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Investigation on the penetration performance and “self-sharpening” behavior of the 80W–14Cu–6Zn penetrators

Xiaoliang Fang^{a,b}, Jinxu Liu^{b,*}, Xing Wang^d, Shukui Li^{b,c}, Wenqi Guo^b^a School of Reliability and Systems Engineering, Science & Technology Laboratory on Reliability & Environment Engineering, Beihang University, Beijing 100191, People's Republic of China^b School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, People's Republic of China^c State key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, People's Republic of China^d National Natural Science Foundation of China, Beijing 100085, People's Republic of China

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ABSTRACT

In order to investigate the penetration performance of the 80W–14Cu–6Zn alloy prepared by the pressureless infiltration method, ballistic impact experiments were conducted, and the 90W–7Ni–3Fe alloy and 35CrMnSiA alloy were tested for comparison. The 80W–14Cu–6Zn penetrator exhibits the best penetration performance with the penetration depth of 30.35 mm which increases by 29.9% and 99.0% respectively compared with the penetrators made of 90W–7Ni–3Fe alloy and 35CrMnSiA alloy. The remnant of the 80W–14Cu–6Zn penetrator maintains an acute head indicating an excellent “self-sharpening” capacity. On contrast, both the remnants of the 90W–7Ni–3Fe and 35CrMnSiA penetrators show mushroom-like heads. Microstructure analysis indicates that high strength and proper critical failure strain are responsible for the “self-sharpening” effect of the 80W–14Cu–6Zn penetrator. While the 80W–14Cu–6Zn alloy penetrator is subjected to ballistic impact, plastic deformation occurs to the head of the penetrator mainly and deformation layer is formed on the surface of the penetrator. When the plastic strain of the deformed layer reaches the limit of the critical failure strain, the deformed parts will fall off in timely fashion leading to the formation of the acute head. Besides, due to severe impact between the penetrator and the target plates, Cu–Zn matrix has been squeezed out and formed thin Cu–Zn alloy film coating on the wall of the shot hole, which can act as the lubricant and reduce the friction between the penetrator and the target plates. Both the “self-sharpening” capacity and “self-lubricating” effect of the 80W–14Cu–6Zn alloy eventually optimize the penetration performance.

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1. Introduction

The penetrator is the main lethal part of an armor-piercing projectile, which is aiming mostly for destructing tanks, armored vehicles and other armored targets [1–3]. The properties of the materials for kinetic energy penetrator have a direct influence on the penetration performance. At present, due to the high density considerations, tungsten heavy alloys (WHAs) and depleted uranium (DU) alloys are main materials for kinetic energy penetrators [3,4]. Large amount of work have indicated that the penetrator materials should have not only high density, high strength as well as good ductility but also favorable “self-sharpening” ability which ensures that the head of the penetrator remains acute shape [4–6].

Unfortunately, the WHAs are well known to be resistant to “self-sharpening” due to their poor susceptibility to adiabatic shear bands (ASBs) [7]. The WHA penetrators usually form mushroom-like heads, resulting in unsatisfactory penetration performance [8]. Due to the good “self-sharpening” capability induced by high susceptibility to

ASBs, DU penetrators are well known for their excellent penetration performance [9,10]. Under the same experimental condition, the penetration depth of the DU penetrator is increased by 10%–15% compared with that of WHA penetrator [11]. However, DU alloys are radioactive and of chemical toxicity and its applications have raised serious problems with regard to long term environmental pollution and health concerns. Most countries have lost interest in developing DU alloy penetrators [12–14].

Recent studies on this topic have focused on improving the susceptibility of the WHAs to ASBs so as to develop “self-sharpening” capability of the WHA penetrators [3,15–18]. The severe plastic deformation (SPD) methods were used to improve the properties of the WHAs [7,19–22]. Zhou Xiaoqing et al. [20] processed WHAs by hot-hydrostatic extrusion and hot torsion (HE + HT). The result of the ballistic impact experiment proved that the penetrators made of WHAs processed by HE + HT exhibited outstanding “self-sharpening” capacity and better penetration performance than penetrators made of as-sintered and as-extruded WHAs. Although the SPD methods have enhanced the “self-sharpening” ability of the WHAs, it should be noted that the SPD processes with complex procedures are inefficient and expensive, in particular, the HE + HT process. It is therefore of

* Corresponding author.

