Research Article

Taiyong Zhao, Weizhan Wang*, Zhigang Chen, Shunshan Feng, Likui Yin, Jianping Fu, Lele Cheng, and Shuai Yang

Dynamic response characteristics of 93W alloy with a spherical structure

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Abstract: To study the dynamic response characteristics of 93W alloy spherical component under high overload, the deformation patterns of the 93W spherical component under different overloads are obtained by the sphereistic impact test, and the microscopic response characteristics are studied by the metallographic analysis experiments. Finally, the response characteristics are analyzed by the finite element method and the stress wave theory. The results show that with the change of impact overload, the axial direction of the 93W spherical component changes linearly with the radial deformation, and the axial strain increases with the increase of the impact overload. At the same time, along the radial direction from the center of the sphere, the micrograin distribution of 93W appears densely packed and sparsely separated, and the grain density is uniformly changed between dense area and sparse area, showing a ring-shaped “bright band” phenomenon between light and dark, and the width of the “bright band” is related to the size of the dense area of the grain; with the increase of the impact overload, the 93W alloy component first breaks at the central axis and the radial maximum position, and the fracture mode changes from the crystal fracture to the transgranular fracture tendency, and the two fracture forms eventually coexist.

Keywords: impact, deformation, bright band, fracture

1 Introduction

Tungsten alloys are widely used in the defense weapons industry because of their high density, high melting point, high strength, and good machinability. Among them, the 93W alloy tungsten sphere is widely used as a typical killing warhead damage element because of its excellent characteristics of tungsten alloy, small spherical structure drag coefficient, and big specific energy and power. For decades, various researchers have carried out a large number of experimental research studies and theoretical accumulations on 93W alloy tungsten sphere high-speed impact armor steel, successively calculated the ultimate penetration velocity of tungsten sphere [1–3], studied the deformation characteristics [4–6], and analyzed the target crater characteristics in the process of 93W alloy tungsten sphere high-speed impacting thin target and medium-thick target [7,8]. They also carried out experimental studies [9–12] and numerical calculation of the sphere breaking speed threshold and fragment fractal characteristics of the tungsten alloy spherical projectile during the impact of the target plate [12–15]. At the same time, researchers rely on the Hopkinson pressure bar experiment to study the mechanical properties [16–21], fracture mechanism [22–27], and strengthening characteristics of a rod-shaped 93W alloy component with different grain sizes [28], group distribution ratios, and process technology [29–31]. A variety of constitutive models [32–34] for related deformation and fracture failure are given. The experiments and numerical simulation were conducted to investigate the impact of spherical components such as metal and brittle materials on single-layer and multilayer target plates [35–37]. Results showed that the fracture characteristics, deformation degree, and posttarget distribution of spherical components are closely related to the impact overload applied on the components.

The aforementioned research studies are mainly based on the engineering application study of mechanical properties of 93W alloy and the mechanical properties

* **Corresponding author: Weizhan Wang**, National Defense Key Laboratory of Underground Damage Technology, North University of China, Taiyuan 030051, China, e-mail: weizhanw@126.com

Taiyong Zhao: School of Mechatronics Engineering, North University of China, Taiyuan 030051, China

Zhigang Chen, Likui Yin, Jianping Fu, Lele Cheng, Shuai Yang: National Defense Key Laboratory of Underground Damage Technology, North University of China, Taiyuan 030051, China

Shunshan Feng: State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

and constitutive model research of 93W alloy based on the Hopkinson pressure bar test. However, the response mechanism of 93W alloy with a spherical structure under high overload is less studied. It is relatively rare in the current published academic achievements. Therefore, it is of practical significance to study the dynamic response characteristics of 93W alloy with the spherical structure under high overload.

On the basis of mechanical properties of 93W alloy and the typical structural characteristics of the sphere, this article uses a 12.7 mm sphereistic gun to test the impact armor steel of $\varnothing 7.51$ mm spherical 93W alloy component and obtains the deformation patterns of 93W alloy component under different overload conditions. Subsequently, it studies the deformation and the fracture law of the microstructure of 93W component by metallographic analysis and combines the finite element method to numerically calculate the impact process, which better demonstrated the stress, strain change, and macroscopic deformation process of a tungsten sphere. Finally, the theoretical analysis of macroscopic and microscopic experimental phenomena is carried out based on the stress wave theory. Through the aforementioned research, the dynamic response characteristics of the 93W alloy under the spherical member during the impact process are well described.

