第 15 卷　第 6 期
2007 年 12 月

含 能 材 料
CHINESE JOURNAL OF ENERGETIC MATERIALS

Vol. 15, No. 6
December, 2007

文章编号:1006-9941(2007)06-0592-05

Explosive Properties of the Mg-Al/PTFE Composition

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Abstract: The object of the research are explosive properties of the pyrotechnic composite consist of fine grade magnesium-aluminium powder (PAM) and highly dispersed polytetrafluorethylene (PTFE). The composite reveals high resistance to all mechanical and thermal impulses and is extremely sensitive to hot sparks and open fire. The burning rate of the composition changes from 1 cm·s^{-1} to 100 m·s^{-1} along with decreasing its density. Charges of the composition with density below 1 g·cm^{-3} burn so violently, that the phenomena is similar to explosion. Charges with density above 1.1 g·cm^{-3} burn relatively rapidly and stably. The main part of the paper concerns the pressure impulses in the air generated during high-rate burning of the composition of bulk density. The nature of the generated pressure impulse is not that of a typical shock wave. A rise of pressure over the distance from the point of explosion to the maximum value lasts 50 - 100 milliseconds, while for shock waves this factor is less than a microsecond for equivalent charges. The methods of initiation of the composition influence the shape and parameters of the pressure impulse. The explanation of the nature of great changes of the composition burning rate has been proposed. The effect described in the paper was used for evaluation of explosive pressure resistance of industrial doors and windows.

Key words: PTFE as oxidizer; high-rate combustion; blast wave; explosive pressure resistance (EPR)

CLC number: TJ55　　**Document code**: A

1 Introduction

Public and industrial safety is a main concern for many institutions. All buildings in danger of accidental or deliberately caused explosion should be constructed and equipped properly in order to minimize potential loses. The elements of buildings most vulnerable to the destructive impact of air blast waves are windows, doors and shutters. Some additional technical requirements concerning the above-mentioned parts of buildings were established by European Standard no. EN 13124-1-explosive pressure resistance (EPR)[1].

The generation of blast waves in the air requires the application of shock tubes with compressed neutral gases or using high explosive charges, which produce highly compressed and hot gases during explosive transformation. The characteristics of the shock waves generated in shock tubes, such as magnitude or duration, can be varied by adjusting the initial pressure of compressed gases, the volume of the vessel and the shape of the measuring chamber. The possibility of changing the above-mentioned factors enables the use of shock tubes for different applications. Unfortunately, shock tubes as a rule are not portable test stands. It is always impossible to generate blast waves of large plain surface from standard size shock tubes.

Shock waves generated by detonation of high explosive charges are characterized by a relatively high value of front pressure and a sharp drop behind the front wave. It is impossible to generate a pressure impulse in the air at a level of 100 kilopascals (1 bar) lasting more than 10 milliseconds using a high explosive charge even as large as 10 kg. The generation of an air blast wave with positive phase duration time of the order of 20 milliseconds and a maximum pressure up to 200 kilopascals (2 bars) requires the use of a 1000 kg high explosive charge. The desired parameters of a blast wave can be recorded at a distance of about 40 m from the place of explosion.

Much more useful for the generation of blast waves with long impulse time are explosive gaseous mixtures. The detonation pressure of such systems reaches a few megapascals so the expansion of explosion products into the air differs from the expansion of condensed explosive detonation products . The shape of pressure impulses

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Received Date: 2007-02-25　　**Revised Date**: 2007-04-26

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recorded at different distances from the place of explosion is characterized by a moderate level of pressure and its relatively slow drop behind the wave front.

These factors cause that shock tubes seem to be the most useful devices for generating shock and blast waves in the air. This paper presents a new method of generating air blast waves using a pyrotechnic mixture of high burning rate. It doesn't require complicated equipment like shock tubes of large diameter or big high explosive charges detonated on a vast test range. The tool for generating suitable air blast waves to test elements of a building is a pyrotechnic composition consisting of fine metal powder and high dispersion polytetrafluoroethylene (PTFE).

