Full Paper

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Effects of Micro-Encapsulation Treatment on the Thermal Safety of High Energy Emulsion Explosives with Boron Powders

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Abstract: The effects of micro-encapsulation technology on the thermal safety of boron-containing emulsion explosives were experimentally studied. Micro-structures of additives, demulsification states and thermal characteristics of boron-containing emulsion explosives were characterized by the laser particle size analyzer, scanning electron microscope and thermal analysis equipment, respectively. The storage experiments showed that emulsion explosives with boron powders would be demulsified in a short time, while those with micro-encapsulated boron powders were not demulsified and had good surface morphologies and structures. The results of TG-DSC experiments showed that the thermal stability of emulsion explosive with polymethyl methacrylate (PMMA) micro-encapsulated boron powders was higher than that of other samples with boron powders, and the order of thermal stability was as follows: PMMA/Boron sensitized emulsion explosive > Paraffin/Boron-Glass microspheres (GMs) sensitized emulsion explosive > Boron-GMs sensitized emulsion explosive. The experimental data of accelerating rate calorimeter (ARC) tests showed that the addition of boron powders would significantly increase the risk of thermal explosion of emulsion explosives under the adiabatic condition, and PMMA micro-encapsulation for boron powders could largely reduce the thermal explosion risk of boron-containing emulsion explosives compared with paraffin coating. The coating effect of micro-encapsulation technology was much better than that of traditional paraffin coating method, and the compatibility and thermal safety of boron-containing emulsion explosives were also improved.

Keywords: Micro-capsule · Boron powder · Emulsion explosive · Thermal safety · Stability

1 Introduction

Emulsion explosive is a kind of water-in-oil industrial explosives formed by the supersaturated solution of soluble oxidant (ammonium nitrate) emulsifying in the oil-phase at a high shearing speed [1–3], which has been widely used in engineering blasting and mining industries due to its excellent performance of water resistance, safety and storage stability [4,5]. As a water-containing explosive, the explosion power of traditional emulsion explosive is relatively low, which severely hinders its application and development [6,7]. In order to improve the explosion power and work capacity of emulsion explosive, researchers added metal powders, high-energy explosives, hydrogen storage alloys and other high-energy additives into it. As an important high-energy fuel, boron powder has a mass calorific value of 58.81 MJ/kg and a volume calorific value of 137.94 kJ/cm³, so it is widely used in pyrotechnics delay, solid propellant and explosives. M. N. Makhov et al. [8] showed that the addition of aluminum powder and boron powder remarkably increased the explosion heat of explosives. Y. Chen et al. [9] found that the aluminized explosive with boron powders had higher values in shock wave over-pressure, surface temperature and duration of explosion fireballs than TNT and aluminized explosive without boron powders. E. C. Koch et al. [10] studied the detonation velocities and pressures of the boron-based high explosives, and discovered that the detonation velocities of the boron-based compounds were always higher than that of the corresponding carbon-based compounds. W. Cao et al. [11] found that the combustion heat of metallic explosives enhanced with the increasing content of boron powder within certain limits.

The addition of high energy additives in explosives would not only improve their explosion power and work capacity but also increase their sensitivity, decrease their stability and even cause accidental explosion. Over the years, explosion accidents of explosives occurred frequently due to their low stability, and the safety of explosives has

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always been the hot issue. K. Okada et al. [12] found that the thermal hazards of ammonium nitrate (AN) emulsion decreased with the increase of water content by the differential scanning calorimeter (DSC) and a 1.5 L pressure vessel. V. A. Teselkin et al. [13] found that boron powder, carborane, nanometer aluminum and other additives would increase the impact sensitivity of HMX and cause the explosion of it. X. H. Wang et al. [14] studied the non-isothermal kinetic characteristics of thermal decomposition reaction of emulsion explosives containing iron and manganese metal ions through TG and DSC methods, and the results showed that a large number of metal ions would seriously reduce the thermal stability of emulsion explosive.

Energetic additives encapsulation is an effective way to improve the safety of high energy explosives, and various methods for coating energetic materials had been developed, including sol-gel coating [15], crystal coating [16], spray drying coating [17] and in-situ polymerization coating [18,19]. However, there were many problems of traditional coating methods in ensuring the stability and the compatibility of energetic additives in emulsion explosives, for instance, poor coating effect and low strength of coating membrane [20]. Micro-encapsulation technology could encapsulate liquid, solid particles and gas in a polymer shell, which could regulate and control the release rate, volatilization and dissolution time of the functional materials, and isolate them from the outside environment [21]. In order to obtain a better coating effect, an PMMA microcapsule for energetic additives was developed by an improved suspension polymerization method in our previous study [20], which had advantages of high shell strength and good acid resistance [22].

