Effect of Heat Treatment Process and Composition on Deformation and Damage Behavior of WHA under Detonation Loading

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Abstract. The excellent material properties of tungsten heavy alloy (WHA) make it widely used in the military field. When used as killing elements of weapons, its dynamic mechanical properties under detonation loading directly determine the damage effect of weapons, which makes the research on its mechanical behaviors under high pressure and high strain rate loads such as detonation loading of great significance. In this paper, several WHAs with different compositions and processes are selected, and the mechanical properties and deformation and damage behavior under static explosion test are analyzed by combining macro and micro study, so as to provide guidance for the subsequent optimization of the performance design of WHA.

Keywords. Tungsten heavy alloy, detonation loading, heat treatment process, mechanical property.

1. Introduction

Tungsten heavy alloy (WHA) is a kind of alloy formed by taking tungsten as the matrix phase and combining nickel, copper, iron and other elements. It both has the advantages of tungsten (W) phase and matrix phase [1, 2]. Its performance advantages are mainly high density, usually 16.5~19.0 g/cm³, high strength, high hardness, good toughness, low coefficient of thermal expansion, high coefficient of thermal conductivity, high temperature resistance, good impact toughness and machinability, etc [3-5]. So it has been widely used in various fields. In addition, under the condition of high-speed collision, WHA can maintain good penetration ability and killing power. It is often used as the killing element of weapons and ammunition, such as the core of armor-piercing projectile, shaped charges, killing fragments in warhead, etc [6].

Due to the remarkable military performance of WHA, many scholars have shown great interests in them. From the aspects of composition and process [7, 8], the effects of different tungsten content [9] or the addition of Cu, Co, Mo and other alloy elements [10-12] on the microstructure and mechanical properties of WHA are considered. It is found that the W-W interface is a weak area in WHA. The increase of tungsten content will increase the W-W connectivity and significantly reduce the plasticity of the material, but the existence of matrix phase can effectively prevent the crack propagation. In addition, alloy elements will also have impacts on the strength and toughness of WHA. For example, Co can optimize the high temperature properties [13-15] of WHA and prevent the formation of γ-phase (W-Ni) intergranular compound, which strengthens the properties of bonding phase. Although the addition of Mo
slightly improves the strength, it significantly reduces the elongation and impact toughness of WHA. Considering the service environment, the performance response of WHA under different strain rates and different temperatures are studied. In general, the yield strength of WHA will increase with the increase of strain rate due to work hardening effect, and will decrease with the increase of temperature due to the thermal softening. Adiabatic shear bands also appear in some WHAs at high strain rates, which is of great significance for the self sharpening effect of alloys and improving penetration performance. In addition to the basic performance research, considering that the application environments of WHA are often extreme as ammunition, and the service loads generally have the characteristics of instantaneous ultra-high temperature and high pressure, many scholars have also carried out research on military applications.

Based on the military application background of WHA, it is of great significance to study its mechanical behavior under high pressure and high strain rate loads such as detonation loading. In this paper, four kinds of WHA are prepared by different processes after liquid phase sintering. They are made into standard specimens and cube shapes required for static explosion test, in order to study the deformation and damage behaviors under detonation load. Firstly, the mechanical property test and fracture analysis are carried out. Then, the static detonation test is carried out. Combined with metallographic observation, the micro performance differences of fragment loading surfaces before and after detonation loadings are discussed, and the morphology and deformation of recovered fragments are statistically analyzed. The change and influence of detonation load on the properties of different materials are discussed by combining macro research and micro research, so as to obtain the mechanical response of WHA under this extreme load and provide guidance for the subsequent optimization of the performance design of WHA.