E-mail address: liujinxu@bit.edu.cn (J. Liu).



Fig. 1. Photographic view of the penetrator.

vital importance to develop WHAs with “self-sharpening” capacity by nature for kinetic energy penetrator.

In recent work, we prepared 80W–14Cu–6Zn alloy. The mechanical properties of the 80W–14Cu–6Zn alloy are enhanced compared with that of 90W–7Ni–3Fe alloy. The yield strength of the 80W–14Cu–6Zn alloy is increased and the critical failure strain is controlled within 0.2–0.4 [23]. The enhanced properties were achieved by adjusting the matrix structure. The result of the ballistic impact experiment has proved that the 80W–14Cu–6Zn alloy has desired “self-sharpening” ability, however, the penetration performance and the “self-sharpening” mechanism still need to be discussed. In the present study, the penetration performance of penetrators made of 80W–14Cu–6Zn alloy is investigated via ballistic impact experiments. The 90W–7Ni–3Fe alloy and 35CrMnSiA alloy penetrators are tested for comparison. Scanning electron microscopy (SEM) was employed to investigate the detailed microstructure of the penetrator remnants and the target plates after the penetration process. The penetration performance of the 80W–14Cu–6Zn alloy penetrators is demonstrated, and the correlated mechanism of “self-sharpening” is discussed.

2. Experimental

The initial material was 80W–14Cu–6Zn alloy fabricated by W skeleton infiltrated of Cu–Zn alloy. In order to investigate the penetration performance and deformation mechanism, the prepared 80W–14Cu–6Zn alloy was machined into penetrators with the dimension of $\Phi 12 \text{ mm} \times 30 \text{ mm}$, as shown in Fig. 1. In order to promote the interaction between penetrator and gun bore line, a copper ring was wound onto the top of the penetration, so that the penetrators would spin

and keep a stable flight status. The penetrators made of 90W–7Ni–3Fe alloy and 35CrMnSiA alloy were also machined into the same size for comparison.

A schematic diagram of the ballistic impact setup is shown in Fig. 2. Ballistic tests were conducted using a solid-propellant gun with the bore of 12.7 mm. The gun was placed at a distance of 8 m in front of the target plates. The ballistic bullet made up of penetrator and cartridge charged with gunpowder will be installed into the solid-propellant gun and then the penetrator is loaded. By adjusting the amount of the gunpowder, the velocity of the penetrator can be controlled. To measure the impact velocity of the penetrators, a speed measuring device was positioned 1 m in front of the target plates, as shown in Fig. 2. The speed measuring device consists of two layers of Tinfoil which were separated by a distance of 1.58 m. A timer was triggered when the penetrator penetrated the two layers, and the time interval was recorded for speed calculation. The semi-infinite target plates made of four medium carbon steel were perpendicular to penetration direction, and the overall thickness of the target plates was 40 mm. Sandbags were placed behind the target plates for retrieving the remnants.

Before the test, the central axis of every part of the experiment device should be kept coincident, as the dotted line shown in Fig. 2, making sure that the penetrator bear upon the center of the target plates. In order to guarantee the reliability of the results, duplicated tests for each kind of penetrators were repeated three times, and then the penetration performance was analyzed subsequently. After the impact tests, both the penetrator remnants and target plates were retrieved. For the purpose of further observation, the penetrator remnants were sectioned along the plane of symmetry by wire electrical discharge machining (WEDM), and the sectioned surfaces were polished to a mirror finish and etched. To evaluate the penetration performance of the 80W–14Cu–6Zn alloy, the target plates were also sectioned by WEDM to observe the morphology of the surface of the shot holes. Scanning electron microscopy (SEM) was employed to investigate the characteristics of the microstructure and analyze the “self-sharpening” mechanism of the 80W–14Cu–6Zn alloy penetrators.

