A study of impact energy release mechanism and reactive characteristic of Ni-Al-W reactive material fragments

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Abstract. To study the impact reaction characteristics and energy release mechanism of Ni-Al-W reactive material fragments. As the research object, the fragments had been added to W with different mass fraction and particle size. Ballistic rifle test method had been adopted. Quasi-static overpressure which had been produced from the reaction under certain impact conditions had been measured. The residual particles had been collected so that the microstructure and the reaction products after impact-response were contrastively analyzed, with XEDS (X-ray energy dispersive spectroscopy) and X-ray diffraction (XRD) analysis. The characteristics of quasi-static overpressure and the mechanism of energy release had been analyzed. The results showed that when the impact velocity was 1000±50m/s, several Ni-Al-W metal reaction fragments with different W content could initiate the chemical reactions, release energy and form quasi-static overpressure. By adding a small amount of W to the component, it is beneficial to improve the energy release level of the impact reaction, initiated by the Ni-Al-W reactive fragments impacting the targets. When the mass fraction of W component was 10%, the quasi-static overpressure was maximized. The mechanism of energy release reaction for metallic reactive fragments was mainly the intermetallic reaction of Ni and Al and the oxidation reaction of Ni metal with air, producing NiAl and NiO at the impact velocity of 1000±50m/s. The particles formed after the fragments impacting the chopping block was smaller, the part of the reacted reactive fragments was more and the degree of the reaction was higher and more intense.

1. Introduction

The application of new material technology to improve the damage performance of the fragments of warhead is an important task in the field of warhead technology. The reactive fragments are significantly different from the inert fragments which had been commonly used. The chemical reactions can be triggered by them under impact conditions then combustion or similar detonation can be produced and chemical energy be released. As a result, a combined kinetic and chemical energy damage effects can be produced on the targets, becoming one of the important technical approaches to improve the damage power of the fragment warhead [1-5].

More different types of the reactive materials have been used in the reactive fragments, mainly thermite, metal/polymer, metal compounds, metastable molecular compounds and hydride [3]. There into, the metal/polymer have been studied mostly at present. The systematic researches for its formulation, preparation techincs, mechanical properties, reaction energy-released characteristics and damage-enhanced effects have been carried out [5-12], however, the application of the metal/polymer reactive fragments to the fragment warhead have been limited by what the mechanical strength is only
a few tens of MPa. In recent years, the metallic reactive fragments have better engineering application foreground in the fragment warhead due to its high density and mechanical strength [13]. Metallic reactive fragments are mainly composed of two or more reactive metals and the intermetallic compounds can be produced in the effect of impact and energy can be released to enhance the damage effects. Typical metallic reactive materials, such as W-Zr, Al-Ti, Al-Ni, Ta-Al, Nb-Al, W-Al and Al-Ni-W, the highest energy content among them is Al-Ni. The Al-Ni reactive structure materials, with the mole ratio of 1:1, had been prepared by cold pressing and sintering method in literature [14] and its tensile strength and compression strength were 66.0 MPa and 294.6 MPa respectively. The 35Al-65Ni reactive materials had been prepared by accumulative roll bonding process and the tensile strength was about 370 MPa in literature [15]. The mechanical properties of the Al-Ni-W reactive materials had been studied further in literature [16] and the dynamic compression strength was not less than 500 MPa. Metallic reactive fragments have become increasingly popular research subjects in recent years, however, the researches mainly focus on their preparation technology and mechanical properties, thus the characteristics of the reactions and mechanism of the energy release for the reactive materials in the effect of impact need to be studied further.

In this study, the Al-Ni-W reactive fragments as the research object, referring to the VCC test methods which can be used to study the energy release characteristics of the metal/polymer reactive fragments [17], the quasi-static overpressure of the fragments had been measured at the impact velocity of 1000 ± 50 m/s and the reaction characteristics had been analyzed. And then, by using the SEM morphology analysis and the XRD component analysis, the types the reactions and mechanisms for energy release had been analyzed and concluded. The results will provide certain s for the design and engineering application of the Al-Ni-W metallic reactive fragments.