2 Explosive properties of pyrotechnic composition

Pyrotechnic compositions consisting of magnesium powder and different fluoropolymers have been well known for about 40 years. They were first applied in aircraft flares used as infrared decoys for self-guided antiaircraft missiles[2]. The following features of the composition are important for such applications: ① High level of combustion heat reaching 9000 $kJ \cdot kg^{-1}$ and high burning temperature of up to 3500 K[3]; ② Relatively high burning rate, usually at least several $mm \cdot s^{-1}$, with a moderate dependence on outer pressure; ③ Thermal signature of combustion products similar to that of aircraft engine exhaust gases in the infrared band of the spectrum.

The high-temperature chemical reaction of magnesium and PTFE is specific: a fluoro-polymer plays the role of oxidizer and metal particles are a fuel. All combustion products are solid at normal conditions but at a high temperature the reaction products of PTFE and magnesium thermolysis exists in a gaseous state. The stoichiometric reaction is written down as follows:

$$Mg + (—CF_2—) \longrightarrow MgF_2 + C$$

This paper is concerned with the exothermic composition of PTFE and the metallic alloy of aluminum and magnesium (Al_3Mg_4). Such a pyrotechnic composition is regarded as the most suitable basic component for manufacturing both infrared radiation emitting flares and smoke screen grenades[4-5]. The Al_3Mg_4 powder (PAM) seems to be a very suitable ingredient of pyrotechnic compositions due to its better chemical resistance, better handling safety and lower price in comparison to magnesium powder. The combustion reaction of PTFE and PAM expresses as follows:

$$2Al_3Mg_4 + 17(—CF_2—) \longrightarrow 6AlF_3 + 8MgF_2 + 17C$$

The explosive properties of PTFE/PAM composition were studied by author using a mixture consisting of dispersed PTFE (grain diameter about 40 μm) – 50%, and fine grade PAM powder (grain diameter below 63 μm) – 50%. The composition was prepared in a drum mixer and carefully sifted to make the mixture more homogeneous.

Sensitivity of the bulk density composition to impact was tested using a conventional Cast hammer apparatus. The results showed a high resistance of the composition to mechanical impact. The impact energy up to 49 J did not cause the reaction of samples. The compositions of PTFE and magnesium powder show much higher sensitivity to impact, where the energy threshold of initiation equals 4 J[6]. Sensitivity to friction was tested using a conventional Peters friction apparatus. The results were similar to those described above: no reaction under the highest loading (350 N). The similar test results are obtained in studying the properties of Mg/PTFE compositions[7].

Sensitivity of the tested composition to electrostatic discharge is very low. Discharging strong electrostatic charges with energy of up to 1 J close to the composition sample did not cause ignition despite scattering the composition, and showed no traces of chemical reactions.

However, in spite of high resistance to mechanical impulses, the author witnessed at least two industrial accidents where ignition and fire caused damages, even victims, during energetic process operations using the composition.

Sensitivity to heating is unusually low in comparison to typical high explosives. While the latter decompose rapidly, as a rule, at a temperature exceeding 450 – 500 K, the PAM/PTFE composition is stable up to about 750 K[8].

Sensitivity of the composition to open fire and hot sparks, contrary to the above-described features, is extremely high. Exposition to flame from burning paper or wood, single sparks emitted by Bickford cord or mechanically generated hot sparks, easily cause explosion of the whole sample. The composition consisting of equal parts of PTFE and PAM, with a bulk density of about 0.5 $g \cdot cm^{-3}$, initiated by open flame or hot sparks, explodes violently with a loud thunder producing a large, bright ball of fire. This phenomenon occurs even with composition samples smaller than 1 g. The burning rate of the composition has been determined at bulk density using a high-speed infrared camera. The test was carried out in the open air. A composition sample of 1 kg was formed into a line charge (about 0.5 m in length) on the ground. The composition was initiated with an electric igniter applied to one side of the charge. The estimated burning rate of the composition was determined to be 120 m · s^{-1}.

The dependence of the burning rate (u) on the composition density (ρ_0) has been studied. Measurements have been carried out using cylindrical charges of 20 mm diameter and 15 – 40 mm height. Charges of different density were placed in vertical position and ignited by flame from the top. All studied charges with density in the range of 1.1 – 2.1 g · cm^{-3} were burning violently at a rate increasing with the decrease of density. For charges with a density below 1.0 g · cm^{-3}, an explosion took place in every case. The measurement results are presented in Table 1.