3. Results and discussion

3.1. Penetration performance

Table 1 presents the density of these three kinds of penetrators and the amount of the gunpowder. In Table 1, the impact velocity, the penetration depth and the shot hole diameter of these three kinds of penetrators are compared, which are important indicators to evaluate the penetration capacity of the kinetic energy penetrators. As tungsten is a kind of heavy metal, the density of the 90W–7Ni–3Fe penetrators reaches 17.00 g/cm^3 , while the density of the 80W–14Cu–6Zn penetrators is 15.00 g/cm^3 which is lower than that of the 90W–7Ni–3Fe penetrator due to the lower content of tungsten. It is well known that high density is beneficial

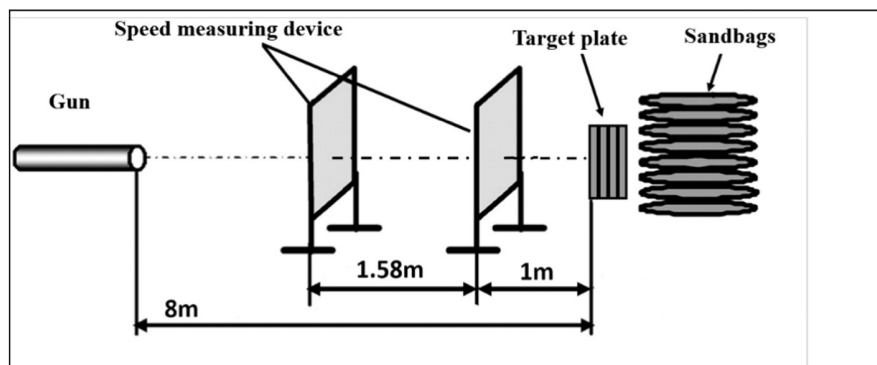


Fig. 2. Schematic diagram of the ballistic impact setup.

Table 1

Penetration parameters of the three different kinds of penetrators.

Penetrators made of	Density of penetrators (g/cm ³)	Amount of gunpowder (g)	Impact velocity (m/s)	Penetration depth (mm)	Shot hole diameter (mm)
35CrMnSiA	7.85	12	923.5	15.25	23.5
90W–7Ni–3Fe	17.00	12	639.4	23.36	20.10
80W–14Cu–6Zn	15.00	12	689.1	30.35	18.32

to improving the penetration depth. In order to guarantee the comparability of the result, the amount of the gunpowder was set as 12 g in each condition of the ballistic impact experiment, so that each of the penetrators gained the same amount of the piercing kinetic energy. As shown in Table 1, the 80W–14Cu–6Zn alloy penetrators exhibit the best penetration performance with the penetration depth of 30.35 mm and shot hole diameter of 18.32 mm. Compared with 90W–7Ni–3Fe and 35CrMnSiA penetrators, the penetration depth is increased by 29.9% and 99.0% respectively, and the shot hole diameter of the 80W–14Cu–6Zn penetrator is 18.32 mm which is the smallest among these three kinds of penetrators, indicating a significant improved penetration performance.

Fig. 3 shows the retrieved target plates impacted by penetrators made of (a) 35CrMnSiA, (b) 90W–7Ni–3Fe and (c) 80W–14Cu–6Zn. As displayed in Fig. 3(a), the penetrator made of 35CrMnSiA is held up in the target plates, and the penetration depth is much smaller than the others. Fig. 3(b) shows the target plates impacted by the penetrator made of 90W–7Ni–3Fe alloy, it can be observed that the head of the shot hole shows a spherical feature. The target plate impacted by 80W–14Cu–6Zn penetrator, as shown in Fig. 3(c), exhibits an acute head, which indicates an obvious “self-sharpening” capacity of the 80W–14Cu–6Zn penetrator during the impact process. Moreover, it can be found that the wall of the shot hole is covered with a coating of golden film in Fig. 3(c).

Fig. 4 displays the retrieved remnants of the 35CrMnSiA, 90W–7Ni–3Fe and 80W–14Cu–6Zn penetrators. From Fig. 4(a), it can be observed that the 35CrMnSiA penetrator has suffered a severe plastic deformation and exhibits an obvious mushroom-like head, which is responsible for the poor penetration performance. Fig. 4(b) shows the remnant of the 90W–7Ni–3Fe penetrator after ballistic impact which also forms

a mushroom-like head, but the plastic deformation that occurred is not as severe as the 35CrMnSiA penetrator. It can be obviously seen in Fig. 4(c), that the 80W–14Cu–6Zn penetrator remains an acute head shape with no mushroom-like head forming, indicating an excellent “self-sharpening” capacity.

