Study on mechanical properties and fragmentation under detonation loading of different types of tungsten alloys

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Abstract. In practical engineering, the fragments of warhead may be deformed and broken due to strong extrusion, material softening and other factors, which seriously affects the damage strength of warhead. In this paper, 93W-Ni-Fe, which is commonly used as fragment material, was selected as the research object. The static and dynamic properties of 93W fragments obtained by two different heat treatment processes were tested, and the crushing property and dynamic stress-strain curve were obtained. The static explosion test was also carried out. After the fragments were recovered, it was found that 1# fragment can basically ensure the integrity, 2# fragment had more fragmentations. The study showed that the fragmentation of tungsten alloy fragments was closely related to its structural characteristics and dynamic properties. The low stress and large deformation characteristics of 2# fragile specimen may be related to the distribution of the bonding phase.

1. Introduction
Fragments are the main killing elements of the warhead, which dynamic mechanical response under high-speed driving directly determines the damage effect of the warhead. Tungsten alloy is widely used in the killing fragment because of its high density, good toughness and high strength. However, it is found that even if the tungsten alloy material with excellent mechanical properties is selected, it is often difficult to avoid the phenomenon of damage crack and breakage under the detonation loads, which reduces the quality of single fragment and presents irregular shape, resulting in the lack of kinetic energy of fragment and the weakening of penetration ability.

A lot of researches have been carried out on the fracture characteristics of tungsten alloy at home and abroad. Mott and other scholars [1] in the UK first carried out a series of researches on the mechanism of one-dimensional ring expanding and breaking under the action of internal charge explosion. Tan Duowang [2] in China studied the deformation and breaking of spherical tungsten alloy fragments driven by detonation, and found that the crushing rate of fragments with diameters of 6.0 and 7.5mm was 2%~3%. The crushing rate of 8.5mm diameter was 45%. Wang Yingchun [3] studied the fracture forms of different tungsten alloys under the same explosion conditions, combining with the analysis of strength factors. He found out the brittleness characterization parameters of tungsten alloy materials under the explosion conditions. In addition, the heat treatment method of tungsten alloy fragment is also important. Different heat treatment methods will lead to different performances, for example, different sintering temperatures will affect the compression property of tungsten balls [4], and then influence its integrity under detonation loads.

In this paper, 93W-Ni-Fe alloy fragments were prepared by two heat treatment processes. The mechanical properties and integrity under detonation loads of the two kinds of tungsten fragments
were compared. The mechanism of fragmentation under detonation loads was analyzed to provide technical support for the process optimization of tungsten fragments.

2. Mechanical property test

2.1. Static crushing properties

At present, the acceptance of fragment materials is mainly based on crushing property. It is considered that fragment materials that can pass crushing property test are up to standard, and can be applied to warhead kill components and ensure a certain damage power. According to the requirements of GJB3793A-2018 specification for Tungsten alloy balls for ammunition, the crushing property is carried out on the material testing machine. First, measure the size of the tungsten alloy cube with a micrometer, select the corresponding load according to the crushing property index table, then place the cube on the special clamp of the testing machine, apply the load at the speed between 5mm/min and 10mm/min, and maintain the pressure for 10s. After pressure reliefs, conduct visual inspection if there is any crack on the surface of the specimen after deformation, then measure the height of specimen with micrometer and calculate the deformation rate of tungsten alloy fragment according to equation (1):

\[ \delta = \frac{L_0 - L}{L_0} \times 100\% \]  

(1)

Where, \( \delta \) is the deformation rate of the sample, \( L_0 \) is the initial side length of the sample(mm), \( L \) is the height of the sample after deformation(mm). According to the national military standard, the deformation rate is no more than 40% and no obvious cracks are found, that is to say, it is considered that the material has passed the acceptance of crushing property.

