to 700 °C and also from 25 °C to 1100 °C with subsequent

XRD analysis on the recovered heated products. These heating cycles coupled with XRD analysis allowed evaluation of product species formed during the exothermic events that occurred within these temperature ranges.

Additionally, heating rates of 5 °C/min, 15 °C/min and 20 °C/min in the same oxidative environment were conducted for TGA data to analyze the apparent activation energy using a Kissinger kinetic analysis method [9–11].

3. Results

Fig. 3a and b show SEM images of Al and Al–Si particles that have similar spherical shape. Particle size analyses (Fig. 1) show similar size distributions with each having a peak intensity at ~1 μ m diameter. Fig. 3c and d show TEM images of Al and Al–Si particles. The Al–Si particles have an outer shell similar to Al particles that would suggest analogous combustion dynamics. Such combustion dynamics include diffusion through various polymorphs of the alumina shell that is a function of temperature [8]. The imaging and size distribution measurements were performed to ensure that variations in oxidation dynamics may be attributed to differences in composition (i.e., one powder includes Si while the other is purely Al) rather than physical properties such as size, morphology, or passivation shell structure.

Fig. 4 shows the DSC data (Fig. 4a) and corresponding TGA data (Fig. 4b) for melting behavior associated with Al and Al–Si particles. The Al–Si particles have a lower onset melting temperature (574 °C) than Al particles (659 °C), consistent with the reduced melting temperature from the Al–Si phase diagram [7]. The melting enthalpy of Al–Si is -815.4 J/g and about twice that of Al (-396 J/g). Given that the melting enthalpy of Si is -1787 J/g [13], for a mass fraction of 7.3% Si in Al–Si, the mixing enthalpy of melted Al–Si is -317.281 J/g. No mass change was

observed in the melting experiments, as expected in an inert environment without oxidation reactions.

Fig. 5 shows DSC data (Fig. 5a), corresponding TGA data (Fig. 5b), and the differential of the TGA data, i.e., Derivative Thermogravimetry (DTG) (Fig. 5c) in the oxygen-rich environment for Al–Si and Al particles. In both particle types there is overlap between melting and the first exothermic event (Fig. 5a). In the first exothermic event, the enthalpy is higher for Al-Si at 1125 J/g compared with 862.2 J/g for Al. For Al, the melting temperature and endotherm fall towards the downslope of the first oxidation reaction, while for the lower temperature melting Al-Si particles, the endotherm falls on the upward slope of the oxidation reaction. Therefore, the first stage of oxidation initiates in the solid phase for Al-Si powder, but further reaction ensues in the liquid phase. In contrast, for Al particles the first stage of oxidation also occurs in the solid phase, but the liquid phase does not manifest until later in the reaction. The higher enthalpy in the first stage of Al-Si reaction is attributed to greater diffusion of fuel with oxygen in the Al-Si particles. The first stage of oxidation is faster for Al-Si prior to melting but the rate of mass gain tapers off earlier for Al-Si, likely due to earlier formation of the limiting oxide barrier retarding further oxidation

At higher temperatures, there is a second exothermic event for both powders in Fig. 5a. For the Al particles, the onset temperature of the second exothermic event is 732.9 °C with enthalpy 9405 J/g. For the Al–Si particles, the onset temperature occurs earlier at a temperature of 710.1 °C and the exothermic event has an enthalpy of 9778 J/g, higher than for the Al particles. The TGA data in Fig. 5b indicates that more oxygen reacts with Al–Si than Al because there is a larger mass gain in Al–Si particles. In fact, Fig. 5b shows two stages of mass gain for both particles coinciding with the two exothermic events in Fig. 5a. This is also consistent with the XRD results shown in Fig. 6, particularly at 1100 °C where there is the largest difference between Al and Al–Si in



Fig. 3. SEM pictures showing similar size distributions of (a) Al–Si particles (nominal size 1–2 µm) at 24,500× magnification and 10 kV accelerating voltage (b) Al particles (nominal size 1–2 µm) at 18,500× magnification and 10 kV accelerating voltage. Also included are TEM pictures at 200,000× magnification and 300 kV accelerating voltage of (c) Al–Si particles and (d) Al particles. Shell thickness surrounding both particles is on average ~ 4 nm. Picture Type: Black and white in online and print version, 2 column size.