Table 1 Dependence of the charge density and the burning rate

ρ_0/g · cm^{-3}	0.5	1.1	1.29	1.50	1.80	2.11
u/m · s^{-1}	120	0.02	0.003	0.002	0.0016	0.0013

3 Pressure impulse generated by PAM/PTFE

Measurements of pressure impulses generated by explosion of the bulk density composition have been performed in two series of experiments. Initial tests with small charges of the composition (10, 15 and 25 g) were carried out at laboratory conditions using a 1.5 m^3 explosive chamber. Large-scale tests with charges of several kilograms were performed in the open at a test range. Measurements of the pressure profile in time were done using a PCB pressure gauge (Piezotronics Inc., USA) and the results of the experiments were recorded on a digital oscilloscope.

Small-scale experiments were carried out using 10, 15 and 25 g samples of the composition. Charges were confined in thin aluminum foil and initiated using a weak electric igniter. A charge was placed in the chamber, close to the rear wall, in its center. A pressure gauge was mounted at a distance of 1.2 m from the charge, on the opposite mobile wall made of thick multi layer glass installed in a window frame. The records of the pressure-time dependence are presented in Fig. 1. As indicated in the plots, the value of maximum pressure is proportional to the mass of the charges, while the duration time of impulses is constant (about 300 ms) and independent of the mass of the charges. Additional tests were made using a detonating cap for charge initiation instead of a weak igniter. In Fig. 1, the lowest curve presents the pressure impulse obtained for 15 g charge initiated by a detonating mining cap containing about 1g of high explosive. In this case, the rise of pressure to the maximum value is faster in comparison with an equal charge initiated by flame, except that the total impulse is reduced approximately by half.

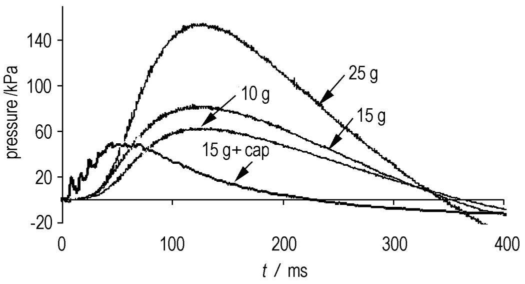

Fig. 1 Impulses of pressure generated by explosion of the PAM-PTFE composition recorded in small-scale tests

Shock initiation causing fast burning of the composition was applied in the case of large-scale tests with charges of a few kilograms conducted in the open at a test range (Fig. 2). A 3 kg quantity of ANFO supplied with 150 g pressed TNT booster was used as an initiation charge. ANFO is a relatively powerful explosive with a low detonation velocity[9]. The main charge generating blast air waves was the PAM/PTFE pyrotechnic composition. A combined charge of the explosive and the pyrotechnic composition was placed at a height of 1 m above the ground. The pressure gauge was mounted at a distance of 7.5 m at the same height. The measurement results of pressure impulses for the 1 kg and 4 kg compositions are presented in Fig. 3. The first small pressure peak lasting several milliseconds, with 50 kilopascals amplitude, was formed by the detonation of the ANFO charge. The following big pressure impulses with relatively gentle slopes were generated by the pyrotechnic composition burning at high speed. The amplitude of pressure impulses is proportional to the mass of the pyrotechnic charges while the duration time of the positive phase of the pressure doesn't vary significantly for the 1 kg and 4 kg charges. The key conclusion following from these large-scale experiments is the huge difference between the values of the total impulse generated by high explosive charges (ANFO + TNT) and the nearly equivalent-energy charges of the PAM /PTFE high burning rate composition. It can be concluded that the pressure impulses generated by the composition under study are two orders of magnitude stronger than those produced by the detonation of high explosive charges with energy of a comparable quantity released during a high-speed process.