According to the above specifications, two kinds of tungsten alloy cube fragments in this study were tested by crushing test. The crushing load was 30kN. As shown in figure 1, two kinds of tungsten fragments have different degrees of deformation, but there is no obvious crack. After measuring their height, the deformation of 1# fragment was calculated as 15%, and 2# fragment was calculated as 23%, which were both less than 40% deformation required by crushing index. According to the current acceptance criteria, both of them can meet the property requirements of the national military standard for fragment materials.

![Figure 1](image.png)

**Figure 1.** Crushing property test results.

2.2. Dynamic mechanical properties

The dynamic property experiment was carried out on a split Hopkinson pressure bar(SHPB). Its working principle is that the impact bar impacts the left end of the incident bar at a certain speed under the driving of high pressure gas, forming a direct incident compression pressure wave in the input bar and recording the strain \( \varepsilon_i \) through a strain gauge. After the incident wave compresses the specimen, it produces a reflected stress wave and transmitted stress wave, which are recorded as \( \varepsilon_r \) and \( \varepsilon_t \) by strain gauge respectively. The function of the absorption bar at the right end is to absorb the transmitted stress wave and reduce the error caused by multiple reflections of stress wave. Under the assumption of one-dimensional strain and stress uniformity, the dynamic stress-strain curve of the specimen can be deduced. Figure 2 is the schematic diagram of the experimental device.
In this experiment, three groups of SHPB experiments were carried out on the two kinds of samples with \(\Phi 5 \times 2\) mm cylinder at room temperature of 20\(^\circ\)C. As shown in figure 3, the true stress-strain curves of the two specimens at different strain rates were obtained. From the overall trend, the two tungsten alloy samples showed certain strain rate effects, but under the same experimental conditions, the two materials showed completely different dynamic mechanical properties. The 1\# sample had an explicit elastic rising section, a plastic yielding section and a stress relaxation section. With the increase of strain rate, the specimen exhibited the characteristics of increasing yield strength and decreasing failure strain, while the trend of 2\# specimen was more abnormal (excluding experimental operation factors), which was similar to the dynamic stress-strain trend of the foam materials. First the specimen appeared large deformation under the action of load, then the stress increased rapidly until the damage occurred instantaneously. Different stress histories may lead to different integrity under detonation loads.

3. **Research on static explosion test**

According to the requirement of charge-weight ratio of the warhead used in the static explosion test, the shape and size of the fragment are determined as the cube with side length of 6mm. For these two kinds of tungsten alloy fragments accepted by crushing test, the research team selected a certain type of warhead, tested the lethality of fragments through static detonation test, and studied the mechanical response of fragments under detonation loads. The test was carried out in a test base, as shown in figure 4 and figure 5, which were the fragment area distribution and the shooting range layout of the test sample projectile. 1\# and 2\# fragments occupied 180\(^\circ\) semicircle areas respectively, and 10mm thick steel target plates and rubber plate recovery devices were erected at a distance of 6m from the explosion center. The steel target plates were used to evaluate the damage power and armor penetration performance of the fragments. And the fragments were recovered by the recovery devices, so as to study the material characteristics such as fracture mode and fracture morphology.
Figure 4. Fragment area distribution.

The perforation photos of the two kinds of fragments in the static explosion test of the warhead principle prototype were shown in figure 6. The painted dots represented that the fragments successfully penetrated the target plate. Comparing the two figures, it was found that there were many holes in the target plate of 1# fragment, which indicated that the fragments made of this material can maintain certain integrity after being driven by detonation loads, and had high penetration probability to steel plate, which indicated that the detonation energy of explosive was fully utilized. However, the number of holes in the target plate of fragment 2# was less than fragment 1#, which indicated that the fragmentation in this area was serious after being subjected to detonation loads, resulting in low penetration ability of steel plate, reducing the damage strength of warhead, and failing to achieve the expected damage effect of warhead design.

Figure 5. Shooting range layout.

Figure 6. Perforation diagram of target plate.