Fig. 4. (a) DSC heat-flow data for melting of Al and Al—Si powders in Ar environment. (b) Corresponding TGA data showing unchanged mass for Al and Al—Si powders in Ar environment All experiments were performed at a heating rate of 10 °C/min. Picture Type: Color in online version, black and white in print, 2 column size.

terms of unreacted Al. Specifically, in Fig. 6a for Al particles there is more unreacted Al consistent with lower mass gain associated with Al oxidation observed in Fig. 5b. In Fig. 5a. Only Al powder exhibits a third exotherm and corresponding mass gain signifying additional oxidation beginning at ~1100 °C; a third exotherm is not observed for Al–Si powder ostensibly due to oxidation of Al–Si being complete at the end of the second exothermic stage. The third stage oxidation results in Al particles having very little unreacted Al remaining at the end of the



Fig. 5. (a) Average of triplicate scans for DSC heat-flow data showing oxidation of Al and Al—Si powders. (b) Corresponding TGA data showing mass gain from oxidation of Al and Al—Si powders. (c) DTG for Al and Al—Si powders showing distinct stages of oxidation. All experiments were performed at a heating rate of 10 °C/min in 80 vol% O₂: 20 vol% Ar environment. Picture Type: Color in online version, black and white in print, 2 column size.



Fig. 6. Diffraction patterns and wt% composition from XRD analysis of Al and Al—Si powders recovered after heating in the DSC-TGA to a) 700 °C b) 1100 °C and c) 1400 °C, then cooled to ambient temperature. Peaks are labeled using the database provided in MDI Jade-X v7.7 software. Greek symbols (γ , Θ , α) indicate phases of alumina (Al₂O₃). Details of peak fitting using whole pattern Rietveld refinement are included in *Supplementary Information* Fig. A3-A8. Picture Type: Color in online version, black and white in print, 2 column size.



Fig. 7. Apparent activation energy graph from TGA data with stages of oxidation identified as (1), (2), and (3) with associated curve fit equations. Note stage (1) has two parts (1a) and (1b) on top curve. Picture Type: Color in online version, black and white in print, 2 column size.

Table 1

Comparison of stage-wise apparent activation energies of Al and Al—Si during DSC/TGA oxidation from Fig. 7.

Stages identified in Fig. 7	Stage of oxidation	Activation Energy (kJ/mol)	
		Al	Al-Si
1 a	Stage 1a	473.8	342.3
1 b	Stage 1b		686.0
2	Stage 2	201.3	195.1
3	Stage 3	215.5	

experiment (Fig. 6), i.e., oxidation reaching levels close to that seen in Al–Si particles.

The XRD patterns of the recovered heated products are shown in Fig. 6. The results suggest Si may not chemically participate in combustion because there is not much change in Si concentration between reactant (Fig. 2b) and product (Fig. 6b) and no SiO_2 peaks were detected in the heated products. It is noted however that SiO_2 may be in an amorphous phase and therefore not detectable by XRD.

An analysis of apparent activation energy for the various stages of oxidation is shown in Fig. 7 based on the TGA data in Fig. 5b. Apparent activation energies calculated from Fig. 7 that correspond to the main stages of oxidation (Fig. 5b) are listed in Table 1. Apparent activation energy is calculated from Fig. 7 using Eq. (1) based on an analysis detailed in Dreizin et al. [8].

$$E_a/RT - c = -\ln \left(\Delta m/\Delta t\right) - \ln \left(f(r_i, r_0)\right) \tag{1}$$

In Eq. (1), E_a is apparent activation energy, R is universal gas constant, c is a constant, T is absolute temperature, $\Delta m/\Delta t$ is the rate of change of mass with time and $f(r_i, r_0)$ is a function of inner radius (r_i) and outer radius (r_0) of the growing alumina layer such that $f(r_i, r_0) = m/m_0-1$, where m_0 is the initial mass. In Fig. 7, Y(TGA) is the right-side of Eq. (1) which when plotted against the inverse of temperature provides a straight line fit for the oxidation stages as demarcated in Fig. 7 and Table 1. The slope of the straight-line fit provides the apparent activation energy for each oxidation stage.

For the first stage of oxidation, Al–Si initially has a lower apparent activation energy than Al (prior to Al–Si melting) but towards the end of the first stage, there is an inflection in the curve fitting and Al–Si shifts to a higher apparent activation energy. The switch from low to high apparent activation energy for Al–Si is likely due to initially more enhanced oxidation of Al–Si that generates an oxide barrier hindering further oxidation compared with the slower oxidation of Al particles.



Fig. 8. Multiple heating rates for oxidation of Al powder showing mass gain and rate of mass change, respectively a) TGA data b) DTG data. Similar multiple heating rates for oxidation of Al–Si powder showing c) TGA data d) DTG data. All experiments were performed in 80 vol% O₂: 20 vol% Ar environment. Picture Type: Color in online version, black and white in print, 2 column size.



Fig. 9. Kissinger kinetic analysis for determination of apparent activation energy based on peak rate of mass change for overall process, which corresponds to the peak for the second stage of oxidation. Picture Type: Color in online version, black and white in print, 1 column size.

