Experimental study on impact-induced initiation thresholds of al/ptfe/w composite

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Abstract: Al/PTFE/W is a typical kind of reactive material, which has a variety of potential applications in the future. Impact experiments were conducted with a gas gun and a steel target to investigate the impact-induced initiation thresholds of Al/PTFE/W (18.55 wt.%/51.45 wt.%/30 wt.%) rods. The Al/PTFE/W rods were prepared by using the cold press and hot sinter method. A high-speed camera was used to observe the time sequence of events and to measure the speed of the rods by the grids on the background board. At low velocity, no initiation occurred and the rods only appeared upsetting. Above an initiation threshold of around 127m/s, extensive chemical reaction with strong flare was observed after impact. There was a time interval for the flare after impact, and this time interval decreased with increasing of impact velocity, from 138μs(127.4m/s) to 68μs (235m/s). Several experiments were performed for PTFE and Al/PTFE (26.5 wt.%/73.5 wt.%) rods for comparison with the Al/PTFE/W rods. The effect of impact velocity and composition on the impact-induced reaction of Al/PTFE/W was discussed.

1. Introduction

Al/PTFE/W is a typical kind of reactive material prepared by a specific process. It was first proposed by Hugh E. [1] in a patent in the form of a reaction fragment. Due to its high energy release characteristics, and its insensitivity under quasi-static conditions, it has received widespread attention in military applications [2]. It is mainly used in the form of reaction fragments and energetic liner in highly effective warheads. During the process of destroying the target, the material causes a chemical reaction due to impact, releasing a large amount of energy and causing additional secondary damage such as explosion and combustion effect, achieving multiple damage to the target [3]. In recent decades, studies on reactive materials have been focused on the preparation technology and mechanical properties. It is usually mixed with other powders to improve Al/PTFE materials mechanical properties during preparation. Zhou [4] added tungsten to aluminum polytetrafluoroethylene to enhance the penetration ability of the fragment. Through quasi-static pressure test, it was found that for reactive materials after sintering, increasing the tungsten content...
will significantly increase the failure strength of the material. Xiao [5] found that the compressive strength, elastic modulus, and compressive strength of the Al/PTFE/W reactive material gradually increased with increasing density in range of 2.73 to 6.67 g/cm³. It was found that the cracks in the Al/PTFE/W reactive material mainly occurred at the interface with PTFE-filled metal particles by scanning electron microscopy. Liu's [6] mechanical experiments show that under dynamic compression, the strength increases with the increase of tungsten. When the tungsten content changed from 0 to 60%, the dynamic compressive strength of the Al/PTFE/W reaction material increased by 21% [7]. The PTFE matrix is elongated in the nanofiber during impact compression deformation, which significantly improves the reactivity of Al/PTFE/W composites. Nanofiber structure is necessary for Al/PTFE/W composite reaction. The formation of PTFE nanofibers must undergo severe plastic deformation, which is the reason for the excellent insensitivity of Al/PTFE/W composites.

Drop-weight test, ballistic impact and taylor anvil experiments are the most widely used methods to test the impact-induced initiation mechanism of reactive materials. Previous studies have been focused on mechanical behavior, reaction character of Al/PTFE based composite, and the role of additives such as tungsten, ceramic on the above properties. Little attention has been focused on the threshold of the impact-induced initiation of Al/PTFE based composite. Therefore, the main objectives of the work are performed to investigate the reaction process of Al/PTFE/W under high-speed impact conditions to obtain the threshold of the impact-induced initiation threshold. At the same time, it compares with Al/PTFE to get some regular practical significance.

2. Experimental section

2.1. Fabrication of Al/PTFE/W rods

The Al/PTFE/W rods were prepared by using the cold press and hot sinter method. In addition, the same method was used to prepare Al/PTFE rods and pure PTFE rods for comparison. In this study, the Al/PTFE/W granular composites with mass ratios of 18.55/51.45/30, and the Al/PTFE granular composites with mass ratios of 26.5/73.5. The specific related parameters and the manufacturer of the materials are listed in table 1. The material powders were first initially mixed according to the mass ratio, then mixed by a planetary ball mill at a certain speed for one hour. The uniformly mixed powders were drying in thermostatic oven, then put into a hardened steel mold and pressed at a pressure about 70MPa. The formed specimens were placed in a vacuum furnace for sintering, and the sintering temperature control curve was referred to document [4]. The temperature history of the sintering cycle is shown in figure 1.

| Material name       | Density(g/cm³) | Material size | manufacturer                                           |
|---------------------|----------------|---------------|--------------------------------------------------------|
| Aluminum(Al)        | 2.712          | 100-200 mesh  | Sinopharm Chemical Reagent Co., Ltd., Shanghai, China   |
| Polytetrafluoroethylene (PTFE) | 2.152          | 150 μm        | Shandong fluorine chemical Co., Ltd., Shandong, China   |
| Tungsten(W)         | 19.235         | 200 mesh      | Sinopharm Chemical Reagent Co., Ltd., Shanghai, China   |