2 Experimental plan

2.1 Experimental research

The experiment is carried out in the National Defense Key Discipline Laboratory of Underground Target Damage Technology of North University of China. A 12.7 mm caliber sphereistic gun is used to launch a $\varnothing 7.51$ mm spherical 93W alloy component to vertically impact the 603 armored steel with a thickness of 6.7 mm. The 93W alloy has a density of 17.8 g/cm^3 and a weight

of $3.95 (+0.05) \text{ g}$. It is sintered by the powder metallurgy method from W, Ni, and Fe composite powders. The powder injection molding method is used to prepare a tungsten alloy ball for military industry, and its injection defects are eliminated by adjusting the injection parameters. The comprehensive performance is mainly improved by adjusting the appropriate injection rate, injection pressure, and injection temperature process. Tungsten powder, nickel powder, and iron powder are mixed according to a certain mass ratio. Then, 93W NiFe and a certain proportion of a binder are mixed well in a XSM 1/20–80 type rubber mixer, and the mixed materials in a single extrusion granulation are transferred to a screw extruder. After drying in BOY50T2 injection molding on an injection molding machine, the shaped blank is degreased in homemade hydrogen. The product is degreased in a furnace and finally sintered in a hydrogen furnace. After the test, the tungsten sphere residue is recovered, and a metallographic analysis experiment is performed on the axial profile. Figure 1 shows the experimental equipment. Figure 2 shows the spherical 93W alloy component patterns and the 603 armored steel entity.

The impact velocity of the 93W alloy tungsten sphere is controlled from 401 to 1,511 m/s by adjusting the emission charge to study the dynamic response law of the 93W alloy component with the spherical structure under different overloads. The macroscopic and microscopic test phenomena of deformation and fracture of 93W alloy are observed and analyzed by adjusting the metallographic microscope objective lens at 0.8 times and 200 times.

2.2 Finite element research

To deeply study the dynamic response characteristics of 93W alloy tungsten sphere in the process of impacting

Figure 1: Experimental equipment: (a) 12.7 mm sphereistic gun, (b) JMC-K500 speed target, and (c) target frame.

Figure 2: Experimental spherical 93W alloy component and 603 armored steel: (a) $\varnothing 7.51$ mm 93W alloy tungsten sphere and (b) 6.7 mm thick 603 armored steel.

603 armored steel, based on the results of 2.1, the ANSYS/AUTODYN software is used to simulate the process of tungsten sphere impacting armor steel. A 1/4 axisymmetric 3D penetration model is established based on the vertical penetration environment of the component. The calculation grid uses Solid164 eight-node hexahedron units. The 93W component mesh size is 0.1×0.1 mm, the target grid size is 0.15×0.15 mm, and the whole model has 8,48,162 units. The Lagrange algorithm is used for the analysis of components and targets, and the face-to-face algorithm is used for the analysis of the contact between them.

In the impact process, the short action time, the high strain rate, and the plastic rheology of the metal material at high temperature and high pressure are considered. Both the 93W alloy and the armored steel adopt the JOHNSON-COOK thermal viscoplastic constitutive model and the GRUNEISEN state equation. The JOHNSON-COOK thermal viscoplastic constitutive model can better describe the strain hardening, strain rate strengthening, and coupling effect of a tungsten sphere and a target material during penetration. The plastic flow stress expression is given as follows:

$$\sigma_y = (A + B\bar{\epsilon}_p^n)(1 + C \ln \dot{\epsilon}^*)(1 - T^{*m}), \quad (1)$$

where σ_y is the material flow yield strength, A is the static yield stress, B is the strain hardening coefficient, n is the strain hardening index, C is the strain rate

correlation coefficient, m is the temperature correlation coefficient, $\bar{\epsilon}_p$ is the effective plastic strain, and $\dot{\epsilon}^* = \bar{\epsilon}_p / \dot{\epsilon}_0$ is the dimensionless effective plastic strain rate, considering $\dot{\epsilon}_0 = 1 \cdot s^{-1}$ as the reference strain rate. $T^* = (T - T_r)(T - T_m)$, where T_r and T_m are room temperature and material melting temperature, respectively. The specific parameters of 93W and 603 steel are presented in Table 1.