Our previous study mainly focused on the synthesis of energetic microcapsules and the detonation performance of the related emulsion explosives. Compared with GMs-TiH_2 sensitized emulsion explosive, the detonation properties of PMMA/TiH_2 type of energetic microcapsules sensitized emulsion explosives were improved [20]. In this paper, to study the effect of micro-encapsulation treatment on the thermal stability of boron-containing emulsion explosives, non-isothermal experiments of emulsion explosive samples were conducted by TG and DSC, and the decomposition kinetics data of different boron-containing emulsion explosive samples under adiabatic conditions were studied by the adiabatic accelerating rate calorimeter (ARC) to evaluate the risks of thermal runaway.

2 Experiment

2.1 Experimental Materials

Glass microspheres (GMs, commercial grade, American 3 M company), deionized water (made by laboratory). Boron powder (B, 99%, 10–20 μm), paraffin (AR), methyl methacrylate (MMA, AR, 99%), 2,2'-azobis (2-methylpropionitrile)

(AIBN, 98%), pentane (99%), ethylene glycol dimethyl acrylate (EGDMA, 98%), sodium hydroxide (NaOH, AR), magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$, AR), sodium dodecyl sulfate (SDS, CP, 98%), were purchased from Mclean reagent Co., Ltd. The composition of emulsion matrix is shown in table 1.

2.2 Preparation of Energetic Microcapsules

The improved suspension polymerization method was used to encapsulate the boron powders with polymer microcapsule. The specific coating process was as follows: firstly, 4.5 g $MgCl_2 \cdot 6H_2O$ and 1.5 g NaOH were dissolved into 50 g deionized water, respectively, and these prepared NaOH solution and $MgCl_2$ solution were mixed to form a stabilizing agent. After that, 0.7 g 1wt% SDS solution was added into the mixed stabilizing agent to form a aqueous phase. Secondly, the 20 g monomer MMA, 20 g boron powders, 0.36 g initiator AIBN and 0.04 g crosslinking agent EGDMA were mixed and dissolved to form the oil phase (internal phase). Thirdly, the oil phase mixture (internal phase) was poured into the aqueous phase and homogenized at a speed of 1000 rpm for 0.5 min to obtain a stable oil-in-water (O/W) emulsion, in which the oil droplets contained boron particles. Fourthly, immediately poured the oil-in-water (O/W) emulsion into the high-pressure reaction kettle, and pressurized the kettle with nitrogen to 0.5 MPa and slowly raised its temperature to 75 °C, and then kept the polymerizing reaction for about 5 h at a certain stirring speed. Finally, the synthesized energetic microcapsules were repeatedly washed with dilute hydrochloric acid and deionized water, and dried in a vacuum oven at 30 °C for 24 h, and then the energetic microcapsules with boron powders inside were obtained.

2.3 Preparation of Emulsion Explosives

Four groups of emulsion explosive samples with different components were prepared by mechanical mixing different additives with emulsion matrix, and the formulations of them are listed in table 2. Sample A was a pure emulsion explosive sample sensitized with GMs, and Sample B was a emulsion explosive sample added with GMs and untreated boron powders. The high-energy additive in Sample C (sensitized by GMs and paraffin coated boron powders) was prepared by sol-gel coating method with a mass ratio of paraffin and boron powders of 8:92 [15], and the energetic microcapsules in Sample D was prepared by MMA and bor-

Table 1. Composition of emulsion matrix.

Components	NH_4NO_3	$NaNO_3$	$C_{18}H_{38}$	$C_{12}H_{26}$	$C_{24}H_{44}O_6$	H_2O
Mass fraction (wt%)	75	10	4	1	2	8

Table 2. Formulations of four emulsion explosive samples.

Emulsion explosive	Mass fraction (wt%)				
	Emulsion matrix	GMs	B powders	Paraffin/B powders	PMMA/B powders
Sample A	92	8	0	0	0
Sample B	92	4	4	0	0
Sample C	92	4	0	4	0
Sample D	92	0	0	0	8

on powders with a mass ratio of 1:1 by an improved suspension polymerization method [20]. Different from adding the boron powders and sensitizers of GMs separately in Samples B and C, the energetic microcapsules in Sample D combined the function of energetic additives and sensitizers, and the bulk density of energetic microcapsules was 0.52 g cm^{-3}. The density of emulsion matrix was 1.31 g cm^{-3}, which was produced by Shun Tai Chemical Co., Ltd. (Huainan, China). The mass fraction of boron powders and emulsion matrix in each group was the same.

2.4 Characterization

2.4.1 Particle Size Distribution and Micro-Structure Analysis of Energetic Materials

The particle size distribution and micro-structure of explosive materials were characterized by a laser particle size analyzer (Mastersizer 2000, Malvern, UK) and a scanning electron microscope (SEM, VEGA3, TESCAN). SEM was used to observe the changes of micro-structure of emulsion explosive samples with different additives over the time.