During the penetration process of the 35CrMnSiA and 90W–7Ni–3Fe penetrators, the piercing kinetic energy is consumed excessively in the transverse effect area of the target plates, the formation of the shot hole with larger diameter consumes more piercing kinetic energy. Besides, the plastic deformation of the penetrators themselves consume some amount of piercing kinetic energy as well. The formation of the shot hole with large diameter and the severe plastic deformation of the penetrator are both responsible for the poor penetration performance of the 35CrMnSiA and 90W–7Ni–3Fe penetrators. In addition, it is well known that penetrators with a higher density usually exhibit a better penetration performance; however in this study, the penetration depth of the 80W–14Cu–6Zn penetrators is increased by 29.9% compared with that of the 90W–7Ni–3Fe penetrators despite of the fact that the 90W–7Ni–3Fe penetrators have higher density than the 80W–14Cu–6Zn penetrator. As shown in Table 1, the impact velocities of the 35CrMnSiA, 90W–7Ni–3Fe and 80W–14Cu–6Zn penetrators are respectively 923.5 m/s, 639.4 m/s and 689.1 m/s, correspondingly the strain rate is approximately within the range of 10^4 – 10^5 s^{−1} during the penetration progress. There is no big difference in the strain rate of these penetrators. In order to investigate the influence of “self-sharpening” behavior on the penetration performance, the ballistic impact experiments were conducted under the condition that all the penetrators have the same amount of piercing kinetic energy. Furthermore, according to the experiment results, the impact velocity of 80W–14Cu–6Zn penetrator is relatively low. It can be presumed that the advantage in penetrator performance of the 80W–14Cu–6Zn alloy will be more obvious in the case of same impact velocity. Thus, it can be reasonably concluded that the good “self-sharpening” ability contributes to the significantly improved penetration performance of the 80W–14Cu–6Zn penetrators.

3.2. Mechanism of the “self-sharpening” capacity

As we have reported in Ref. [23], at the strain rate of 10^3 s^{−1}, the yield strength of the 80W–14Cu–6Zn alloy is 1350 MPa which is higher

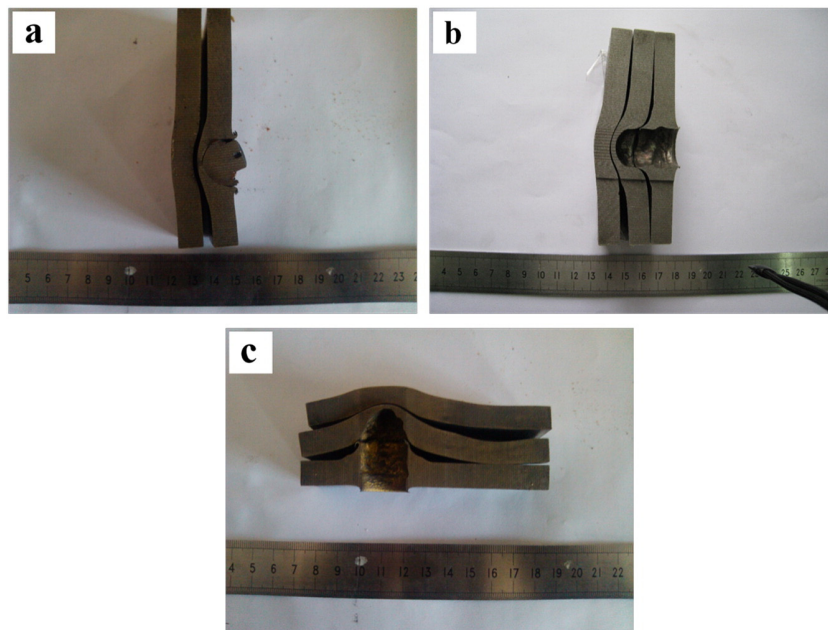


Fig. 3. The photograph of the remnants of the target plates: (a) remnants of the target plates impacted by 35CrMnSiA penetrator; (b) remnants of the target plates impacted by 90W–7Ni–3Fe penetrator; and (c) remnants of the target plates impacted by 80W–14Cu–6Zn penetrator.