2. Experiment
In this study, 93W-4.9Ni-2.1Fe (wt.%) and 92.5W-4.9Ni-2.1Fe-0.5Co (wt.%) are prepared respectively according to the types of WHAs commonly used in the warhead. The raw powder parameters are shown in table 1. Tungsten powder, nickel powder, iron powder and cobalt powder are mixed into the ball mill in proportion. The ball mill is made of stainless steel, the ball material ratio (BPR) is 2:1, and ground at the speed of 80 r/min for 48 h. The fully milled powder is added into a specific mold, which is pressed at 300 MPa for 20 min for cold isostatic pressing, and then liquid-phase sintering is carried out. The sintering temperature is 1460°C, the holding time is 2 h, and the sintering atmosphere is hydrogen. After sintering, it is kept in a vacuum sintering furnace at 1150°C for 3 h, and the vacuum degree is 10⁻³ Pa.

| Powders | W   | Ni  | Fe  | Co  |
|---------|-----|-----|-----|-----|
| Particle size/μm | 9±0.3 | 3±0.5 | 7±0.7 | 4±0.5 |
| Purity/% | 99.9 | 99.5 | 99.5 | 99.7 |
| Density/(g/cm³) | 19.32 | 8.91 | 7.8 | 8.9 |

The standard tensile test specimen and cube fragments are obtained by wire cutting, and the density is measured by Archimedes drainage method. After the basic standard metallographic preparation procedures such as cutting, inlay, grinding and polishing, microstructural study is carried out using scanning electron microscope, and the element content is analyzed with the help of Energy Dispersive Spectrometer (EDS) analysis system, so that the corresponding microstructure characterization parameters are obtained, such as W grain size, W-W contiguity, volume fraction of matrix phase, etc. The W-W contiguity $C_g$ is usually calculated by the following formula:
\[ C_g = \frac{2N_{WW}}{2N_{WW} + N_{WM}} \]  

(1)

where, \( N_{WW} \) is the number of W-W interfaces in unit length, \( N_{WM} \) is the number of W-M (W phase-matrix phase) interfaces per unit length. In order to reduce the errors, the number of \( N_{WW} \) shall not be less than 200 [16]. The quasi-static tension test is carried out on a universal material testing machine at room temperature (20°C) at a loading rate of 0.005 m/s.

According to the requirements of the backfill ratio of the projectile often used in the static explosion test, the shape and size of the fragments are determined as cubes with a side length of 6 mm, and the dynamic mechanical response and deformation of different fragments under detonation loading are tested. As shown in figure 1 and figure 2, the area of fragment distributions and test range layout of the test projectile are shown. The fragments of each WHA account for 1/4 of the arc surface. The fragments are recovered in the rubber plate recovery devices which place 6 m away from the detonation center. Then the deformation and fracture rate of the recovered fragments are counted, and the fracture morphology and fracture mode after detonation loading are studied by the scanning electron microscope. The initial velocity of fragments is measured by the cut-off method.

**Figure 1.** Fragments distribution of projectile.  
**Figure 2.** The arrangement of test range.

3. Results and Discussions

3.1. Microstructure

The research shows that when the ratio of Ni to Fe is in the range of 2~4, the mechanical properties of WHA are better. For the WHA commonly used in warheads, the ratio of Ni to Fe of is usually 7:3, which effectively inhibits the formation of intermetallic compounds. Considering the influence of Co content on the density and mechanical properties of WHA, the addition amount is usually between 0.5%~3%. As shown in table 2, W-Ni-Fe and W-Ni-Fe-Co are prepared according to different compositions and processes. 1# and 2# WHA are sintered, 3# WHA is vacuum heat treated after sintering, and 4# WHA are swaged after vacuum heat treated to obtain higher strength properties.
Table 2. Composition and processing of WHA.

| No. | Composition/wt.% | Heat treatment process | Density/(g/cm³) |
|-----|------------------|-----------------------|----------------|
| 1#  | 93W-4.9Ni-2.1Fe  | Sintered              | 17.56          |
| 2#  | 92.5W-4.9Ni-2.1Fe-0.5Co | Sintered          | 17.60          |
| 3#  | 92.5W-4.9Ni-2.1Fe-0.5Co | Vacuum          | 17.58          |
| 4#  | 92.5W-4.9Ni-2.1Fe-0.5Co | Swaged           | 17.24          |

