Thermal behavior and combustion performance of Al/MoO₃ nanothermites with addition of poly (vinylidene fluorine) using electrospraying

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Abstract
To investigate the effect of the addition of poly (vinylidene fluoride) (PVDF) on nanothermites, Al/MoO₃/PVDF energetic nanocomposites were prepared using electrospraying method. As a control group, Al/MoO₃ was also designed. Then, both samples were tested by FE-SEM, XRD and TG-DSC. TG-DSC results showed that the Al/MoO₃/PVDF energetic nanocomposites released more than 934.0 J g⁻¹ with two obvious exothermic peaks. Compared with the control group of 800.7 J g⁻¹ heat, it changed the thermal performance to some extent. There were Mo₂C among the residues products after the reaction via XRD. The activation energy (Ea) was analyzed using the Kissinger method under different heating rates by DSC. The addition of PVDF reduced the Ea of the thermites. To explore the combustion performance, a preliminary experiment was designed. The Al/MoO₃/PVDF energetic nanocomposites were easier to ignite and the burning was more durable, which was significant in solid propulsion and applications requiring extended combustion time.

1. Introduction

With the development of nanotechnology, nanothermite, as a high-energy material containing metal oxidant and fuel, has short diffusion distance, large contact area and good uniformity, which has aroused widespread concern [1–4]. It has a lower ignition temperature, better reactivity and faster propagation speed, which is significantly better than traditional thermite. Carrying out a powerful redox reaction in a short time, it can be applied in ammunition primer, [5] nano welding, [6] gas generator [7] and explosive propellant [8, 9].

Preparing a more homogeneous structure and reducing the diffusion distance between fuel and oxidant help improve the thermal performance of thermite, which has attracted many scholars to study. For example, Kim [10] and Zachariah realized the directional assembly and close contact between fuel and oxidant using the electrostatically enhanced method. This approach intensifies the interaction and improved the reactivity of energetic nanocomposites. Wang [11] and his co-authors chose sol-gel technology to prepare Al/Fe₂O₃ nanocomposites. The results showed that the Fe₂O₃ particles fabricated by the sol-gel method could successfully encapsulate nano-Al, avoiding the oxide film’s generation. However, this method had many influencing factors. Some of them were difficult to control. Besides, Ke Xiang and co-authors [12] used the magnetron sputtering method to prepare CuO/Al core/shell structured nanothermites with stable combustion process and flame propagation speed. The good thermal performance and excellent energy retention performance had been proved. Further, Song [13] and his co-authors added potassium perchlorate (KClO₄) to the Al/MnO₂ nanothermites system by electrospray method, which effectively reduced the activation energy of the thermite system. Wang and his co-authors successfully prepared Al/CuO, Si/CuO nanothermites with core–shell…

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structure by self-assembly method and electrophoretic deposition method, which showed excellent thermal performance [14–16].

Zhou [17] filled the micron and nanometer passivated aluminum particles with PVDF to make composite materials, which significantly improved the thermal conductivity and relative dielectric constant. This phenomenon is the free electron transport of aluminum metal particles, which are embedded in the PVDF matrix, forming a uniform and dense microstructure. Fluorine, as the most abundant halogen, is the most electronegative and non-polarizable element known at present. The nature of its chemical bond reflects the physical properties of a fluoropolymer. C-F bond is the strongest single key inorganic substances (450 kJ mol$^{-1}$) and more than 100 kJ stronger than a C-Cl bond, so its reactivity is reduced by more than 100 times. The addition of a fluoropolymer can also bring some other excellent properties, such as moisture resistance and super-hydrophobicity [18]. To explore new fluoroplastic materials, throughout the 1950 s, researchers studied and prepared many fluoropolymer mixtures, fluorinated ethylene propylene (FEP), which was TFE’s first copolymer [19]. The following year, polyvinyl fluoride (PVF) and PVDF were created, the former with one type of fluorine and the latter with two types of that. Nevertheless, in terms of solubility, most fluoropolymers are insoluble, but PVDF has great solubility in polar organic solvent dimethylformamide (DMF), [20] so it is most commonly used. Song [21] prepared Al/MnO$_3$/PVDF using an electrostatic spray. The activation energy of the thermite system has significantly been reduced. Li [22] synthesized Al/PVDF/CuO composites using solvent synthesis and explored its properties.