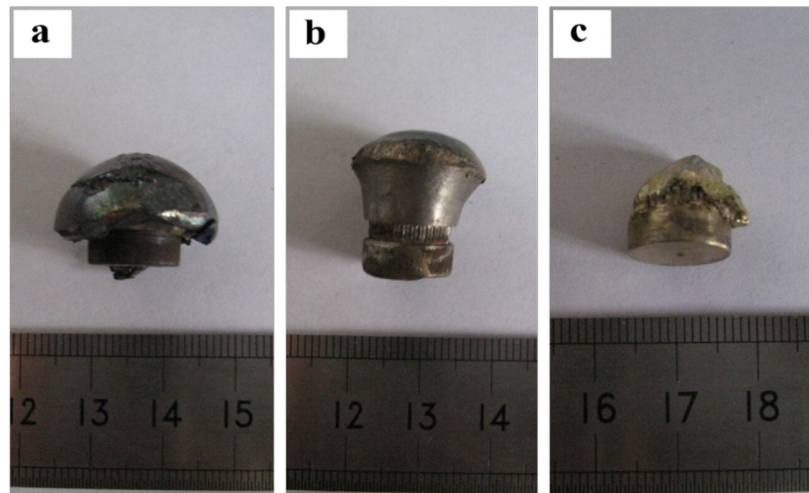


Fig. 4. Photographic view of the retrieved remnants of the penetrator made of: (a) 35CrMnSiA; (b) 90W-7Ni-3Fe; and (c) 80W-14Cu-6Zn.

than that of the 90W-7Ni-3Fe alloy due to the solid solution strengthening effect of Zn. Moreover, the critical failure strain of the 80W-14Cu-6Zn alloy is controlled within 0.4 so that no excessive plastic deformation will occur to the alloy during dynamic loading. Previous research have shown that the W-Ni-Fe alloy with the critical shear failure strain more than 0.4 formed obvious mushroom-like heads

which evidently decreased the penetration performance [20]. In the present study, for further analyzing the “self-sharpening” capacity of the 80W-14Cu-6Zn alloy with high yield strength and proper critical shear failure strain, detailed microstructure analysis on the retrieved target plates impacted by the 80W-14Cu-6Zn alloy and the remnant of the 80W-14Cu-6Zn penetrator itself was conducted.