2.4.2 TG-DSC Tests of Boron-Containing Emulsion Explosives

In order to study the thermal decomposition characteristics of emulsion explosive samples with different additives, non-isothermal experiments were conducted on the emulsion explosive samples using a synchronous thermal analyzer (TGA, Mettler Toledo TGA/DSC2, Switzerland). In the experiments, the mass of each explosive sample placed in an alumina crucible for heating was ca. 10 mg. At the same time, N$_2$ was used as the protective gas with a flow rate of 20 mL/min. The corresponding TG-DSC curves of each explosive sample were measured by heating it from 30 to 400 °C with varying heating rates of 5, 10, 20 and 30 K/min. The actual thermal decomposition reaction process of emulsion matrix was very complex, so a transformation method (such as Friedman and Ozawa method) was used to calculate the activation energy of emulsion explosive under different heating rates. The thermal decomposition activation energies of four groups of emulsion explosive samples could be de-

termined by Ozawa method [23]. In this model, the relationship of heating rate and activation energy with temperature was inversely proportional, and the equation was as follows:

$$\lg\beta = \lg\left(\frac{AE}{RG(\alpha)}\right) - 2.315 - 0.4567\frac{E}{RT} \tag{1}$$

Where, β is the heating rate, A is the pre-exponential factor, E is the activation energy, R is the universal gas constant, and $G(\alpha)$ is the mechanism function. The slope between $lg\beta$ and $1/T$ is used to get the activation energy for each conversion step.

2.4.3 Adiabatic Experiments of Boron-Containing Emulsion Explosives

ARC was originally developed by the American institute of chemistry to provide adiabatic data for evaluating emergency rescue systems in emergency situations [24]. The Heat-Wait-Search (H—W-S) mode was selected as the standard operating procedure. It was a very widely used adiabatic calorimeter with a low heat capacity test unit, which could ensure that the generated reaction heat kept in the test sample and the thermal runaway reaction carried out safely [25]. Therefore, ARC was used to study the thermal decomposition behavior of each group of emulsion explosive samples under adiabatic conditions. By analyzing the data of temperature (*T*), pressure (*P*), temperature rise rate (d*T*/d*t*) and pressure rise rate (d*P*/d*t*) obtained from the adiabatic experiments, the thermal runaway reaction risk of each group of emulsion explosive samples was evaluated and the corresponding thermal risk was determined. The experimental condition parameters of the adiabatic experiments are shown in table 3.

Table 3. Experimental conditions of emulsion explosive samples by ARC.

Parameters	Values	Parameters	Values
Sample mass (g)	0.40	End temperature (°C)	400
Test cell type	HC-MBQ	Temperature step (°C)	5
Test cell mass (g)	15.60	Temperature rate sensitivity (°C·min^{-1})	0.02
Start temperature (°C)	200	Wait time (min)	15

3 Results and Discussion

3.1 Particle Size Distribution and Micro-Structure of Additives

Figure 1 shows that the particle size distribution and micro-structure of GMs, B powder, paraffin/B powder and PMMA/B powder (energetic microcapsules). The particle size distribution of GMs was from 11.5 to 158.5 µm, and the average particle size was 55.6 µm (see Figure 1a). B powders had a narrow particle size distribution changed from 0.6 to 17.4 µm with an average particle size of 2.8 µm (see Figure 1b). Compared with the uncoated B powders, the particle size of B powders coated by paraffin (Paraffin/B powder) increased slightly, and the particle size range of them was from 0.9 to 30.2 µm with an average particle size of 3.2 µm (see Figure 1c). The particle size of the energetic microcapsules of PMMA/B powders increased significantly compared to that of uncoated boron powders, the particle size range of them was 11.5–182.0 µm, and their average particle size was 56.6 µm (see Figure 1d).

3.2 Demulsification States of Boron-Containing Emulsion Explosives

Figure 2 shows the micro-morphology structure of emulsion matrix with GMs, GMs—B powders, Paraffin/B-GMs powders and PMMA/B powders of energetic microcapsules