The mechanical properties of WHA are generally determined by the micro property parameters such as the size of W grains, the volume fraction of matrix phase, the content of W in matrix phase and W-W contiguity, and will also be affected by the mixed elements. Detailed parameters are shown in table 3. Compared with W-Ni-Fe, the average grain size of W-Ni-Fe-Co decreases slightly, which is due to the addition of Co. Figure 7 is the SEM photographs of WHAs. On the left is the microstructure of the original fragments of the material. It can be seen that the basic micro morphology of WHA is composed of W grains and Ni-Fe-W or Ni-Fe-Co-W matrix phase. And 1# and 2# WHA have large grain size dispersions, while 3# reduces the grain size dispersion after vacuum heat treatment, improves the distribution uniformity of matrix phase and W grain, and reduces the contiguity of W-W grain. In addition, the content of W in the matrix phase of 2#, 3# WHA increased significantly compared with 1#, because Co and Ni can be solubilized indefinitely, which can reduce the wetting angle of WHA, increase the solubility of W in the matrix phase, and thus increase the strength of the matrix phase. It shows that the higher the W content in the matrix phase, the lower the wetting angle of tungsten heavy alloy. Meanwhile, it can enhance the bonding strength of the interface between W phase and matrix phase, to make sure the effective transfer of stress between W grain and matrix phase, so as to improve the mechanical properties such as strength.

3.2. Tensile Properties
The static tensile stress-strain curves of WHAs are shown in figure 3. And the test results of mechanical properties are shown in table 4. For 1# and 2# WHAs with the same heat process treatment, the W-W contiguity of WHAs with Co containing is low, and the W-W interfaces are the weakest bonding interfaces in the alloy and the primary area of crack nucleation. Lower contiguity means lower fracture ratio of W-W interfaces, which corresponds to better alloy plasticity. In addition, the matrix phase forms Ni-Fe-Co ductile phase, and Co increases the solubility of W in the matrix phase and the bonding strength of W-matrix interfaces. Therefore, the mechanical properties of 2# alloy with Co are better than 1#, which shows higher strength, elongation and hardness.

Figure 3. The static tensile stress-strain curves of WHAs.
The processing technology will also significantly affect the mechanical properties of the material. After vacuum heat treatment, the hydrogen content in the texture is reduced, the defects of residual pores caused by sintering atmosphere are improved, the distribution uniformity of matrix phase is improved and the average size of W grains is reduced. Compared with 2# WHA, the plastic property of 3# is improved and its strength is slightly increased. The strength and hardness properties of 6# alloy increase significantly after swaged, but the plasticity decreases greatly due to the work hardening behavior with the plastic deformation.

Impact toughness usually reflects the ability of materials to resist impact deformation and represents the toughness of materials under dynamic loadings. It is usually affected by material compositions, grain sizes and other microstructures, as well as impurities, pores and other defects in the alloy. The elongation of the swaged 4# WHA is only 3.37%, which shows the characteristics of brittle materials. Therefore, its impact toughness is only 90J/cm², which is significantly lower than that of other WHAs. Combined with the SEM photographs shown in figure 4, 3# WHA has excellent micro-morphology with uniform grain size, uniform matrix phase distribution and low porosity. At the same time, it has excellent performance in strength and plastic properties, which makes it obtain high impact toughness.

| Alloy | 0.2%YS/MPa | UTS/MPa | Elongation/% | Impact/(J/cm²) | Hardness/HRC |
|-------|-------------|---------|--------------|----------------|--------------|
| 1#    | 661.25      | 1056    | 10.2%        | 100            | 28.75        |
| 2#    | 708.06      | 1114    | 15.8%        | 185            | 31           |
| 3#    | 736.31      | 1217    | 19.5%        | 220            | 31.5         |
| 4#    | 1247.63     | 1369    | 3.37%        | 90             | 41.5         |