Because of the high speed of static explosion test and the complexity of test environment, it is difficult to recover fragments. In this test, several pieces of fragments were successfully recovered by means of multilayer rubber plate. As shown in figure 7, the morphology of the fragments was recovered from 1# and 2# materials respectively after being subjected to detonation loads.
Apart from some small defects on the surface, 1# fragments can basically keep the original shape of a cube, and only have obvious extrusion deformation along the direction of detonation wave propagation. It can mainly keep the flight state according to the design direction and angle of dispersion, and had certain detonation strength. According to the recovered samples, the fragmentation rate was estimated to be about 2%~3%. However, the 2# fragments of were obviously broken. At present, the generally failure modes of tungsten alloy driven by detonation are tensile failure, shear failure, spallation, crushing, etc. It can be seen from figure 7(b) that the fracture mode of 2# fragment was mainly tensile failure. There were many cross fracture sections in splitting form, accompanied by a small amount of shear failure surfaces and some recovered debris fragments which may be related to the back and forth propagation of detonation wave, interaction and material softening caused by high temperature and pressure. According to the 2# recovered samples, it can be seen that almost all of them were broken due to the serious deformation of fragments.

4. Analysis of the fracture mechanism of detonation loading

Combined with the dynamic properties and microstructure of the two tungsten alloys, the fracture mechanism of the two materials under detonation loads was analysed respectively. The crushing rate of 1# sample under detonation loads was only about 2%~3%. The overall trend of its dynamic stress-strain curve was consistent with the trend of dynamic mechanical properties of common metal materials. A complete mechanical response stage was presented in which the elastic segment rose first, and then plastic yield occurred until failure, showing obvious strain rate effect. The results showed that under detonation loads due to the thick buffer layer in the warhead, the actual compression load of 1# specimen was lower than its compressive strength so that it can bear the impact compression load under the condition of short time and small strain. When the shock wave was introduced into the fragment from one end, the other end would be affected by the tensile wave reflected by the air, so that it was far away from the explosion source at a speed of more than 2000m/s, which was conducive to its integrity. Figure 8(a) showed the microstructure of the recovered 1# specimen. It can be seen that the shape of tungsten particles was approximately circular. Except for the tight connection between a small part of tungsten particles, most of the tungsten particles were evenly wrapped by the bonding phase, which maintained a good biphasic structure. It also showed that the specimen had not undergone the overall large deformation.

The 2# specimen was almost completely broken under the detonation loads, which indicated that although the shock wave pressure was attenuated by the buffer layer, it still led to a large overall deformation, which made the fragments fracture. It can be seen from its stress-strain curve that 2# specimen had similar properties with aluminium foam materials. The large deformation at low pressure occurred first at the initial stage of loading. This may be due to the uneven distribution of the binder phase and the formation of local aggregation in 2# tungsten alloy. The rapid increase of stress in the later stage may be due to the deformation and flow of the binder phase and the collision of tungsten alloy particles. The electron microscope analysis was carried out on the recovered 2# specimen. Figure 8(b) showed the end face of the recovered 2# specimen. It can be seen that the particles varied in shape, and the binding phase had obvious flow traces. Figure 9 showed the fracture morphology of the 2# specimen, and it can be seen that the average particle size at the fracture was
significantly lower than its end face, which verified the fracture behaviour of tungsten alloy particles due to collision under the condition of large deformation.

![Figure 8. Morphology of fragment microstructure.](image1)

![Figure 9. The fractographic morphology of 2# fragment.](image2)

5. Conclusions

(1) The static crushing properties of tungsten alloy fragments obtained by different heat treatment methods were similar, but the dynamic mechanical properties showed obvious differences. The 2# specimen showed characteristics of low stress and large deformation, which may be related to the distribution of bonding phase.

(2) Under detonation loads, the integrity of 1# fragment was obviously better than that of 2# fragment. The fragmentation of tungsten alloy fragment was closely related to its structural characteristics and dynamic properties. The results of static crushing test were not enough to characterize its fragmentation characteristics under detonation loads.

References

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