over the time, respectively. In the experiment, the states of sample A and D had almost no changes, sample B and C occurred demulsification and crystallization phenomena (as arrows labeled in Figure 2). Over the time, sample B was partly demulsifed at first, and then separated out some ammonium nitrate crystals and demulsifed completely at last. The variation trend of sample C was similar to sample B, and its demulsification and crystallization phenomena were not so serious as sample B. In addition, the demulsification states of emulsion matrix in each sample were compared with that in sample A (no B powder was added), and it showed that demulsification and crystallization of emulsion matrix with uncoated B powder (Sample B) were much more obviously than the other two types of boron-containing emulsion explosives (sample C and D) with the same storage time. The emulsion matrix added with paraffin/B powders appeared only a small amount of demulsification and crystallization phenomena, which indicated that the paraffin membrane could effectively prevent the demulsification. However, the strength of paraffin membrane on the surface of boron powders was low [20, 26], and when the paraffin/B powders were mixed with emulsion matrix, frictions among the coating membrane, sensitizer and emulsion matrix generated, and the coating membrane would be damaged due to its low strength and then release the B powders, which caused the demulsification and crystallization of emulsion matrix. In contrast, these phenomena did not occur in the emulsion matrix added with energetic microcapsules of PMMA/B powders. That was because the
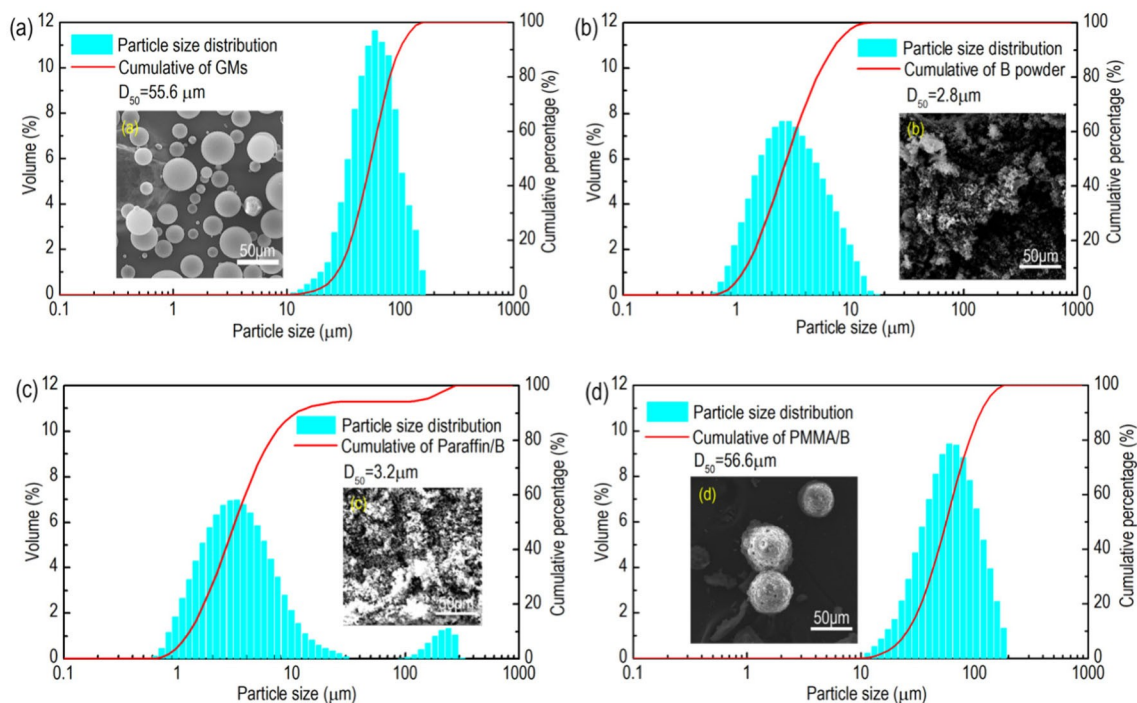