Table 1. Related parameters of the materials.
2.2. Experimental Process

A gas gun with an inner diameter of 14.5 mm was used to launch the rod-shaped specimens in this experiment, and a booster with an outer diameter of 14.5 mm was designed to keep the rods in a good attitude. The sintered specimens had diameter of 10 mm and length of about 25 mm. The three kinds of prepared rods and the processed booster are shown in figure 2. Six 10mm thick acrylic plates were used to make a transparent box with a side length of 30cm, which had good light transmission performance, long service life and excellent rigidity and strength. A circular hole with a diameter of 20 mm was drilled at a suitable position on the front side of the box to allow the rod to be injected. A uniform armor plate as target with a diameter of 160 mm and a thickness of 30 mm is placed on the back of the box. The history of the events was recorded by high-speed photography, and the field of view was illuminated by two high-intensity lights. The transparent acrylic box and experimental layout are shown in figure 3.

![Figure 1. The temperature history of the sintering cycle.](image1)

![Figure 2. The rods and the boosters.](image2)

![Figure 3. The acrylic box and the experimental layout](image3)
3. Analysis and discussion

![Figure 4](image)

**Figure 4.** Three representative phenomena of the impact: (a) impact at 121.6 m/s; (b) impact at 127.4 m/s; (c) impact at 187.5 m/s.

Although the maximum launch speed of the experimental rod is about 220 m/s, the experimental conditions are sufficient to meet the initiation threshold of the rod in a good attitude. Figure 4 shows three representative phenomena of the impact, which was recorded by high-speed photography. The Al/PTFE/W rod impact speeds in figure (a), figure (b), and figure (c) are 121.6 m/s, 127.4 m/s, and 187.5 m/s, respectively. When the impact speed of the rod was 121.6 m/s, no fire was observed during the impact. The rod only appeared upsetting at the beginning of the impact, and then cracked and broke. When the impact speed of the rod was 127.4 m/s, the reaction flare could be observed. The moment at which the reaction flare was observed occurred earlier when the impact velocity of the rod was 187.5 m/s. After the end of the experiment, the impacted sample was recovered from a transparent acrylic box. The inside of the acrylic box was cleaned every time, so each recyclate did not infect each other. Figure 5 shows the recyclate of the above three cases. It could be observed that the lengths of the remaining rods were different from each other in the three cases. At the speed of 121.6 m/s, the impact end of the rod body presented the shape of the petal and the debris was less; at the speed of 127.4 and 187.5 m/s, the impact end of the rod body was severely deformed, and there are black substances on the impact surface, more debris and more small debris. It indicated that there was a critical value for the impact reaction of Al/PTFE/W. When the impact condition was below the critical value, the Al/PTFE/W rod would be upsetting and even fragmented. When the impact condition was above the critical value, the Al/PTFE/W rod would react and the reaction flare would appear. The situation of Al/PTFE was similar, but the critical impact velocity was different. For PTFE, no reaction flare was observed and there were no signs of reaction from the recovered material. It indicated that
PTFE cannot react under impact conditions.

Figure 5. The recylcate: (a) 121.6 m/s; (b) 127.4 m/s; (c) 187.5m/s.

The relationships between impact velocities and impact pressures during the impacting of Al/PTFE/W rods and Al/PTFE rods are showed in figure 6. The shock parameters of the materials that are used in this study refer to Zhou’s [8] doctoral dissertation. It can be found that under the same impact velocity conditions, the impact pressure of Al/PTFE/W is higher because of the higher density of Al/PTFE/W. The gray area is the part where no reaction occurs. Therefore, the initiation impact velocity threshold of Al/PTFE/W is between 124~127 m/s. For Al/PTFE, the critical value is between 145~160 m/s. But the initiation impact pressure threshold of the two materials are about 600MPa. It seems that the addition of tungsten does not show an advantage in the initiation impact pressure threshold of Al/PTFE composites, but many studies have proved that the addition of such metals significantly improves the mechanical properties of Al/PTFE composites. Some scholars believe that impact velocity or impact pressure is insufficient to predict the initiation of Al/PTFE [9, 10], impact pressure and strain rate jointly affect the initiation threshold of Al/PTFE composites. The impacting strain rates can be calculated from the ratio of impact velocity and the specimen length. Figure 7 shows the relationship between impact pressure and strain rate of the rods. Two straight lines separate the reaction from the unreacted portion, and the part of the reaction appears at the top right of the intersection of straight lines. It can be observed that the initiation threshold of Al/PTFE and Al/PTFE/W composites are enough to be described on the same level, when the impact pressure is greater than 600MPa and the strain rate is greater than 5100s⁻¹, the reaction will occur.

Figure 6. The relationships between impact velocities and impact pressures.