2. Experiment design
According to the characteristics of chemical energy release, resulted by the chemical reactions which had been triggered with the Ni-Al-W reactive fragments impacting the targets, the test system had been designed, as shown in figure 1. The test system had been composed of 14.5mm ballistic rifle, sabot, reactive fragment, zone-block velocity measurement targets, closed pressure tank and pressure measurement system. The velocity of the reactive fragment impacting the targets could be controlled with the propelling charge of the ballistic rifle. The law of impact reactions of the reactive fragments could be analyzed with the quasi-static overpressure of the closed pressure tank, measured with the pressure measurement system. Meanwhile the mechanisms for energy release could be analyzed and concluded by the morphology analysis for the recovered products and the component analysis for the products.

![Figure 1](image)

1-ballistic rifle 2-sabot 3-reactive fragment 4-zone-block velocity measurement targets 5-closed pressure tank 6-pressure measurement system

**Figure 1.** Schematic diagram of experimental devices.

2.1. Experimental fragments samples
Four Ni-Al-W all-metal reactive fragments with different W mass fraction and particle size had been used in the experiment, numbered 1# ~ 4# and cylindrical in shape, as shown in figure 2. They had been prepared by vacuum ball milling, cold pressing molding and high temperature vacuum sintering, and the parameters of them were shown in table 1. SEM and EDS analysis had been performed on the
four samples after polishing and the microscopic images were shown in figure 2. According to the results of the EDS energy spectrum analysis, no chemical reactions had been triggered among the components during the preparation processes and they still existed in the form of simple substance. White particles represented W, gray represented Ni and black represented Al. It can be seen that Ni and Al were cross-linked in the form of agglomeration, and W was embedded between Ni and Al.

![Figure 2](image2.png)

**Figure 2.** The reactive fragments sample.

| Sample Description | Components (mass ratio) | size(mm) | mass(g) | density(g · cm$^{-3}$) |
|--------------------|-------------------------|----------|---------|------------------------|
| 1#                 | 68%Ni32%Al              | φ 10*10  | 3.84    | 4.89                   |
| 2#                 | 75%Ni20%Al 5%W          | φ 10*10  | 4.55    | 5.79                   |
| 3#                 | 75%Ni15%Al10%W          | φ 10*10  | 5.01    | 6.45                   |
| 4#                 | 75%Ni5%Al20%W           | φ 10*10  | 6.35    | 8.09                   |

![Figure 3](image1.png)

**Figure 3.** The SEM photo of reactive fragments.
2.2. Closed pressure tank

The closed pressure tank adopted a closed container with a diameter of 0.3m, a length of 0.38m and a volume of 27L. The 2A12 aluminum, with a 3mm-thick plate, had been located in front of the container. The internal impact chopping block with 20 mm thick had been made of 45 steel, subjected to quenching and hardening what made its hardness to reach 50-55 HRC, and the distance between the impact surface of the chopping block and the bottom of the container was 0.1m. The quasi-static overpressure could be measured by the pressure sensor, located on the circumferential wall of the container, and the horizontal distance between the pressure measuring point and the chopping block is 0.15m. The closed pressure tank had been placed at a distance of 10 m from the ballistic rifle.

2.3. Pressure test system

The pressure test system were composed of a sensor and an acquisition instrument. The sensor was a PCB type pressure sensor, and the pressure data, acquired with the sensor acquisition, was converted into a pressure-time curve through an acquisition instrument. The typical quasi-static overpressure test curve was shown in figure 4, and the peak pressure of the curve was the quasi-static overpressure formed by impact reaction of the fragments.