3.3. Static Explosive Test Results

Detonation load is a kind of instantaneous ultra-high temperature and high pressure load condition. The instantaneous pressure is nearly 50 GPa and the temperature is up to thousands of degrees. It is also accompanied by the propagation of detonation waves. Due to the extremely high loading speed and complex loading environment, it is difficult to explicitly point out the deformation degree and fracture modes of fragments. From a macro point of view, the main failure modes of fragments under detonation load are: (1) the tensile failure of materials caused by the interaction of detonation waves in materials; (2) extrusion deformation of fragments and material softening caused by high pressure and temperature produced by detonation.

The warhead initiation mode is central initiation, and the detonation energy is uniformly distributed along the circumferential and axial directions, so as to ensure the consistency of the initial dispersion angle and initial velocity of the circumferential fragments. The average initial velocity of the fragments is 2053.4 m/s measured by the velocity target.

The deformation and fracture mode of recovered fragments are statistically analyzed to characterize the mechanical response of different WHAs driven by detonation loading. The fragments recovered from each WHA are shown in figure 4. The recovered 1# fragments are seriously damaged and deformed. There are not only irregular large deformation and thickness reduction due to extrusion, but also splitting or spalling due to tension. There are many cracks on the face of fragments, and the mechanical properties are obviously weakened, which has a great impact on the subsequent killing capacity. The deformation of 2#, 3# and 4# WHAs is slightly less than 1# WHA, but there are still some cracks on 2# and 4# faces. The ability of 3# WHA to resist the impact of detonation waves is obviously stronger than other materials, which can better maintain the original shape to complete the established killing mission.
Considering the difference of macroscopic morphology and deformation characteristics of different fragment materials driven by detonation, as shown in figure 5, the number of recovered fragments is counted according to the difference of deformation degree. Meanwhile, the average thickness of fragments along the propagation direction of detonation wave is measured.

According to figure 6, except for 4# materials, the number of fragments recovered from each material is about 25. It can be considered that the recovery quantity is basically stable, which means the error caused by uncertain factors can be controlled under the extreme detonation environment. The number of
4# recovered fragments is only 15, which is significantly less than that of other materials. It is indicated that this WHA has a weak ability to maintain structural integrity under ultra-high temperature and high pressure load driven by detonation, which increases the possibility of catastrophic fractures.

When the target is far away, the intensity of shock waves generated by explosion decays rapidly in the air for the killing warhead. In this case, only high-speed fragments become the main damage element. Therefore, the mechanical properties of fragments driven by detonation loading directly determine the damage effect of the warhead. Among the 1#, 2# and 3# materials, which are recovered in similar quantities, 1# fragments are seriously damaged and deformed, and multiple fragments have obvious cracks and damage fractures. Only 6.7% of 1# fragments can maintain the morphology of the original fragments. Compared with the original size of 6 mm, the average residual thickness of 1# fragments is only 4.33 mm along the propagation direction of detonation wave, and the deformation rate is as high as 27.7%, which is much larger than other materials. It should be noted that when the fragments have large deformation or cracks, on the one hand, the defects will absorb detonation energy, resulting in the reduction of kinetic energy, on the other hand, excessive deformation makes it difficult for the fragments to maintain the original dispersion direction of the warhead, which will weaken the damage ability of killing fragments. From a macro point of view, the mechanical properties of 3# fragments are obviously better than those of other materials, which have strong resistance to deformation and damage. 63% of fragments can maintain the original shape well after being impacted by detonation wave. The average thickness along the wave propagation direction is 5.02 mm, which just have a little deformation. So the energy loss is reduced as much as possible in the process of converting detonation energy into damage energy, which has high damage efficiency.

3.4. Microstructure after Detonation

As shown in figure 7, the right column is the microstructure of the recovered fragments after detonation loading. Compared with the original SEM graphs, the average grain size of recovered fragments and the W-W contiguity increases significantly.
Figure 7. Microstructure of fragments before and after detonation loading.