3 Results and analysis

A total of 14 $\varnothing 7.51$ mm spherical 93W alloy component impacting steel target tests are carried out, and the 93W component and the plugging pattern are recovered as shown in Figure 3. Figure 4 shows a schematic diagram of the axial section structure of the recovered spherical 93W component. The test data are presented in Table 2.

3.1 Macroscopic deformation analysis

The finite element method is used to carry out the numerical simulation of spherical 93W components with 507–1,511 m/s vertical impacting steel targets. Three kinds of 93W alloy component patterns under different impact overloads are selected for the study. As shown in

Table 1: Material performance parameters

Material	$\rho / \text{cm cm}^{-3}$	G_0 / GPa	μ	T_0 / K	T_m / K	$c / J \times (\text{kg K}^{-1})$	A / MPa	B / MPa	n	C	m
93W	17.8	137	0.3	293	1,723	134	1,506	177	0.12	0.015	1.00
603 steel	7.8	75	0.33	293	1,793	477	1,120	500	0.26	0.014	1.03

Figure 3: 93W components and squeezing patterns under different impact overloads.

Figure 4: Schematic diagram of spherical 93W alloy component. Note: h is the axial height of the component and d is the radial dimension of the component.

Table 2: Test measurement data

Number	1	2	3	4	5	6	7
Mass/g	3.93	3.91	3.91	3.98	3.87	3.94	3.99
h/mm	6.93	6.88	—	6.83	6.72	6.60	6.48
d/mm	7.63	7.68	—	7.71	7.77	7.91	8.02
Number	8	9	10	11	12	13	14
Mass/g	3.91	3.95	3.79	3.89	3.96	3.91	3.94
h/mm	—	6.40	6.31	6.21	6.02	5.93	5.82
d/mm	—	8.13	8.20	8.28	8.35	8.37	8.39

Figure 4, with the increase of impact overload, the spherical 93W alloy component undergoes axial compression and radial upset deformation (Figure 5). The axial shape variable (d/D) and the radial shape variable (h/D) show an approximately linear relationship change, and the finite element calculation results are compared with the experimental results, as shown in Figure 6, which shows that the results of the two are basically consistent. It can be seen that the finite element calculation has certain reliability.

Figure 7 shows the relationship between the axial height h and the radial dimension $d/2$ of the 93W component, and Figure 8 shows the axial strain cloud diagram of the 93W component under the 1,511 m/s speed overload. It can be seen that the strain is distributed in a band shape, mainly based on the compressive strain, and there is only a slight tensile strain at the top of the sphere. The compressive strain from the impact surface to the top surface of the sphere gradually decreases and eventually changes to tensile strain. In Figure 9, it can be seen that the axial strain increase rate of the 93W spherical component gradually increases with the increase of the impact overload at the same height position in the axial direction. If the self-intrusion surface axial H is in the range of 0–0.8 mm and 3–7 mm, then the strain increase rate is large; if H is in the range of 1–2.5 cm, then the strain increase rate is small. Combined with Figure 7, it can be found that the radial dimension $d/2$ of the tungsten sphere is the largest in the range of 1–2.5 mm, and the axial strain change rate of the 93W tungsten sphere is small. If h is in the range of 0–8 mm and 3–7 mm, the radial dimension $d/2$ of the 93W tungsten sphere is small, but the tungsten sphere has a large axial strain change rate. The reason is analyzed. When the stress wave sweeps through the different cross-sectional area of the 93W tungsten sphere, the momentum conservation $mv = I$, the larger the radial dimension of the tungsten sphere, the larger the corresponding cross-sectional area, the larger the corresponding mass m in the unit axial height, the smaller the stress wave propagation speed, and the smaller the corresponding strain change rate per unit time. From $m = \Delta h \times \pi d^2 \rho$, it can be seen that the axial strain change rate of the tungsten sphere changes inversely with the radial dimension $(d/2)^2$.

From the experimental phenomenon, the internal stress wave propagation characteristics of the 93W component are analyzed. Under high-speed impact, the

Figure 5: The recovery of 93W component at the impact velocity of (a) 407 m/s, (b) 988 m/s, and (c) 1,511 m/s.

Figure 6: Relationship between axial and radial deformation of components under different impact overloads.

Figure 8: Axial strain distribution of 93W component at 1,500 m/s.