Molybdenum trioxide (MoO$_3$) has unique electrochemical, catalytic and environmental characteristics, excellent electrochemical colour development and electrocatalytic function, which is widely used in battery material research [23]. Compared with CuO, Fe$_2$O$_3$ and MnO$_2$, the enthalpy of Al/MoO$_3$ thermite reaction is the highest when MoO$_3$ is used as a metallic oxidizer in the thermite system, according to the stoichiometric ratio [9]. What is more, the Al/MoO$_3$ composites can provide more remarkable ignition characteristics. Wolenski, C and his co-authors [24] engineered the composition and morphology of particles in the Al-NP/MoO$_3$ thermite system. The results showed that this method could promote an enhanced response and adjust the combustion behavior.

In this work, as a binder, PVDF was added to the Al/MoO$_3$ nanothermites system to explore its impact on combustion and thermal performance. Firstly, the Al/MoO$_3$ nanothermites were fabricated by ultrasound method. Then, based on the role of PVDF binder, PVDF was uniformly dispersed into Al/MoO$_3$ by electrospay method to prepare Al/MoO$_3$/PVDF energetic nanocomposites. At the same time, Al/MoO$_3$ also was prepared as the control group. Next, the Al/MoO$_3$ nanothermites and Al/MoO$_3$/PVDF energetic nanocomposites were characterized and tested by Field Emission Scanning Electron Microscope (FE-SEM), x-ray diffraction (XRD) and Thermogravimetric Analysis and Differential Scanning Calorimetry (TG-DSC). To calculate and discuss their activation energy, DSC was implemented at different heating rates. In the end, the preliminary combustion test was designed to observe the actual combustion performance of the thermites.

2. Experimental

2.1. Materials

All chemicals were analytical grade reagents and were used directly without any treatment or purification. Nano-Al (∼100 nm) was obtained from Aladdin Industrial Corporation (Shanghai, China). Nano-MoO$_3$ particles (∼50 nm) were purchased from Nano Chemical Technology Co., Ltd (Guangzhou, China). The energetic additive, PVDF was supplied by Sinopharm Chemical Reagent Co., Ltd. And the molecular mass of PVDF was 476 $\times$ 10$^3$ g mol$^{-1}$. Besides, the absolute ethanol and DMF were obtained by Nanjing Chemical Reagent Co., Ltd. Deionized water, absolute ethanol as well as DMF were chosen as solvent and dispersant.
2.2. Precursor preparation
At first, ultrasonic mixing method was applied to synthesis the Al/MoO₃ nanothermites. According to the stoichiometric ratio, 62 mg of MoO₃ and 38 mg of nano-Al (considering the effect of aluminum oxide layer) were magnetically stirred in cyclohexane for about 30 min. At the same time, 43 mg of PVDF was dissolved in 1 ml of DMF. Then, the PVDF/DMF solution was poured into the Al/MoO₃ solution under ultrasonic conditions. The mixed solution appeared black without precipitation. 43 mg of PVDF accounts for 30 wt% of the total solution mass of 143 mg. Also, Al/MoO₃ thermite without PVDF additive was prepared as an experimental control group.

2.3. Electrospray experiment
As shown in figure 1, the precursor solution was contained in a syringe with a flat needle whose diameter was 0.42 mm at the end. A syringe pump was used to apply a flow rate of 4.0 ml·h⁻¹, and a voltage of 13.5 V was applied between the nozzle and the receiving plate (a square aluminum foil with a side length of 30 cm) to form the Taylor cone. The distance between the nozzle and the receiving plate was about 10 cm. The relative humidity of the experimental environment was 75%.