![Figure 4](image)

**Figure 4.** The typical quasi-static overpressure-time curve.

2.4. Others

The zone-block velocity measurement targets were composed of two wire mesh targets. The first target was placed 7m from the ballistic rifle and that of the second target was 9m what made the fragments velocity from the ballistic rifle 8m could be measured. The velocity of the fragments impacting the targets could be obtained by using the method proposed in [18]. The sabot was made of nylon 1010. The sabot would be separated from the fragments at a certain distance from the launching port of ballistic rifle, and then the closed pressure tank was impact by the fragments only.

3. Results and analysis

3.1. Analysis of quasi-static overpressure

In order to compare and analyse the impact-initiated reaction and energy release process of four fragments, the pressure-time curve data measured by the experiment had been derived, and the zero time had been triggered uniformly by data processing. Origin software had been used to redrawn, and the typical curves of quasi-static overpressure-time of four reactive fragments had been obtained, as shown in figure 5. It can be seen from figure 5 that the quasi-static overpressure-time curve of impact-initiated reaction of Ni-Al-W reactive fragments was similar to that of metal-polymer reactive materials proposed in [9]. Within about 25 milliseconds, the energy had been released rapidly to the maximum, and then the quasi-static overpressure decreased gradually lasting for hundreds of
milliseconds under the action of decompression, produced by the penetrated holes at the front of the panel. The velocity of the reactive fragments impacting the targets had been controlled about 1000±50m/s, and at least three valid data had been collected for each fragment. The quasi-static overpressure data of the four fragments at this velocity had been measured, as shown in table 2. It could be found that with the increase of W component content, the quasi-static overpressure increased at first and then decreased. The quasi-static overpressure was the largest when W component was 10%. The relationship between the energy release of reactive fragments and quasi-static overpressure was given in [17].

\[ \Delta E = \frac{v}{\gamma-1} \Delta P \]  (1)

In the formula, \( \Delta E \) represented the energy released in the impact process of the reactive fragments. \( v \) represented the velocity of the reactive fragments impacting the targets. \( \gamma \) represented the air insulation index, usually take 1.4. \( \Delta P \) represented the quasi-static overpressure measured by the experiment. Therefore, when the content of W was 10%, the energy release of the reactive fragments was maximized. It could be seen that the addition of a certain mass fraction of W components what had been proven to be beneficial to increase the energy release efficiency of Ni-Al-W reactive fragments.

![Figure 5. The quasi-static overpressure-time curve of four fragments.](image)

**Table 2.** The quasi-static overpressure of the reactive fragments.

| Sample Description | Impact velocity | Quasi-static overpressure | Average Quasi-static overpressure |
|--------------------|----------------|--------------------------|----------------------------------|
| 1#                 | 988            | 0.043                    |                                  |
|                    | 1044           | 0.044                    | 0.046                            |
|                    | 1046           | 0.052                    |                                  |
|                    | 974            | 0.083                    |                                  |
| 2#                 | 997            | 0.077                    | 0.077                            |
|                    | 1010           | 0.071                    |                                  |
|                    | 984            | 0.112                    |                                  |
| 3#                 | 1003           | 0.133                    | 0.128                            |
|                    | 1025           | 0.138                    |                                  |
|                    | 957            | 0.089                    |                                  |
| 4#                 | 987            | 0.102                    | 0.093                            |
|                    | 995            | 0.087                    |                                  |
3.2. **Analysis of the residual particles after reaction**

The residual particles had been collected which had been left after the impact on the chopping block of the reactive fragments, and the screen mesh had been used for grading them depend on the diameter of the particles. Take the residual particles of 3# sample as an example, as shown in figure 6. It shows that the reactive fragments had been broken into a lot of small particles after impacting the chopping board, and the diameter of particles ranging from tens of micrometers to several millimeters. SEM analysis had been performed on each diameter level of particles, as shown in figure 7. It shows that the morphology of the residual particles after impact was quite different under different particle scales. When the particle diameter was $0.075 < d < 0.9$ mm, under the condition of enlarging to 20-micron scale, the surface of the particles was furry that could be identified as the metal particle oxide. When the particle diameter of the particles was less than 0.075, various forms was presented in the particles of the reaction products, and there were two-phase metal particles, empty shell particles and furry particles, and the above experimental phenomenon proved that the reactions should be more complex.