Figure 1. The particle size distribution of: (a) GMs, (b) B powders, (c) Paraffin/B powders and (d) PMMA/B powders.
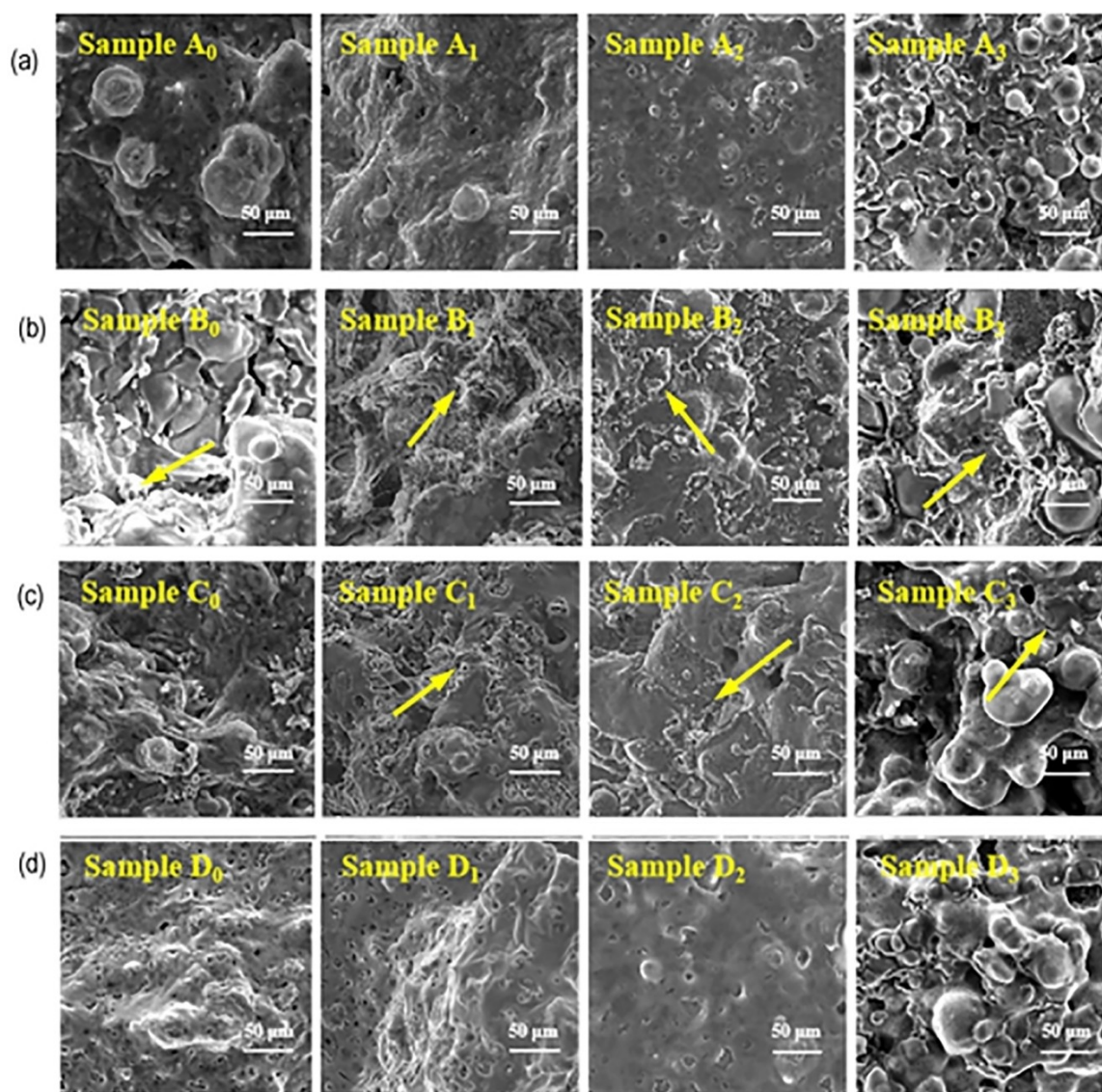
Figure 2. SEM images of different emulsion explosives stored with vary times: (a) Sample A, (b) Sample B, (c) Sample C and (d) Sample D, and the subscript numbers 0, 1, 2 and 3 represent initial stage, stored one day, one month and five months, respectively.

energetic microcapsules had a similar micro-structure of GMs, whose PMMA shell had high strength and good acid resistance in emulsion explosives, avoiding the reaction between boron powders and emulsion matrix [22]. The surface of the energetic microcapsules was smooth and could prevent the pointed edges and corners of boron powder in the microcapsules from damaging the interface membrane of emulsion matrix. As shown in Figure 2, the micro-structure of emulsion matrix with GMs (sample A) had no significant change during the storage, while the demulsification and crystallization phenomena of sample B and C became more seriously with the increase of storage time, especially the sample B. This was because the contact between boron powders and emulsion matrix destroyed the interface membrane of emulsion matrix and led to demulsi-

fication and crystallization. In addition, the crystallized ammonium nitrate would further puncture the interface membrane of the surrounding emulsion droplets and accelerate the demulsification of emulsion matrix. However, the emulsion matrix with energetic microcapsules of PMMA/B powders (sample D) had no significant change in micro-structure during the storage over the time, which was mainly because the good coating effect of PMMA microcapsules for boron powders.