Under the action of a strong electrostatic field, the precursor liquid advanced through the nozzle, and the nanoparticles adhering to the charged droplets were accelerated by the electric field and formed a Taylor cone. Because the electrostatic force was bigger than the liquid’s molecular cohesion, the sprayed liquid broke into a large number of small droplets. Simultaneously, the solvent evaporated quickly, leaving concentrated nano-solid particles diffused to the receiving plate to form uniform, highly polymerized thermite composites. Finally, a scraper was used to collect the deposits on the receiving plate and installed it in an anti-static bottle.

2.4. Characterization and thermal analysis
The MoO₃ sample phase structures and chemical reaction composition were characterized by using XRD analysis (Bruker, D8 Advance, Germany) with CuKα radiation (λ = 0.1542 nm). The morphology, particle size and mixing quality of the materials and mixture were observed by FE-SEM analysis (HITACHI High-Technologies corporation, S-4800II, Japan).

TG-DSC (NETZSCH STA 449F3, Germany) analysis was applied to investigate both components and thermite samples’ thermal behaviours. All the experiments were conducted under the argon atmosphere with the heating rates of 15 K min⁻¹ with the temperature range from 40 °C to 1000 °C. To further calculate the activation energy, in a corundum crucible, a sample with a mass of about 5 mg was heated through the DSC at a heating rate of 10, 15, 20, 25 K min⁻¹.

2.5. Theoretical model
As one of the most famous isoconversional methods, the reliable Kissinger method was accessed to obtain the Ea of Al/MoO₃. The Kissinger method of the model equation can be provided as follows [27, 28].

\[
\ln \left( \frac{\beta}{T_p^2} \right) = \ln \frac{AR}{E_a} - \frac{E_a T_p}{R}
\]

Where \( \beta \) is the linear heating rate (K min⁻¹), \( T_p \) the absolute temperature (K), \( R \) the gas constant (J mol⁻¹ K⁻¹), \( A \) the pre-exponential factor (s⁻¹) and \( E_a \) is the activation energy (kJ mol⁻¹).

The plot of \( \ln \left( \beta/T_p^2 \right) \) Versus 1/T should be a straight line when hypothesizing that the rate of reaction reaches the maximum at the peak temperature, and the slope can be considered as the value of the activation energy \( E_a \).
2.6. Preliminary combustion tests

The potential energy capacity of thermite can be characterized by thermal analysis, while the combustion performance is an indicator that reflects the actual properties, which is essential for practical applications.

Heating wire ignition experiments tested the burning characteristics of samples. The heating wire diameter was 0.1 mm, which was heated by a DC power supply to ignite 8 mg samples. A high-speed camera (FAST CAM-AZ) was used to record the combustion processes with a sampling rate of 20,000 frames per second and a frame size of approximately 1024×512 pixels. The aperture value was adjusted to 6.4. The schematic diagram of the experimental device is shown in figure 2.

3. Results and discussion

3.1. Results of nano-MoO$_3$

To explore the properties of the samples, XRD was used to test the phase structure, and SEM was introduced to observe the morphology.

**XRD analysis**

The XRD pattern of the sample is shown in figure 3. The sample shows the diffraction peaks from 5° to 90° can be attributed to MoO$_3$ (ICSD No. 76–1003 MDI Jade 6.0). The diffraction pattern for the samples have six broad
Figure 5. XRD pattern of the samples.

Figure 6. FE-SEM images of nanocomposites, (a) Al/MoO₃ nanothermite, (b) magnified image of Al/MoO₃ nanocomposite, (c) Al/MoO₃/PVDF nanocomposite, (d) magnified image of Al/MoO₃/PVDF nanocomposite.
peaks at 12.4°, 23.0°, 24.9°, 26.5°, 33.8° and 51.3°, corresponding to (100), (011), (200), (111), (−211) and (400), respectively. The lattice constants are a = 7.122 Å, b = 5.366 Å, c = 5.566 Å.