![Figure 6. The residual particles after reaction.](image)

![Figure 7. The SEM photos of reaction products.](image)

**Table 3.** Normalized mass distribution.

| Samples | the residual particles after reaction mass | Mass and percentage of the residual particles with different diameters |
|---------|------------------------------------------|---------------------------------------------------------------|
|         |                                          | 0.15–0.9 mm | 0.075–0.15 mm | <0.075 mm           |
The graded particles of four fragment reaction products had been weighed separately to obtain the normalized mass distribution. From table 3, it could be found that the small particle, produced from the fragments impacting the chopping board was increased with the improvement of the mass percentage of W added to the material component. The mass percentage of the was maximized when the mass fraction of W was 10%. The number of small particles was decreased when the mass of W reaches up to 20%, which may be affected by the mechanical properties of the material. The strength and plasticity of Al-Ni-W active material of fine W particles are higher than that of coarse W, which was not conducive to the fragmentation of the fragments after the impact.

3.3. Analysis of reaction mechanism
The study has indicated that the formation of Al, Ni, W particles are quite different under different environmental conditions. Possible exothermic reactions were revealed in [13], as shown in table 4.

| reactants   | products | reaction heat (kJ·g⁻¹) |
|-------------|----------|-----------------------|
| Ni+Al       | NiAl     | 1.38                  |
| 3Ni+Al      | Ni₃Al    | 0.75                  |
| 3W+Al       | W₃Al     | 0.13                  |
| Al+3/2O₂    | Al₂O₃    | 31.2                  |
| Ni+1/2O₂    | NiO      | 4.1                   |
| W+O₂        | WO₂      | 3.22                  |

Table 4. Possible exothermic reactions of the Al-Ni-W reactive fragments.
Based on the possible product types, the XRD component analysis had been used to analyze the components of the residual particles of four fragments. It could be seen from figure 8 that partial all four reactive fragments had been reacted. The graded particles were smaller while the peaks’ of XRD diffraction curve was more, which indicated that the types of the reaction products were more and the degree of the reaction was higher and more intense, what was consistent with the SEM analysis results. The residual particles of 1# fragment were AlNi, NiO and a small amount of AlNi5 which was only present in d < 0.075mm particles. The residual particles of 2# fragment were AlNi and NiO. The residual particles of 3# fragment were AlNi and NiO. The residual particles of 4# fragment were AlNi, NiO and a small amount of WO2. All of which exemplified that intermetallic reaction and oxidation reaction were the main reaction types of Al-Ni-W metallic reactive fragments, and the reaction products were mainly AlNi and NiO. Since all four reactive fragments contained unreacted residues, it is impossible to determine the main type of the reaction based on the final energy release value. The study [16] showed that the energy release efficiency of the metal reactive fragments increased with the increase of the velocity of the reactive fragments impacting the targets. Therefore, improving the impact velocity of the fragments would be considered in the subsequent studies, so that the residual particles was free of unreacted components as much as possible, so as to analyze the reaction mechanism of the reactive fragments qualitatively.

4. Conclusions
(1) When the impact velocity was 1000±50m/s, several Ni-Al-W metallic reactive fragments with different W content could initiate the chemical reactions, release energy and form quasi-static overpressure.
(2) By adding a small amount of W to the component, it is beneficial to improve the energy release level of the impact reaction, initiated by the Ni-Al-W reactive fragments impacting the targets. When the mass fraction of W component was 10%, the quasi-static overpressure was maximized.
(3) The mechanism of energy release reaction for metallic reactive fragments was mainly the intermetallic reaction of Ni and Al and the oxidation reaction of Ni metal with air, producing NiAl and NiO at the impact velocity of 1000±50m/s. The particles formed after the fragments impacting the chopping block was smaller, the part of the reacted reactive fragments was more and the degree of the reaction was higher and more intense.

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