Fig. 2　The view of the stand for large-scale test

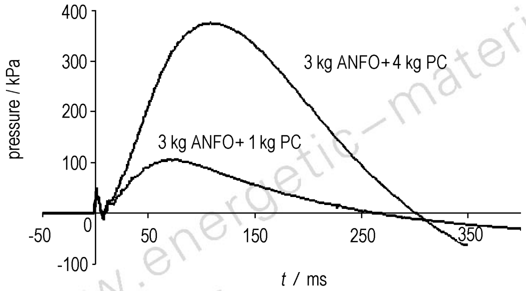

Fig. 3　Impulses of pressure generated by explosion of the PAM-PTFE composition recorded in large-scale tests

4　Discussion of results

A strong interdependence was observed between the burning rate and the density of the pyrotechnic composition under study. The burning rate of the composition under atmospheric pressure, in the range from 0.5 to 2.1 g · cm^{-3}, changes hundred thousand times (10^5). Below the density of 1 g · cm^{-3} the composition burns so fast that the phenomenon seems to be an explosion with all its external features: a flash, a huge acoustic effect and a strong air blast wave. The charges made of mixture of a density higher than mentioned above still burn very rapidly but do not explode. Above the density of 1.5 g · cm^{-3} the composition burns at a moderate rate of the order of several mm · s^{-1}. One can conclude that it is the porosity of the composition which plays a crucial role in the burning process in this case.

In order to explain the differences in the burning process of the PAM/PTFE and Mg/PTFE mixtures, we compared the physical properties of their initial and final products. The decomposition reaction process of the PTFE and magnesium mixture begins at 730 – 800 K and runs similarly to the thermal decomposition of pure PTFE[10]. At a temperature of 600 – 630 K, PTFE melts so that a reaction between the liquid and solid body occurs, since magnesium melts at 924 K. PAM is an intermetallic alloy melting at 730 K, which causes faster reaction between the two liquids. The products of burning of Mg/PTFE composition are high-boiling compounds: the boiling point of magnesium difluoride is 2500 K and is double that for carbon. Additionally, aluminum trifluoride with a boiling point of 1530 K appears among the products of burning of the PAM/PTFE composition. Considering that the burning temperature of the described composition exceeds 3000 K, it can be claimed that it is the extremely hot gaseous products of burning (AlF_3) that are responsible for the fast propagation of burning process through the whole high-energetic composition. In the case of the low-density PAM/PTFE charges, the velocity of hot gaseous streams is so high that an explosion takes place.

To increase the density of charges means to decrease the porosity of the composition causing harder conditions for the penetration of gaseous streams into the composition. It is the thermal conductivity factor that begins to play a greater role in the burning process propagation, especially for charges with a density exceeding 1.3 g · cm^{-3}. Within this density range the burning rate is determined mainly by thermal conductivity of the pressed composition.

5 Conclusions

The fine grain composition of Mg-Al alloy powder and PTFE reveals high resistance to all mechanical and thermal impulses and is extremely sensitive to hot sparks and open fire. The burning rate of the composition changes from 1 cm · s^{-1} to 100 m · s^{-1} along with its density decreasing. Charges with the composition of density below 1 g · cm^{-3} burn so violently, that the phenomena is similar to explosion. Charges with density above 1.1 g · cm^{-3} burn relatively rapidly and stably.

The burning, at a high subsonic velocity, of the pyrotechnic composition under study causes powerful air blast. The external features of such a phenomenon (light, thunder, flame and an air blast wave) make it similar to explosion. The nature of the generated pressure impulse is not that of a typical shock wave. A rise of pressure over the distance from the point of explosion to the maximum value lasts 50 – 100 milliseconds, while for shock waves this factor is less than a microsecond for equivalent charges. The methods of initiation of the composition influence the shape and parameters of the pressure impulse. Surprisingly, a strong detonation initiation creates a much lower pressure impulse than in the case of initiation by a weak flame.

The charges of low density PAM/PTFE composition, which are energetically equivalent to the ANFO high explosive in terms of explosion heat, produce air blast waves with a total pressure impulse hundreds times bigger. The effect described in the paper was used for evaluation of explosive pressure resistance of industrial doors and windows. It also seems feasible to use the described effect for manufacturing explosive charges with enhanced demolition ability.

Acknowledgments: The author is deeply grateful to Dr. J. Paszula for his assistance during measurements of pressure impulses.

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向作者致谢

近年,《含能材料》得到了广大作者的支持,为表达我们深深的谢意,特向2006~2007两年来发表两篇以上论文的作者(第一作者)赠送2008年全年《含能材料》。本刊期望在新的一年能得到广大作者更多的关心!欢迎赐稿!

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