**SEM analysis**

Figure 4 shows the FE-SEM image of the MoO₃. Figure 4(a) is the overall FE-SEM image of the nano-MoO₃. For more accurate observation, the red box in figure 4(a) is enlarged, as shown in figure 4(b). The pictures show that the nano-MoO₃ particles have a round shape with a diameter of 50–80 nm. The surface is smooth and flat with less reunion, but some big blocks have some minor effects on the subsequent thermal effects.

### 3.2. Results of nanocomposites and nanothermites

**XRD analysis**

The XRD pattern of the synthesized nanocomposites and PVDF is shown in figure 5. The red line indicates the XRD of Al/MoO₃/PVDF, and the blue line represents the control group Al/MoO₃. The black line is the XRD of PVDF. Obviously, peaks appearing in the red line can be well indexed to MoO₃ (ICSD No. 76–1003 MDI Jade 6.0) and Al (ICSD No. 04–0787 MDI Jade 6.0). Also, the diffraction peaks are sharp and intense, indicating their highly crystalline impurity peaks are observed, confirming the high purity of the products.

But no characteristic diffraction peaks of PVDF are observed, which could be caused by its lower loading content and weak crystallization, on the other hand, implying the good dispersion of the tiny PVDF clusters on the Al/MoO₃ surface. Generally, PVDF undergoes a process of rapid evaporation and recrystallization. However, according to the preparation method of the precursor, under the action of a high-voltage electric field, PVDF is difficult to recrystallize after evaporation and dispersion, especially polymers with large molecular masses. Therefore, it is hard to find the obvious characteristic peaks in the XRD pattern.

The blue line is not much different from the red line, showing similar characteristics.

**SEM analysis**

To better understand the morphological characteristics of the composites, FE-SEM is used to observe its features. It is worth noting that there are no obvious characteristic peaks of PVDF seen in the XRD diffraction pattern, but PVDF can be clearly captured in FE-SEM.
Figure 6 shows the morphology of the synthesized nanocomposites. Figure 6(a) is the image of the control group Al/MoO₃, and figure 6(c) is that of Al/MoO₃/PVDF. Figures 6(b) and (d) are enlarged views of the corresponding red boxes. Since both nano-MoO₃ and nano-Al are spherical with similar nano-size, to better observe the microstructure and composition distribution of Al/MoO₃/PVDF nanocomposites, SEM-Mapping is further introduced, shown in figure 7. Figure 7(a) is the scan area chosen to do SEM-mapping. (b) is the Al element on behalf of nano-Al, (c) the Mo of MoO₃ and (d) the F element of PVDF characteristic. Figure 7 shows the distribution overlay of element Al, element Mo and element F, indicating that these elements have been evenly distributed and confirmed the uniformity of the distribution of several components.

Combining the results of Figures 6 and 7 can be found that Al is directly attached to MoO₃, and its dispersion is relatively uniform with few agglomerations. As we all know, agglomeration is inevitable [29], but the method of electrostatic spray can effectively reduce the reunion phenomenon. In figures 6(c) and (d), it can be observed that PVDF used as an adhesive can tightly glue Al and MoO₃ together. The bonding effect of PVDF can be clearly seen in figure 6(d). Besides, when the polyfluoride is heated to a specific temperature, a decomposition reaction will release heat. At this time, PVDF becomes a reactant in the redox reaction and participates in the reaction [30].