Figure 7: The relationship between 93W member axial height h and radial dimension $d/2$.

Figure 9: Axial strain distribution of tungsten sphere at the impact velocity of 400–1,500 m/s.

propagation of the internal shear wave is neglected, and the elastic wave and the plastic wave are equivalent to

the shock wave. Figure 10 shows a schematic diagram of shock wave propagation by the finite element analysis and theoretical analysis. When an impact collision

Figure 10: Stress wave propagation in a 93W tungsten sphere at different times: (a) at time t_1 , (b) at time t_2 , and (c) at time t_3 .

occurs, at time t_1 , the 93W component produces a shock wave B1 that faces away from the impact surface, and the 93W component is axially compressed. The tensile wave R3 reflected by the target plate at the impact surface and the tensile wave B2 reflected from the free surface of both sides of the 93W component internal compression wave B1 propagate together to the inside of the component. Since B2 is a nonrigid wall vertical reflection, the stress wave B2 intensity is much smaller than B1. At time t_2 , since B2 fails to completely unload the shock wave B1 of the initial incoming 93W component before it reaches the free face, the compression wave B1 of the initial incoming 93W component is reflected on the free surface as the tensile wave R1. Under the action of the tensile wave and the shock wave B1, the top free surface of the 93W component produces axial tensile plastic strain. At time t_3 , the tensile wave B2 formed by the reflection of the free surface of B1 on both sides converges radially toward the central axis, and the concentrated tensile wave interacts at the axis to form a reverse tensile wave R2 to spread in

the form of an approximately radial spherical wave, causing the spherical 93W to undergo radial plastic tensile deformation and then upset deformation.

3.2 Microscopic deformation analysis

To study the microstructural variation of the spherical 93W component, the metallographic analysis experiment is carried out on the 93W component model with a velocity of 988 m/s under impact overload. Figure 11(a) shows that a ring-shaped “dark band” and a ring-shaped “bright band” are clearly observed in a 0.8-fold field of view. Samples are taken at axial, radial dark, and bright band positions (Figure 11(b) and (c)).

PhotoShop7.0 software is used to extract the pixel ratio of tungsten particles and binder phase in the sampling interval. As shown in Figure 12, the ratio of the image area of tungsten grains at each position is calculated to indicate the dense degree of tungsten grains. The calculation of the

Figure 11: The bright, dark band, and sampling positions of the tungsten sphere axial section.

Figure 12: Example of tungsten grain pixel extraction: (a) unextracted tungsten grain pixels and (b) extracted tungsten grain pixels.

Table 3: Tungsten grain pixel ratio at different sampling positions

Bright band sampling position	A	B	C	D	E
Tungsten grain ratio	0.805	0.784	0.781	0.764	0.791
Bright band sampling position	F	G	H	I	J
Tungsten grain ratio	0.851	0.788	0.774	0.848	0.861
Dark band sampling position	K	L	M	N	O
Tungsten grain ratio	0.751	0.705	0.666	0.701	0.715
Dark band sampling position	P	Q	R	S	T
Tungsten grain ratio	0.764	0.712	0.755	0.808	0.850

Note: the dimensions of the pictures in Figure 13 are the same as those in Figure 12.

tungsten grain ratio at the A–T sampling positions is presented in Table 3. Figure 13 shows the distribution of tungsten grains at the A–T sampling positions.

Referring to the “bright band” and “dark band” sampling positions in Figure 11, combined with the tungsten grain sampling distribution map of Figure 13, it can be seen that the tungsten particle dense region is the “bright band” position, and the tungsten particle sparse region is the “dark band” position. According to Table 3 and Figure 14, the tungsten grains show a dense–sparse–dense–sparse distribution trend along the axial direction of the component, and the tungsten grain density gradually increases from the center of the sphere along the axis to the bottom of the sphere and the top of the sphere. At the same time, the tungsten particles also exhibit a variety trend of dense-sparse-dense-sparse distribution along the radial direction, and the density of the tungsten particles gradually increases from the center of the sphere along the radial direction, and it is found that the axial and radial tungsten dense are larger with the more dense regions, and the corresponding