Table 2

Comparison of apparent activation energies based on Kissinger kinetic analysis of Al and Al—Si TGA/DTG data.

Heating Rate (β) (°C/min)	Peak Temperature (T _p) (K)		Apparent Activation Energy (kJ/mol)	
	Al	Al-Si	Al	Al-Si
5	1249.3	1155.0	405.8	138.8
10	1269.1	1202.7		
15	1270.7	1236.0		
20	1293.0	1260.6		

For the second stage of oxidation, the apparent activation energy for Al–Si is once again lower at 195.1 kJ/mol for Al–Si compared with 201.3 kJ/mol for Al and corresponds well with the faster mass gain and oxidation in Al–Si seen in the TGA/DTG data in Fig. 5. It is noted that Al has a third oxidation phase with an apparent activation energy of 215.5 kJ/mol.

Further TGA data at multiple heating rates of 5 °C/min, 10 °C/min (average of triplicate runs), 15 °C/min and 20 °C/min (Fig. 8) were collected for a Kissinger kinetic analysis [9–11] (Fig. 9, Table 2) calculated according to Eq. (2).

$$\ln \left(\beta/T_{p^2}\right) = c - E_a/RT_p \tag{2}$$

In Eq. (2), β is TGA heating rate and T_p is the absolute temperature of peak rate of change of mass for the overall mass gain process (which corresponds to the peak for second oxidation stage). Other variables were previously defined from Eq. (1).

The results show that Al–Si powder has a lower apparent activation energy of 138.8 kJ/mol compared with Al powder of 405.8 kJ/mol. Overall, the multiple heating rate curves shown in Fig. 8 exhibit the general trend, as expected, of a slight shift towards oxidation at lower temperatures with reduced heating rate, consistent with lower heating rates allowing more time for oxidation to occur.

Fig. 10 shows SEM images of heated products recovered from the DSC-TGA experiments for both powders and Fig. 11 shows the corresponding particle size distributions. Both heated products show more particles of a larger and smaller size compared to as-received powders (Fig. 1) but Al appears to have a broader size distribution than Al–Si. There may be more agglomeration in Al than Al–Si. Fig. 10 also shows ruptured, fragmented particles in both powders recovered.

4. Discussion

It is interesting to compare the stages of exothermic reaction and mass gain observed in both Al and Al–Si seen in Fig. 5. For Al–Si powder there are two stages of exothermic activity while for Al powder there are three stages, indicating Al–Si powder oxidation is more efficient than Al.

The first stage corresponds to a small mass gain of 5.45 wt% or 7.7 wt % for Al or Al–Si, respectively. This initial mass gain begins below the melting temperature and overlaps with melting for both the Al and Al–Si particles (Fig. 5). For Al particles, partial onset of oxidation has been observed at temperatures lower than melting and facilitated by changes in the phase of the Al₂O₃ passivation shell [8,14–16]. The phase transitions include a change from amorphous to crystalline (γ)



Fig. 10. SEM images of heated products from a) and b) Al powders, and c) and d) A-Si powders. All images show spherical morphology of the product powders with ruptured particles and agglomeration. Picture Type: Black and white in online and print version, 2 column size.



Fig. 11. Intensity-weighted size distributions of heated products of Al (shaded bars) and Al—Si (open bars) after oxidation in DSC-TGA and cooling to room temperature. Picture Type: Color in online version, black and white in print, 1 column size.

phase which can account for majority of oxidation of nano-sized particles at lower temperatures <650 °C. At higher temperatures, mass gain is attributed to oxide growth and transition between crystalline phases - mainly γ and α [8]. It must be noted that nano-sized Al particles' oxidation at temperatures between 500 and 650 °C [16–18] can occur in the solid phase. Eisenreich et al. [17] showed that the rate of mass gain as a function of temperature is a strong function of Al particle size, with smaller particles exhibiting faster mass gain rates that can occur below the Al melting temperature for nano-sized particles. For Al particles that are non-spherical, Esposito et al. [18] showed that smaller crystallite sizes exhibited earlier onset of oxidation. Since both the Al and Al–Si powders studied here have similar size distributions and morphology, the variations in mass gain are likely related to the inclusion of Si in one powder and not the other.