![Figure 6](image1.png)  
![Figure 7](image2.png)

**Table 1.** Details of the main peak in TG-DSC curves.

| Corresponding peak | Initial reaction temperature (°C) | Peak temperature (°C) | Finish reaction temperature (°C) | Heat release (J g⁻¹) |
|--------------------|----------------------------------|----------------------|----------------------------------|---------------------|
| E                  | 519.8                            | 553.0                | 590.1                            | 568.2               |
| G                  | 722.5                            | 777.8                | 824.8                            | 238.2               |
| I                  | 326.1                            | 448.1                | 487.7                            | 162.7               |
| J                  | 656.2                            | 680.1                | 712.2                            | 771.3               |

Figure 8. TG-DSC analysis results (a) TG-DSC curve of PVDF, (b) TG-DSC curve of Al/MoO₃ nanothermite, (c) TG-DSC curve of Al/MoO₃/PVDF energetic nanocomposite.
3.3. Thermal analysis and kinetics calculation

**TG-DSC analysis**

TG-DSC tested the pure PVDF, Al/MoO₃ and Al/MoO₃/PVDF for investigating the effect of PVDF addition in nanothermites system. The results are shown in figure 8 and the main details are listed in table 1.

Figure 8(a) shows the TG-DSC results of pure PVDF. There are three peaks in the picture. A small endothermic peak (peak A) corresponds to the melting of PVDF at 170 °C. Peak B and peak C, two large exothermic peaks at 480 °C and 690 °C, accompanied by rapid mass loss, representing the decomposition reaction of PVDF, releasing a large amount of heat (1161.12 J g⁻¹). After the decomposition reaction, the quality of PVDF no longer decreases, leaving 30.46%.

The TG-DSC of Al/MoO₃ nanothermite is shown in figure 8(b). Before 400 °C, the mass of the sample decreased slightly by 3% due to both physisorbed and structural H₂O and ethanol, accompanied by a small endothermic peak D. As the temperature increases, the main exothermic peak of the Al/MoO₃ thermite starts at 553 °C. The two exothermic peaks E and G undergo the same thermite reaction process, but an endothermic peak F that respects the melt of Al at 660 °C produces. The exothermic peak E shows a solid-solid phase reaction, while the exothermic peak G indicates a liquid-solid phase reaction between molten Al and solid MoO₃, which might be caused by the big-block part of MoO₃ with melted Al. The process's onset temperature is 519 °C and the endpoint is 824 °C, with heat release 800.72 J g⁻¹.

It can be seen that the space I correspond to the decomposition of PVDF. In the exothermic zone J, the primary thermite reaction occurs between Al and MoO₃ with the exothermic heat is approximately 771.3 J g⁻¹. At the same time, there is no noticeable quality change in the TG curve, implying that Al and MoO₃ are completely reacted, and there is no residual MoO₃. Besides, the contact between Al and MoO₃ will be closer and the reaction will be more complete when Al is melted. Due to the addition of PVDF, the peak exotherm at this stage is 680 °C, which is much earlier than that in figure 8(b). What is more, the total heat release of Al/MoO₃/PVDF energetic nanocomposite is 934.0 J g⁻¹, which changes the heat release of Al/MoO₃ (800.7 J g⁻¹) to a certain degree.

**Analysis of reaction products**

The residues products after the TG-DSC tests are collected and characterized by XRD to analyze the reactant reaction. The results are shown in figure 9.

In the control group, the reactants are Al and MoO₃, and the residual products after the reaction are detected as Mo and Al₂O₃. No reactants are caught in the residue, indicating that the reaction was complete and only one thermite reaction occurred. PVDF is added to the experimental group whose residual products after the reaction are Mo, Al₂O₃ and Mo₂C. It is speculated that some part of the Mo produced after the thermite reaction reacted with PVDF to produce Mo₂C.