bright band is wider. The author believes that the appearance of “dark band” and “bright band” is the result of multiple reflection interactions of shock waves. Combined with the stress wave propagation law in Section 3.1, it is found that after converging of the stress wave B2 at the axis, there is a generation of a tensile stress wave R2 with a large intensity, as shown in Figure 15, and under the action of the stress wave, the bond phase at the center of the sphere first produces radial plastic tensile deformation or even fracture. The fracture crack is shown in Figure 17. The radial tungsten particle spacing increases to form a sparse zone X. With the attenuation of the stress wave R2, the tungsten particle gap does not change any more. The tungsten particles are radially deposited at the radial boundary of the X zone. At this time, the X-zone of the tungsten sphere center is stretch strengthened, and the tensile strength is increased to σ_1 ($\sigma_1 > \sigma_0$, where σ_0 is the tensile strength of the tungsten alloy). When R2 is reflected by the free surface of the tungsten sphere and then concentrated at the center of the sphere, the stress wave R22 is generated (the R22 stress amplitude is less than R2), which no longer causes the strengthened X-zone bond phase deformation. When the stress wave R22 acts on the outside of X zone, the tensile phase of the Y zone is strengthened by radial stretching. The tensile strength of the sparse Y zone is σ_2 ($\sigma_1 > \sigma_2 > \sigma_0$), and the radial spacing of tungsten particles increases, and the tungsten particles are radially stacked at the outer boundary of the Y zone. According to the aforementioned process, the stress wave R22 formed by the convergence causes the formation of the sparse zone Z. Similarly, the tensile waves S1, S3, and R2 have the same principle, forming a sparse zone and a dense zone of axial tungsten particles. In the sparse zone X, Y, and Z junctions, it forms a bright band, which is observed in the experimental phenomenon, that is, the tungsten particle dense region, but because the tensile wave R3 is larger than the tensile wave R1 formed after the spherical free surface reflection, with the attenuation of stress wave many times on the free surface, the

Figure 13: Tungsten grain distribution at the A–T sampling positions.

tungsten particle accumulation is no longer obvious, so the axial width of the bright band gradually decreases from the impact surface to the top.

3.3 Analysis of fracture characteristics

With the increase of the impact overload, under the action of the radial tensile stress R_2 , the fracture first occurs at the radial maximum of the 93W spherical member, as shown in Figure 16. The crack extends in the “Z” shape along the radial direction to the center of the sphere [38,39], and the crack width gradually decreases, as shown in Figure 17. Comparing the 93W microcrack structure under different impact overloads, it can be seen that when the 93W tungsten sphere impacts at a velocity of 809 m/s, the crack is mainly

caused by grain boundary fracture. When the impact velocities are 1,187 and 1,511 m/s, the tungsten particle transgranular fracture begins to appear in the crack. As the impact overload increases, the number of tungsten particles cleaved increases. Finally, the two fracture forms coexist, and the statistical results of the fractured tungsten grains are shown in Figure 18.

According to the spherical wave theory, the deformed flat spherical 93W alloy member is approximated as a spherical finite medium with a cavity radius a (a is much smaller than the 93W tungsten sphere radius r_0), and the stress wave R_2 (stress value is σ_0) is the initial loading wave of the inner wall of the hole. For the powder metallurgy tungsten alloy, since the volume fraction of tungsten particles is much larger than the binder phase, the tungsten particles are in contact with each other, and the radial tensile fracture of the 93W spherical

Figure 14: The axial and radial distribution of grain pixel ratio at the A–T positions: (a) tungsten grain density distribution in axial dark band and bright band, (b) tungsten grain density distribution in radial dark band and bright band.

Figure 15: Schematic diagram of stress wave propagation inside a tungsten sphere.

member can be equivalent to the uniaxial equiaxial tensile fracture. A radical microelement is analyzed as shown in Figure 19.

According to the Taylor theory [29], the equation of motion of a spherical wave is (r is the radius of a radial direction of the tungsten sphere) expressed as follows:

$$\frac{\partial \sigma_r}{\partial r} + \frac{2(\sigma_r - \sigma_u)}{r} = \rho_0 \frac{\partial v}{\partial t}. \quad (2)$$

Since the aperture a is much smaller than the radius r_0 of the tungsten sphere, the initial pressure of

the inner wall of the tungsten bulb cavity is expressed as follows:

$$P_0 = 4\pi a^2 \times \sigma_0. \quad (3)$$

Therefore, the radial tensile stress σ_r and the shear stress σ_μ along the radial attenuation law are expressed as follows:

$$\sigma_r = -\frac{p_0 a}{r} \quad (4)$$

$$\sigma_\mu = \frac{K - \frac{2}{3}G}{K + \frac{4}{3}G} \sigma_r = \frac{\lambda}{\lambda + 2\mu} \sigma_r = \frac{-\nu}{1 - \nu} \cdot \frac{p_0 a}{r} \quad (5)$$

Note: Poisson's ratio of 93W alloy $\nu = 0.3$.