3.3 Thermal Stability of Boron-Containing Emulsion Explosives

3.3.1 Thermogravimetric Analysis and Calorimetric Test of Boron-Containing Emulsion Explosives

Thermal decomposition characteristics of the four groups of emulsion explosive samples added with GMs, B powders, paraffin/B powders and PMMA/B powders were studied by TG-DSC, and each sample was tested over three times. The deviation values of initial decomposition temperature and exothermic peak temperature in each experiment were below 1.5 and 1.0 °C, respectively. Therefore, the temperature difference and size order of thermal stability were reliable in the experiments. Figure 3a shows that the DSC curves of four kinds of emulsion explosives all had three small endothermic peaks when the temperature was changed from 50 to 150 °C, and an obvious exothermic peak occurred when the temperature range was 260–280 °C. Figure 3b shows that the initial weight loss of four explosive samples were all ca. 7.2 % when the temperature was below 150 °C, which was close to the mass fraction of water in emulsion explosive. Therefore, the thermal decomposition reaction of emulsion matrix illustrated in DSC curves was firstly related to water loss (in the temperature range of 50–150 °C, see Figure 3a), and the generation of these endothermic peaks were mainly due to the evaporation of free water generated during the demulsification and crystallization of emulsion matrix. As could be seen from Figure 3b, when the temperature was changed from 150 to 275 °C, the weight loss of four samples were about 73.3 %, and the generation of the exothermic peaks (see Figure 3a) was mainly due to the thermal decomposition of ammonium nitrate of emulsion matrix. The final weight loss of sample C was almost consistent with sample A and B, which was 4 % lower than that of sample D, attributing to the decomposition of corresponding coating materials of PMMA.

As shown in Figure 3a, the initial decomposition temperatures of four groups of emulsion explosive samples were 256, 229, 245 and 256 °C, respectively, and the corresponding exothermic peak temperatures were 269, 262, 266

and 272 °C. The initial decomposition temperature and exothermic peak temperature of sample B were respectively 27 and 7 °C lower than those of sample A, which indicated that boron powder would reduce the initial decomposition temperature and exothermic peak temperature of thermal decomposition reaction of emulsion explosive, affecting its thermal stability by accelerating the thermal decomposition reaction. Compared to sample B (added with GMs and pure B powders), the initial decomposition temperature and peak temperature of sample C (added with GMs and paraffin/B powders) increased 16 and 4 °C, respectively, but were still lower than those of sample A (added with GMs only). The phenomenon indicated that the paraffin coating for B powder could not effectively improve the thermal stability of the related emulsion explosive, for a part of paraffin membranes of B powders would be broken during the mixing process and lost its encapsulation effect. Compared to sample B, the initial decomposition temperature and peak temperature of sample D (added with PMMA/B powders) increased 27 and 10 °C, respectively, which were both higher than those of boron-containing emulsion explosives of sample B and C. The results showed that the PMMA had a better encapsulation effect for B powder than paraffin in terms of thermal stability of boron-containing emulsion explosive. In addition, the initial decomposition temperatures of sample A and D were very close, and exothermic peak temperature of sample D was even a little higher than that of simple A, which further certified that PMMA could improve the thermal stability of the boron-containing emulsion explosive.

3.3.2 Thermal Decomposition Kinetics of the Boron-Containing Emulsion Explosives

In order to further investigate the thermal stability of boron-containing emulsion explosive samples, the non-isothermal kinetics of them were studied by calculating the corresponding activation energies of the thermal decomposition reactions. For activation energies, the fit index R^2 of each sample was greater than 0.98, so goodness of fit-
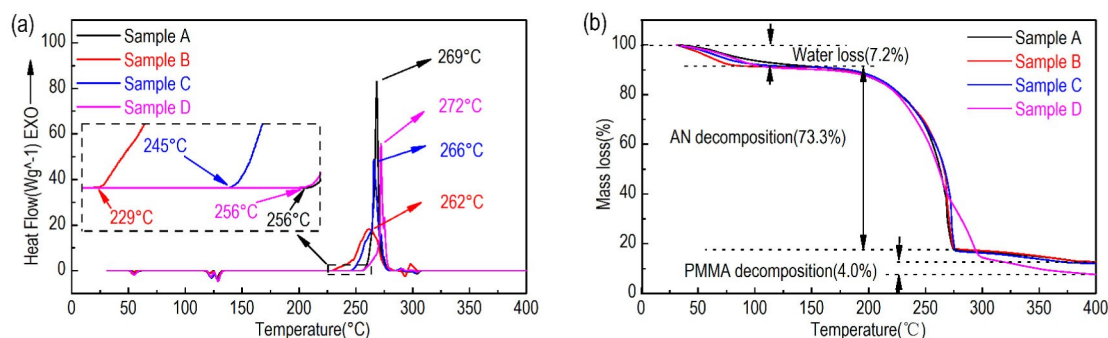

Figure 3. TG-DSC curves of emulsion explosive with different additives at a heating rate of 5 K/min: (a) DSC curves and (b) TG curves.

ting could meet the requirement of data analysis. According to the TG curves (see Figure 3), the thermal decomposition of emulsion explosive was essentially the thermal decomposition reactions of water, ammonium nitrate and additives, and ammonium nitrate had played a dominant role. Over the years, the thermal decomposition of ammonium nitrate had been extensively studied. Obviously, no single mechanism could explain all aspects of its thermal decomposition characteristics. It was generally believed that the thermal decomposition of ammonium nitrate was caused by the endothermic proton transferring reaction, $NH_4NO_3 \rightarrow NH_3 + HNO_3$, which was very slow at a low temperature.