**Kinetics analysis**

Activation energy, reflecting the degree of difficulty of a chemical reaction, represents the minimum energy required for a chemical reaction to occur. Reducing the activation energy of the Al/MoO₃ reaction can promote
Table 2. Details of peak temperature at different heating rates.

| Reactant | 10 K min\(^{-1}\) | 15 K min\(^{-1}\) | 20 K min\(^{-1}\) | 25 K min\(^{-1}\) | Activation energy (kJ mol\(^{-1}\)) |
|----------|-------------------|-------------------|-------------------|-------------------|-----------------------------------|
| Al/MoO\(_3\) A | 814 K             | 820 K             | 826 K             | 828 K             | 294.6                             |
|          B       | 1040 K            | 1047 K            | 1050 K            | 1054 K            | 589.7                             |
| Al/MoO\(_3\)/PVDF | 940 K             | 947 K             | 953 K             | 963 K             | 282.5                             |

Figure 10. DSC curves at different heating rates (a) Al/MoO\(_3\) nanothermite, (b) Al/MoO\(_3\)/PVDF nanocomposite.

Figure 11. The data correlation line according to Kissinger method (a) A area of Al/MoO\(_3\) nanothermite, (b) B area of Al/MoO\(_3\), (c) Al/MoO\(_3\)/PVDF nanocomposite.
easier activation of the response to a certain extent for broader application. The main concern is to reduce the 
activation energy of Al/MoO3 thermite reaction. The well-known Kissinger method is selected to calculate the 
activation energy of Al/MoO3 nanothermites and Al/MoO3/PVDF nanocomposites, and the details of peak 
temperatures are listed in Table 2.

The DSC curves of the Al/MoO3 nanothermites and Al/MoO3/PVDF nanocomposites at different heating 
rates are shown in Figure 10. There are three main exothermic peaks in the picture.

According to the Kissinger method theory, the plots of \( \ln(\beta / T_p^2) vs. 1/T_p \) is constructed, and the result is 
shown in Figure 11. The analytical expression of the data correlation line of the A exothermic peak of Al/MoO3 is 
y = -3544.4x + 26 and the correlation coefficient R is -0.94019. The value of the activation energy \( E_a \) can be 
calculated from the slope of the linear fitting line is 294.6 kJ mol\(^{-1}\). Using the same approaches, the B exothermic 
peak of Al/MoO3 and the Al/MoO3/PVDF are y = -7092.8x + 56 and y = -33981x + 24, corresponding 
the correlation coefficient R are 0.99058 and 0.94698. Prominently, the addition of PVDF allows the thermite to 
react fully. Namely, the reaction of MoO3 with Al after melting is much earlier, and the activation energy is 
significantly reduced.

3.4. Result of preliminary combustion tests

The results of preliminary combustion tests are shown in Figure 12. Figure 12(a) is the control group Al/MoO3 
and (b) is the Al/MoO3/PVDF nano-composites. The time when the sample is just ignited and presents a bright
red light is set as the starting time, specified 0. It can be seen that during ignition and combustion, the flame energy release is concentrated and only a small amount of spark splashes.

Obviously, the figure shows that compared to Al/MoO₃/PVDF, the reaction of Al/MoO₃ is severe brighter fast and shining brightly, reaching the maximum intensity at about 400 μm. However, the excitation current required for Al/MoO₃/PVDF ignition is 0.678 A, which is much smaller than the excitation current required for Al/MoO₃ ignition, 0.838 A, which implies that the addition of PVDF can effectively make the Al/MoO₃ nanothermite easier to ignition. In terms of burning time, almost completely releasing after 10 ms, the release rate of Al/MoO₃ is too fast. In contrast, the release of Al/MoO₃/PVDF is more durable, which can still maintain its most violent state of burning at 20 ms, gradually beginning to extinguish after 35 ms.

PVDF with a mass fraction of 30% may reduce the Al/MoO₃ thermite content, so there will be attenuation to a certain extent. Still, it is of great significance in improving the activity of the thermite, reducing the reaction conditions and increasing the reaction time.