As evidenced by the slope of mass gain in Fig. 5c, the first stage of exothermic oxidation (Fig. 5a) and mass gain (Fig. 5b) occur at a faster rate for Al–Si than Al powders. Faster kinetics are confirmed in Fig. 6 for Al-Si demonstrating a lower initial apparent activation energy compared to Al powder. The differences in reactivity are attributed to factors other than particle size or morphology because the two powders show similar physical features (Figs. 1, 3). Initially the first stage of oxidation occurs prior to melting, therefore the presence of Si may enhance oxidation in the solid phase by enabling more ion mobility to facilitate transport of fuel and oxygen towards each other. From a thermodynamic perspective, as the alloy approaches melting, transport properties promote diffusion as evidenced by lower apparent activation energy (Figs. 7, 9) and generally faster kinetics. Nano-scale particles have been reported to experience inward diffusion of oxygen [19] and micron-scale particles experience outward diffusion of metal [20]. However, the reaction is limited in the first stage such that oxidation is likely restricted to the outer radii of micron-scale particles. Once the oxide barrier grows, further oxidation is paused until higher temperatures. The growth of the limiting oxide barrier is reached earlier in Al-Si as evidenced by the earlier tapering of the TGA data (Fig. 5 b, c) and higher apparent activation energy for Al-Si towards the end of the first oxidation stage (Fig. 7).

The second stage of exothermic oxidation occurs at elevated temperatures because there exists a greater diffusion barrier between the core fuel and surrounding oxidizer owing to the first stage of oxidation inducing shell growth. The second stage begins at temperatures greater than 700 °C (Fig. 5) and accounts for the bulk of oxidation with greater oxidation rates for Al–Si than Al (Figs. 5c, 7, 9). Once again, Al–Si oxidizes shows faster kinetics because the lower melting temperature of Al–Si facilitates ion mobility and mass diffusion relative to pure Al powder resulting in a lower activation energy for Al–Si versus Al (Table 1). The third stage of oxidation is only apparent for Al powders. In comparison, Al–Si oxidation reaches near completion at a lower temperature than Al powder and Al–Si does not exhibit a third stage of oxidation. Therefore, the addition of Si to Al in the form of an alloy results in more efficient combustion with more conversion to product species (Fig. 6) than can be achieved at a lower temperature under slow heating rate conditions.

It is noted that mass gain above the melting temperature may also be affected by the change in available surface area. Fig. 10 shows particles larger than as received. Also, particle size distributions of heated products show a broader size distribution than as received powders (Fig. 11), consistent with observations from the images in Fig. 10. Molten Al may coalesce and solidify into larger spherical particles with a decreased specific surface area that would result in slower oxidation and smaller observed mass gain. For Al–Si particles, the presence of Si may inhibit the coalescence of molten Al. Generally, both powders maintain a spherical shape though some particles are ruptured. There is evidence of hollow particles, confirming that metal diffuses outwards and that the reaction interface is on the outside of the particles similar to prior observations for micron-scale spherical Al particles [20,21]. There is also evidence of agglomeration between particles which can reduce the reactive interface and slow oxidation.

5. Conclusions

Particles composed of 93 wt% Al and 7 wt% Si show more efficient combustion compared with similarly sized Al particles based on analysis of reaction enthalpy, mass gain, kinetics, product species concentrations, activation energy and physical properties of heated products. Microscopy analysis of heated products show spherical particles similar to reactant morphology and indicate that the reaction mechanism for both powders is controlled by diffusion through the oxide shell barrier. An analysis of activation energy of the oxidation processes shows lower activation energies for Al–Si than Al corroborating improved oxidation for Al–Si. Overall, this study shows that the lower melting temperature of Al–Si enhances diffusion of the fuel with oxygen at lower tempeartures and promotes more complete and more exothermic combustion.

Declaration of Competing Interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary material.

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Neil G. Vaz has a Master's degree in Mechanical Engineering from Texas Tech University and is currently pursuing a Ph.D. at Texas Tech University, focused on the study of metal powders. Prior to joining Texas Tech, he worked as a Mechanical Engineer for close to 7 years upon completion of his Bachelor of Technology in Mechanical Engineering at Government Rajiv Gandhi Institute of Technology. Neil's research interests include alloys and the thermodynamics of metal combustion.



Shancita has completed her B.Sc. and MEng.Sc degree in Mechanical Engineering from Bangladesh University of Engineering & Technology, Bangladesh and University of Malaya, Malaysia in 2013 and 2016, respectively. Currently, she is working as a graduate research assistant in Combustion Lab of Texas Tech University, Lubbock, TX, and enrolled as a Ph.D. student at the Department of Mechanical Engineering. Her research interests are in surface chemistry of metal fuels, thermal analysis, particle process and micron and nano materials.



Dr. Pantoya holds a PhD and an MS in Mechanical Engineering, as well as a BS in Aeronautical Engineering from the University of California, Davis. She is the J. W. Wright Regents Endowed Chair Professor at Texas Tech University. Over the course of her career, Dr. Pantoya has conducted extensive research focusing on a variety of topics rooted in the synthesis and characterization of solid fuel systems and their energy generating behaviors.