In the previous publications [27, 23], the meaningful activation energies of AN thermal decomposition was well determined by the Ozawa method, so it was used to calculate the corresponding activation energies of boron-containing emulsion explosives in the paper. In order to compare the thermal stability of each explosive sample more easily, the activation energies of four explosive samples as a function of reaction extents were illustrated in Figure 4. In addition, the initial decomposition temperatures of sample A and D were both higher than that of sample B and C, which indicated that sample A and D had higher apparent activation energies than sample B and C (see Figure 3). The results of activation energy analysis in Figures 3 and 4 showed that the thermal stability of sample D (added with PMMA/B powders) was the best, then followed by sample A and C, and sample B (added with pure B powder) was the worst. The reason for this phenomenon was that, compared to paraffin membrane, PMMA shells had better compatibility with emulsion matrix, higher structure strength and decomposition temperature as well as longer decomposition duration [20], so PMMA shells could effectively avoid boron powder affecting the thermal stability of emulsion matrix until decomposed. Compared to GMs (its decomposition temperature is almost 1723 °C), PMMA shells would decompose around 260 °C and have a long decomposition duration before emulsion explosive had the thermal decomposition reaction according to reference [20]. In

addition, the process of thermal decomposition of PMMA shell was endothermic according to reference [20]. Therefore, PMMA shells would put off the thermal decomposition reaction of emulsion explosives.

3.3.3 Thermal Hazard Assessment of the Boron-Containing Emulsion Explosives

As an explosive material, emulsion explosive has a high thermal explosion hazard under the adiabatic condition. Adiabatic calorimetric method is one of the best ways to study the thermal runaway reaction of materials in a closed environment. Thermal runaway reaction is usually accompanied with high temperature, pressure, calorific value and pressure rise rate, so the adiabatic calorimeter ARC was used to ensure the thermal runaway reaction carried out safely [28]. With the help of ARC, the thermal decomposition processes of four groups of emulsion explosive samples with different additives under adiabatic conditions were studied, and the peak temperature, peak pressure, self-heating rate and pressure rise rate of thermal runaway reaction were important parameters to quantify the risk of thermal runaway reaction [29]. As shown in Figure 5, sample B and C showed obvious thermal runaway reactions in the experiments, while the sample A (reference sample) and sample D (added with PMMA/B powders) appeared only a weak self-thermal decomposition. In the stage of H–W-S, it took only 181 and 126 min for sample B and C from the start of self-thermal decomposition reaction to the maximum reaction rate, respectively, which were called TMR$_{ad}$ (time to maximum rate under adiabatic conditions) values. The peak temperature, peak pressure, temperature rise rate and pressure rise rate of sample B were 378 °C, 6.8 MPa, 3734 °C·min^{-1} and 114 MPa·min^{-1}, respectively, and those parameters of sample C were 355 °C, 7.0 MPa, 4449 °C·min^{-1} and 442 MPa·min^{-1}, and the obvious difference of pressure rise rates should be attributed to the initial protection of paraffin membrane for B powders (slowed down the demulsification of emulsion explosive), for demulsification of emulsion explosive would affect the thermal and explosion performance [26]. High rise rates of temperature and pressure showed that the energy releasing of sample B and C were extremely huge in a short time, and if their decomposition in the confined space could not be controlled, explosion accidents would happen.

Figure 5 shows that the peak pressure, maximum temperature rise rate and pressure rise rate of the thermal runaway reaction of sample B and C in the experiment were all higher than those of sample A and D, and the higher rise rates of temperature and pressure usually meant a higher thermal explosion risk in process of thermal hazard assessment. It was worth noting that thermal runaway reaction did not happen in sample D (added with PMMA/B powders) and sample A under the adiabatic closed condition, and the peak temperature and peak pressure of self-thermal de-
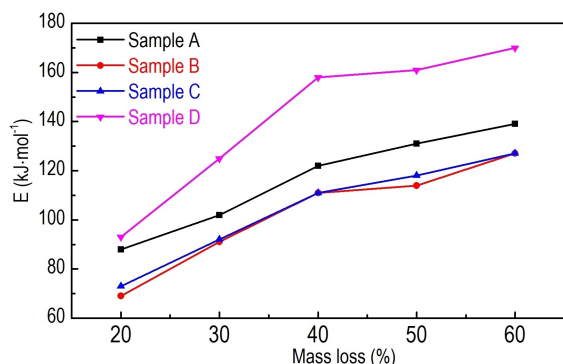