4. Conclusions

In this work, the impact of PVDF on Al/MoO₃ nanothermites system was investigated. Firstly, the MoO₃ was characterized by SEM and XRD. Then the Al/MoO₃/PVDF nanocomposites were assembled via electrospaying method, and the Al/MoO₃ nanothermite was also prepared in the same way as a control group. Agglomerations of components could be effectively reduced through electrospaying method according to the SEM and Mapping results. Besides, all the nano-particles were evenly distributed.

TG-DSC results show that the Al/MoO₃/PVDF energetic nanocomposites have two obvious exothermic areas in the range of room temperature to 1000 °C, which release 934.0 J g⁻¹ heat in total, while the control experiment group, the Al/MoO₃, has a heat release area in the same range with the about 800.7 J g⁻¹ heat releases. The addition of PVDF slightly improves the heat release. Besides, it can be found in the calculation of activation energy that the activation energy of Al/MoO₃/PVDF nanocomposites is significantly reduced, which is carried out by thermal analysis experiments under different heating rates using Kissinger method. As a high-energy additive, the results reveal PVDF can dramatically improve the reaction’s activity and help ignite the thermite at comparatively low energy.

A preliminary combustion test was conducted and recorded by high-speed photography. The excitation current of Al/MoO₃/PVDF being ignited is 0.678 A, compared with the 0.838 A of the Al/MoO₃, which is lower. Meanwhile, Al/MoO₃/PVDF nanocomposites can burning duration time longer. Obviously, the addition of PVDF can ignite easily and increase reaction time, which corresponds with the results of TG-DSC.

Acknowledgments

This work was supported by the National Natural Science Foundation, project no. 51704302. It was performed using the School of Chemical Engineering equipment at Nanjing University of Science and Technology (NUST).