In Figure 20, it can be seen that the radial tensile stress σ_r and the tangential stress σ_μ are inversely proportional to r , which is a result of the diffusion effect of the spherical wave. The radial tensile stress σ_r is the same as the tangential stress σ_μ , which is the tensile stress. When the tungsten sphere is close to the free surface, the two stresses are nearly equal. The shear stress at the end of the crack tip is equal to the tensile strength of the tungsten alloy, and the crack extension is terminated. The crack length in Figure 17(c) is about 1 mm, and in Figure 20, the shear stress at $r = 3.5$ mm is about 1.2 times the shear stress value at $r = 4.5$ mm. The shear stress distribution of the radial crack is shown in Figure 21. It can be seen that in combination with the cracked metallographic structure at the impact velocities of 809, 1,187, and 1,511 m/s in Figure 14, the fracture

Figure 16: Macroscopic crack appearance of 93W alloy at three speeds: (a) 809 m/s, (b) 1,187 m/s, and (c) 1,511 m/s.

Figure 17: Microcrack structure of 93W alloy at three speeds: (a) 809 m/s, (b) 1,187 m/s, and (c) 1,511 m/s.

Figure 18: Statistics on the number of tungsten grains cleavage.

form of the tungsten alloy is mainly dominated by the intergranular fracture under the low impact overload. However, as the impact overload increases, the strain rate increases. Due to the nonuniformity of the material,

Figure 19: Force analysis of radial microelement of 93W alloy tungsten sphere.

local stress concentration occurs, making it easier for the tungsten particles to reach the breaking strength. At the same time, the bond strength and the fracture strength of the tungsten particles increase with the increase of the strain rate. The former increases faster than the

Figure 20: Relationship between radial shear stress σ_μ , tensile stress σ_r , and r .

Figure 21: Tangential tensile stress distribution diagram of port crack.

latter, and even exceeds the latter, so the probability of tungsten particles breaking increases. The strain rate increases, the deformation and fracture time will be shortened, and the deformation and disengagement speed of the grain and binder phase are much lower than the cleavage speed of the grain. At the same time, the tungsten particles are more likely to break. The critical stress e_d (1,973 MPa) of the self-fracture of the second phase tungsten particles proposed by Sun Jun is approximately 3.1 times the critical effective stress e_c (625 MPa) of the interface separation caused by the tensile stress of the tungsten particles and the matrix [39–44]. The shear stress at the crack tip is 1.2 times the shear stress at the outer

edge of the port. When the fracture shear stress is high enough, the two fracture modes of intergranular fracture and transgranular fracture occur simultaneously, and the cleavage of tungsten particles is more likely to occur near the crack tip. This is basically consistent with the result of the metallographic analysis experiment. It can be seen that the application of the stress wave theory can explain the experimental phenomena well.

4 Conclusion

Through the experimental research, theoretical analysis, and finite element calculation, dynamic response characteristics of 93W alloy with the spherical structure are analyzed. The following conclusions are obtained:

- (1) Within a certain range of the impact overload, the plastic deformation law of 93W alloy with the spherical structure is mainly axial compression and radial upsetting, and the axial compression amount changes linearly with the radial upsetting. As the impact overload increases, the overall strain of the spherical 93W member and the axial strain change rate increase.
- (2) Under the action of the spherical stress wave, the tungsten grain densely and sparsely separated along the radius from the center of the sphere, the tungsten grain density changes uniformly from the dense area to the sparse area, and the ring-shaped “bright band” phenomenon appears between the light and dark phases. The width of the bright band is significantly correlated with the proportion of the area occupied by the tungsten grains in the dense region.
- (3) With the increase of the impact overload, the 93W alloy with the spherical structure first breaks at the radial maximum and the central axis, and the crack width and radial extension length increase, and the crack fracture mode changes from the intergranular fracture to the transgranular fracture, and finally the two fracture forms coexist.

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