Figure 4. Activation energy curve of emulsion matrix with different additives at four heating rates.
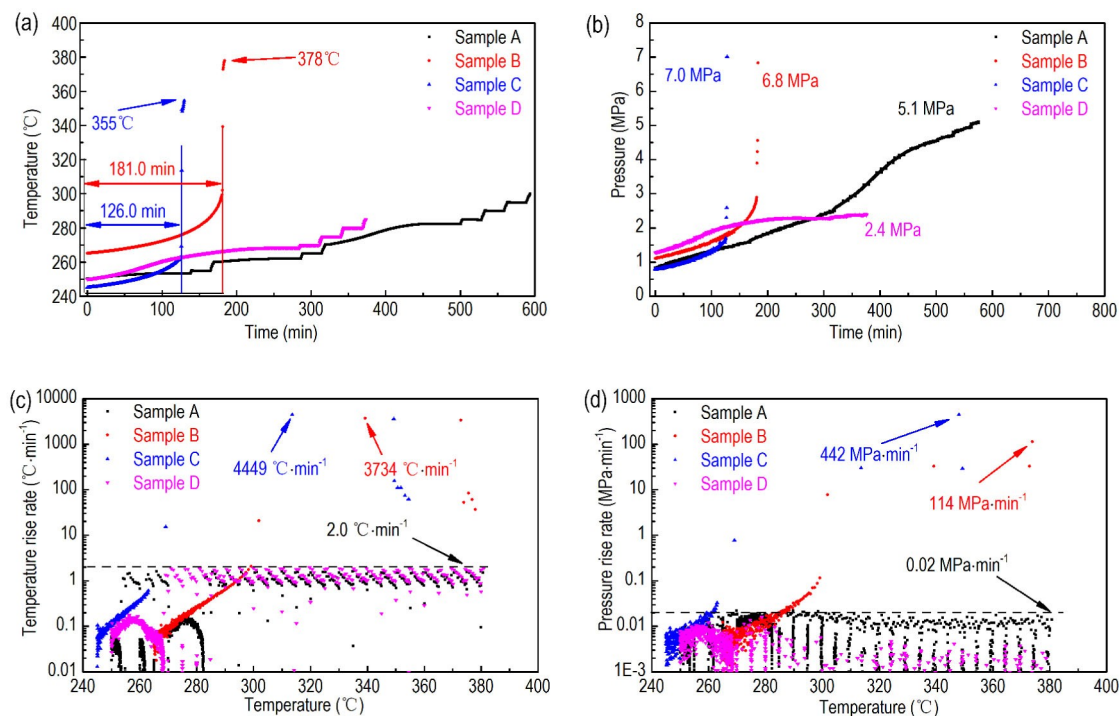
Figure 5. Evaluation of emulsion matrix with different additives in ARC tests: (a) temperature versus time, (b) pressure versus time, (c) self-heating rate and (d) pressure rise rate versus temperature.

composition reaction were even lower than those of sample A (reference sample), as shown in Figures 5a and b. The corresponding temperature and pressure rise rates of sample A and D kept floating at a low level, that is, both less than $2\,°C\cdot min^{-1}$ and $0.02\,MPa\cdot min^{-1}$, respectively (see Figures 5c and d). The ARC experimental results showed that the addition of boron powders could significantly increase the thermal explosion risk of emulsion explosive, and PMMA encapsulation for B powders had a much better effect on improving the thermal safety of boron-containing emulsion explosives than the traditional paraffin coating method.

4 Conclusions

Micro-encapsulation technology was developed for coating high-energy additive of boron powders. Boron powders coated by PMMA shells were spherical with an uniform particle size distribution and average particle size of 56.6 µm. Emulsion explosive added with PMMA/B powders microcapsules did not appear demulsification and crystallization phenomena during the storage for five months. The TG-DSC experiments indicated that the thermal stability of sample D (added with PMMA/B powders) was the best, then followed by sample A and C, and sample B (added with pure B powder) was the worst. The ARC experimental results showed that the boron-containing emulsion ex-

plosives of sample B and C had a rapid thermal runaway reaction accompanying with high temperature and high pressure in an adiabatic closed environment, while the boron-containing emulsion explosive of sample D only had a slow self-thermal decomposition in the experimental process. The addition of boron powders could make the emulsion explosive demulsified and increase the thermal explosion risk of emulsion explosive, and traditional method of paraffin membrane coating for B powder was unable to solve these problems effectively. Micro-encapsulation technology could improve the compatibility between energetic additives and emulsion explosive, and significantly enhance the safety and thermal stability of boron-containing emulsion explosive, which provided a very simple but effective method for improving the thermal safety and stability of high energy emulsion explosives with energetic additives.

Data Availability Statement

No Data available.

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