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

[1] Patrzek G R, Michalowski A, Krumeich F, Nesper R and Baiker A 2004 One-step synthesis of submicrometer fibers of MoO₃ Chemical of Materials 16 1126–34
[2] Bockmon B S, Pantoya M L, Sun S F, Asay B W and Mang J T 2005 Combustion velocities and propagation mechanisms of metastable interstitial composites Journal of Applied Physics 98 064903
[3] Cervantes O G, Kuntz R D, Gash R E and Munir R A 2010 Heat of combustion of tantalum-tungsten oxide thermite composites Combustion & Flame 157 2326–32
[4] Ilunga K, Fabbro O D, Yapi L and Focke W W 2011 The effect of Si-Bi₂O₃ on the ignition of the Al-CuO thermite Powder Technology Lausanne 205 97–102
[5] Yen N H and Wang L Y 2012 Reactive metals in explosives Propellants Explosives Pyrotechnics 37 143–55
[6] Carole R et al 2010 Nanoscale energetic materials Journal of Physics & Chemistry of Solids 71 57–8
[7] Martirosyan K S 2011 Nanoenergetic gas-generators: principles and applications Journal of Materials Chemistry 21 9400
[8] Yan S, Jian G and Zachariah M 2012 Electrospun nanofiber-based thermite textiles and their reactive properties AcS Applied Materials & Interfaces 4 6432–5
[9] Hu X, Xiao L, Jian X and Zhou W 2016 Integration of nano-Al with one-step synthesis of MoO3 nanobelts to realize high exothermic nanothermite Science and Engineering of Composite Materials 25 579–85
[10] Kim S H and Zachariah M 2004 Enhancing the rate of energy release from nanoenergetic materials by electrostatically enhanced assembly Advanced Materials 16 1821–5
[11] Wang Y et al 2014 Mechanism for thermite reactions of aluminum/iron-oxide nanocomposites based on residue analysis Transactions of Nonferrous Metals Society of China 24 263–70
[12] Ke X et al 2018 Surface functionalized core/shell structured CuO/Al nanothermite with long-term storage stability and steady combustion performance Materials & Design 140 179–87
[13] Song J et al 2019 Thermal behavior and combustion of Al nanoparticles/MnO3-nanorods nanothermites with addition of potassium perchlorate RSC Advances 9 41319–25
[14] Wang Q H et al 2020 Facile fabrication of highly exothermic CuO/Al nanothermites via self-assembly approach Nanotechnology 31 7
[15] Wang Q H et al 2019 Facile preparation of Si/CuO energetic materials by electrophoretic deposition and their exothermic studies Vacuum 167 244–48
[16] Wang Q H, Yang S B, Bao H B, Wang Q Y, Li X M and Yang W J 2019 Self-assembled core–shell structured Si/CuO energetic materials for enhanced exothermic performance Vacuum 169 6
[17] Zhou Y, Wang H, Xiang F, Zhang H, Yu K and Chen L 2011 A poly(vinylidene fluoride) composite with added self-passivated microaluminum and nanoaluminum particles for enhanced thermal conductivity Applied Physics Letters 98 182906
[18] Zhou X, Xu D, Lu J and Zhang K 2015 CuO/Mg/fluorocarbon sandwich-structure superhydrophobic nanoenergetic composite with anti-humidity property Chemical Engineering Journal 266 163–70
[19] Nikkel L and Dka R W B 1993 Ullmann’s encyclopedia of industrial chemistry 5th edn Polymer International 32 457–38
[20] Huang C, Yang H, Li Y and Cheng Y 2015 Characterization of aluminum/poly(vinylidene fluoride) by thermogravimetric analysis, differential scanning calorimetry, and mass spectrometry Analytical Letters 48 2011–21
[21] Song J et al 2019 Study on thermal behavior and kinetics of Al/MnO2-poly(vinylidene fluoride) energetic nanocomposite assembled by electrospray RSC Advances 9 25266–73
[22] Li X, Huang C, Yang H, Li Y and Cheng Y 2016 Thermal reaction properties of aluminum/copper (II) oxide/poly(vinylidene fluoride) nanocomposite Journal of Thermal Analysis & Calorimetry 124 899–907
[23] De Castro I A et al 2017 Molybdenum oxides - from fundamentals to functionality Advanced Materials 29 1701619
[24] Wolenski C et al 2018 Nanoscale surface reactions by laser irradiation of Al nanoparticles on MoO3, flakes Nanotechnology 30 045703
[25] Xu Y and Hua S V 2008 Mechanical properties of carbon fiber reinforced epoxy/clay nanocomposites Composites Science & Technology 68 854–61
[26] Veresh, Kumar G B, Rao C S P and Selvaraj N 2011 Mechanical and dry sliding wear behavior of Al7075 alloy-reinforced with SiC particles Journal of Composite Materials 45 J. 1201–9
[27] Badola C, Schoenitz M, Zhu X and Dreizin E L 2009 Nanocomposite thermite powders prepared by cryomilling Journal of Alloys & Compounds 488 0–391
[28] Sánchez-Jiménez P E, Criado J M and Pérez-Maqueda I A 2008 Kissinger kinetic analysis of data obtained under different heating schedules Journal of Thermal Analysis and Calorimetry 94 427–32
[29] Zhou X, Zhu Y, Zhang K, Lu J and Jiang W 2015 An extremely superhydrophobic and intrinsically stable Si/fluorocarbon energetic composite based on upright nano/submicron-sized Si wire arrays RSC Advances 5 106098–106
[30] Li H P, Pan G P, Chen X, Chen H H, Zhu G G and Liu G S 2012 Experimental study on the thermodynamic properties of thermites Advanced Materials Research 550–553 2777–81
[31] McHale J M, Auroux A, Perrotta A J and Navrotsky A 1997 Surface energies and thermodynamic phase stability in nanocrystalline aluminas Science 277 788–91
[32] Williams R A, Schoenitz M, Ermolina A and Dreizin E L 2014 Low-temperature exothermic reactions in fully-dense Al/MoO3 nanocomposite powders Thermochimica Acta 594 1–10