The right column of each parameter in table 3 is the microstructural parameters of the recovery fragments, and the measuring face is the face perpendicular to the direction of explosion loading. It can be seen from the graphs that whatever heat treatment process and composition ratio the WHAs are carried out, the average size of W grains increases obviously due to thermal softening and large strain rate load. Meanwhile, it is accompanied by the increase of contiguity and the slight decrease of the volume fraction of matrix phase. However, as shown in figure 4, the increase of average grain size of 1# WHA is significantly greater than that of 2#, which is due to the addition of Co element so that it shows more
uniform distribution of matrix phase in the alloy, the increase of bonding strength of W-matrix interfaces and the decreasing W-W contiguity. The good toughness of the matrix phase can share the load of W grains through the W-matrix interfaces, so as to reduce the grain deformation. Obviously, the increase of average grain size of 3# material is the smallest, which shows that 3# WHA has excellent microstructure and deformation resistance under detonation loading.

For 4# WHA, due to swaging treatment, the W grains are deformed greatly along the swaging direction and stick together. The microstructure of the original fragments is shown in figure 4(g). There is almost no obvious grain shapes and no obvious W-W interfaces. After detonation loading, the W grains deform tempestuously due to thermal softening caused by the instantaneous high temperature and high pressure. And the original bonded W grains are separated. Figure 4(h) starts to show the obvious circular tungsten grain morphology. Meanwhile, the average volume fraction of matrix phase increases a little after detonation loading.

Table 4. Microstructure parameters of WHAs before and after detonation loading.

| No. | Grain size/mm | Contiguity | W content in matrix phase |
|-----|---------------|------------|--------------------------|
| 1#  | 22.33         | 26.84      | 0.293                    | 19.32% | 21.94% |
| 2#  | 21.91         | 25.92      | 0.425                    | 18.17% | 22.36% |
| 3#  | 25.19         | 30.32      | 0.313                    | 22.34% | 24.19% |
| 4#  | 23.86         | 24.38      | 0.355                    | 22.64% | 22.29% |

3.5. Fractography

The fracture micro morphology of several materials are shown in the figure 5. Figure 5(a-1) ~ (a-4) are static tensile fracture morphology, and (b-1) ~ (b-4) are fracture morphology of fragments after detonation loading. There are four common fracture modes of WHAs: W grain cleavage, matrix phase failure, W-W interface decohesion and W-matrix phase separation. In general, the crack source appears first at W-W interface due to the weak bonding strength. during bearing. At the same time, some impurities, pores and other structural defects will inevitably be introduced in material. These areas are often the source of cracks.

For the static tensile specimens, the fractures are shown in figure 5(b-1) ~ (b-4), which is mainly composed of W-W interface separation and matrix phase failure, accompanied by certain W grains cleavage and W-matrix phase separation. Compared with the fracture of as-sintered WHA, the micropores and the fracture morphology with micropores as the initiation source of as-vacuum WHA in the fracture face are reduced, the failure proportion of the matrix phase is significantly increased, and the flocculent matrix phase reflects the good plasticity of the material. Due to the good toughness of matrix phase, plastic deformation occurs after loading, resulting in the behavior of strain hardening. Meanwhile, high bonding strength of the W-matrix phase interfaces can transfer stress effectively. In the fracture morphology with Co, a large number of circular W grains are well wrapped by the matrix phase, and there is little interface separation phenomenon, showing a high bonding strength of the W-matrix phase interfaces, which makes the material obtain excellent strength and plastic properties. The tensile fracture of the 4# WHA after swaging treatment is shown in figure 5 (b-4). A large number of W grains have river like cleavage texture on the surface, mainly including brittle cleavage fracture of W grains and tearing morphology of matrix phase, accompanied by a few W-W interface separations, which is the same as the research results of weerasoorlya. And there are obvious cracks between the matrix phase and the adjacent W grains. The good bonding interfaces between W and matrix phase are damaged due to swaging, and the tensile load acting on this weak bonding region produces cracks easily, which is consistent with Northcutt's study on the fracture with Scanning Electron Microscope results of W-Ni-Fe alloy after 20%
cold swaging.