Figure 7. The relationship between impact pressure and strain rate.

In addition, the length of the remaining rods recovered in this experiment was measured. Since the impacted end face of the remaining rod body is not flat due to severe deformation, the shortest distance between the end faces is recorded during the measurement. The original length of the rod has been measured before the experiment. Figure 8 shows the relationship between the impact pressure...
and the ratio of the remaining length to the original length of the rod. As the impact pressure rises to 1100 MPa, the ratio decreases from 1 to around 0.2. In the case of low impact pressure, Al/PTFE and Al/PTFE/W composites will not react, the rod will not even be broken, and only appear upsetting as shown in figure 10. The four recovered rods are relatively complete, only deformed in length and diameter. From the perspective of impact pressure, the crushing of Al/PTFE/W occurs under the condition that the impact pressure is greater than 590 MPa, and the crushing of Al/PTFE occurs under the condition that the impact pressure is greater than 560 MPa. From the perspective of the ratio of the remaining length to the original length, the value of Al/PTFE/W is greater than the value of Al/PTFE under the same impact pressure condition. It means that the yield strength and impact resistance of Al/PTFE/W are greater than Al/PTFE. Willis Mock [11] used a power function to describe the relationship between impact pressure and the initiation time which was replaced with the time after impact for first light observed by the high- speed photography. This time was recorded in the same way in this study, and the relationship between time and impact pressure is shown in figure 9. There is a downward trend for the time with the increase of impact pressure although, the dispersion of data is relatively high, and the functional relationship between the two cannot be found. Different from the experiment of Willis Mock, the highest impact pressure of this experiment only reached 1086.9 MPa, and the value reached 6330 MPa for Willis Mock’s experiment. Therefore, the range of the impact pressure of the data in this experiment is narrow and the same conclusion cannot be obtained. In the experiment of pure PTFE, the PTFE rod is basically completely broken into small pieces, as shown in figure 11. Under the same impact pressure (around 760MPa), there is the remaining length for the rods of the other two materials. Therefore, the impact resistance of pure PTFE is relatively weak, and the mechanical properties can be significantly improved by adding metal.

**Figure 8.** The relationship between the impact pressure and the ratio of the remaining length to the original.  
**Figure 9.** The relationship between the time and impact pressure length of the rod.
4. Conclusion

Impact experiments were conducted with a gas gun and a steel target to investigate the impact-induced initiation thresholds of Al/PTFE/W rods. Through the analysis of experimental phenomena and data, the following conclusions are reached:

(1) With the increase of impact velocity, Al/PTFE/W rods went through the process of upsetting, fracture and fragmentation, initiation and reaction.

(2) Only when the impact pressures and the strain rates exceed critical values simultaneously can the Al/PTFE/W materials be initiated. The impact pressure and strain rate threshold for Al/PTFE/W is 600MPa and 5100s\(^{-1}\) in this study. The addition of tungsten does not show an advantage in the initiation impact threshold of Al/PTFE composites.

(3) Al/PTFE/W rods begin to break when the impact pressure exceed 590MPa, yet Al/PTFE rods begin to break when the impact pressure exceed 560MPa. The yield strength and impact resistance of Al/PTFE/W are greater than Al/PTFE.

(4) There is a downward trend for the time after impact for first light with the increase of impact pressure.

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References

[1] Huge E Montgomery 1976 Reactive fragment United States 3961576
[2] Xian-Feng Zhang, and Z. Xiao-Ning 2009 Journal of Energetic Materials 17 731-9
[3] Zhou Jie, He Yong and He Yuan, et al 2016 Journal of Energetic Materials 24 1048-56
[4] Zhou J, He Y and Wang C T et al 2017 Journal of Energetic Materials 25 903-12.
[5] Xiao Y W, Xu F Y and Zheng Y F et al 2017 Quasi-static compression properties of cold
isostatically pressed reactive materials Transactions of Beijing Institute of Technology 37 337-41 and 347.
[6] Liu W, Jinxu L, Shukui L, et al 2015 Materials & design 92 397-404
[7] Zhiyou Chen 2016 Preparation process and dynamic mechanical property of Metal/PTFE reactive materials Beijing Institute of Technology
[8] Zhou Jie 2018 Study on the impact-induced reaction characteristics of typical fluoropolymer-matrix reactive materials Nanjing University of Science and Technology
[9] Ge, Chao, et al 2017 Experimental Study on Impact-induced Initiation Thresholds of Polytetrafluoroethylene/Aluminum Composite Propellants, Explosives, Pyrotechnics 42 514-22
[10] Maimaitituersun W, Chao G E, Chao T, et al 2018 Explosion and Shock Waves 38 957-65
[11] Mock, Willis, and W. H. Holt 2006 Impact Initiation of Rods of Pressed Polytetrafluoroethylene (PTFE) and Aluminum Powders AIP Conference Proceedings American Institute of Physics