The recovered fragments after detonation loading, which are embedded in the rubber plate driven by high temperature and high pressure load, have irregularity fractures, resulting in poor imaging effect. Xing Gong [17] found that the change of test temperature will significantly affect the fracture mode of WHA. As shown in figure 5, the fracture modes are significantly different from the tensile fracture at room temperature. Under the instantaneous ultra-high temperature and high strain rate load, the mixed fracture mode changed into W-W interface and W-matrix phase debonding cracking [18]. Some are accompanied by a small amount of cleavage fracture of W grains, such as 1# and 2#. Due to the obvious weakening of the bonding strength of the interfaces at high temperature, cracks nucleate preferentially at the W grains boundary and the W-matrix phase interface. And the morphology of W grains and matrix phase changed obviously under high temperature. The slip lines on the cleavage face of W grains appeared the flow morphology of solidification after melting, and the matrix phase also showed signs of thermal softening.

Taking 1# WHA as an example, the matrix phase compositions of two fractures are analyzed by energy spectrum, and the content of each element is listed in the table 5. It can be seen that after detonation loading, the content of W in the matrix phase is increased, and the contents of Ni and Fe are decreased a little. Kamrappam, Edmonds et al. [19] found that the brittle phase with W content of about 75% was detected in the 90W-Ni-Fe specimen cooling in the furnace after sintering, which led to the brittle properties of the material. Under the high-temperature and high-pressure detonation load, especially the instantaneous temperature of thousands of degrees, the W grains and matrix phase are rapidly rearranged. At the same time, the WHAs are subjected to strong impact compression and large plastic deformation driven by detonation loading, resulting in severe internal friction and temperature rising, which provides favorable conditions for element migrations and diffusions at the W-matrix interfaces. And the diffusion of W near the interfaces may form brittle phases with high tungsten content, which reduces the deformation coordination ability of the matrix phase, affects the plasticity and strength of the material and reduces the subsequent penetration damage property.

Table 5. Element content of matrix phase in sintered 93W.

| Element | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| W       | 16.59 | 18.52 | 14.61 | 17.89 | 18.53 | 18.56 | 19.18 | 20.48 |
| Ni      | 62.68 | 62.65 | 60.19 | 59.86 | 60.37 | 60.51 | 60.73 | 58.98 |
| Fe      | 20.73 | 22.74 | 21.29 | 22.25 | 21.10 | 20.93 | 20.09 | 20.53 |

(a) As-sintered 93W(Original) (b) As-sintered 93W(After detonation)
4. Conclusions
In this study, four kinds of WHAs are prepared through different composition ratios and processes. Through static tensile test, static explosion test and corresponding metallographic analysis, the different mechanical responses of WHAs after detonation loading are studied. The conclusions are as follows:

Figure 8. Fracture morphology of WHA.
(1) As a high-density hard metal, WHA fragments have strong resistance to deformation and failure under detonation loading. The micro metallographic study shows that when the WHA is subjected to thermal softening and high strain rate loading, the average grain size of tungsten increases obviously, accompanied by the increase of W-W contiguity and the slight decrease of the volume fraction of matrix phase.

(2) Vacuum heat treatment can significantly optimize the micro morphology of WHA. After the addition of Co, the bonding strength of W-matrix phase increases, and the toughness, strength, elongation and impact toughness of matrix phase also increases. Therefore, after detonation loading, 3# WHA (vacuum 92.5W) shows excellent resistance to thermal softening and impact deformation, and 63% of fragments can maintain original shapes.

(3) The strength of swaged WHA increases, but the elongation decreases greatly so that the fragment fracture ratio is higher after detonation loading, and the detonation fracture face presents significant brittle fracture characteristics. It means that the ability to maintain structural integrity is poor.

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