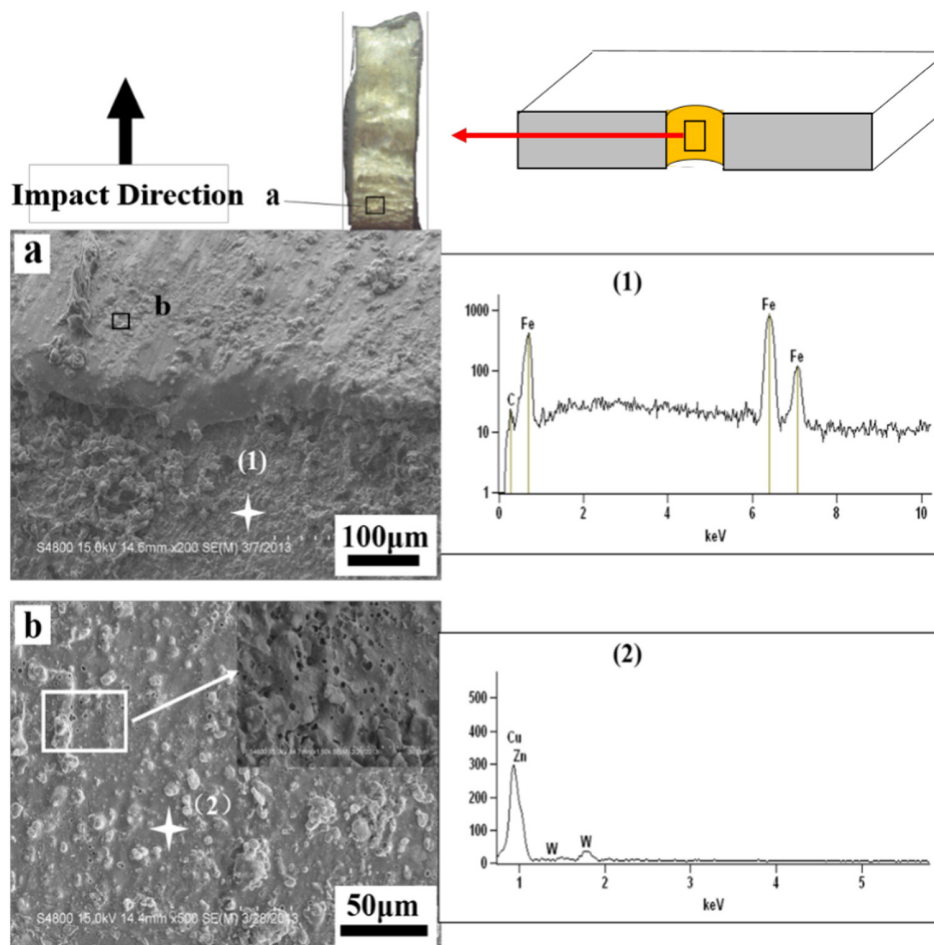


Fig. 5. The photograph and micrographs of corresponding regions of the retrieved target plates impacted by the 80W-14Cu-6Zn penetrator. The EDS results corresponding to the selected part are also shown. The arrow depicts penetration direction. (a) Microstructure of the “part a” on the retrieved target plate; (b) enlarged drawing of the “part b” in (a).

Fig. 5 presents the optical micrograph and SEM micrograph of the section of the retrieved target plates cut apart along the impact direction, which is impacted by the 80W–14Cu–6Zn penetrator. The EDS results corresponding to the selected part are also shown in Fig. 5 in which the arrow depicts the impact direction. Fig. 5(a) shows the detailed microstructural feature of the “part a” on the retrieved target plate. It can be observed clearly that a layer of film is covered on the substrate. The EDS result on the right of Fig. 5(a) shows the chemical component of the marked point (1) on the substrate, which indicates that this part consists of Fe and C, thus the substrate is the shot hole wall of the target plates. It can be concluded that the wall of the shot hole is covered with a layer of film. Fig. 5(b) shows the SEM micrograph of the film coating on the target plate, and the enlarged partial view of the selected area. The EDS result on the right of Fig. 5(b) displays that the film consists of W, Cu and Zn, indicating that the film was dropped off from the 80W–14Cu–6Zn penetrator. Furthermore the amount of Cu and Zn is obviously more than W, which indicates that the film is mainly composed of Cu–Zn matrix. From the enlarged partial view of the selected area in Fig. 5(b), micropores which were formed during the cooling process of the melting alloy can also be observed. Based on these observations, it can be concluded that during the penetration process, the severe impact between the penetrator and the target plate generate a huge amount of heat which leads to that the Cu–Zn matrix is melting and squeezed out from the interstice of tungsten skeleton near the surface of penetrator head. The molten Cu–Zn matrix overlays on the wall of the shot hole, and lubricates the penetrator, which can reduce the friction between the penetrator and the target plates. As a result, the transverse effect area of the target plate is decreased, which is beneficial to promoting the “self-sharpening” capacity of the 80W–14Cu–6Zn penetrator and increase the penetration depth.

Fig. 6 displays the photographic view and enlarged micrographs of the 90W–7Ni–3Fe penetrator remnant. An obvious mushroom-like head can be observed in Fig. 6. Fig. 6(a) and (b) show the detailed microstructure features of the penetrator head. It can be observed clearly from the Fig. 6(a) that the original spherically shaped tungsten grains [20] are compacted into fibrous shape. The tungsten grains closed to

the surface of the penetrator show severer plastic deformation. From Fig. 6(b), it can be observed that plastic deformation has occurred in this area, and the tungsten grains are compacted together closely to each other. When the 90W–7Ni–3Fe penetrator is subjected to ballistic impact, severe plastic deformation occurs to the head of the penetrator rather than that the surficial layer of the penetrator drops off, which results in the formation of the mushroom-like head. Thus the penetration depth of the 90W–7Ni–3Fe penetrator is decreased.

Fig. 7 shows the photographic view and micrographs of the 80W–14Cu–6Zn penetrator remnant, and the arrow indicates the impact direction. In Fig. 7, it can be obviously observed that the 80W–14Cu–6Zn penetrator maintains an acute head and no severe plastic deformation occurs to the bottom side of the penetrator. Fig. 7(a) shows the SEM micrograph of the penetrator head, in which the original spherically shaped W particles are compacted into ellipsoidal shape. The longitudinal direction of the ellipsoidal shaped W particles is perpendicular with the impact direction, and the W particles in this area have been connected closely with each other after the ballistic impact. The severe impact between the penetrator and target generates a huge amount of heat which increase the temperature of the penetrator dramatically. Due to the combined effect of pressure and temperature, Cu–Zn alloy matrix melts and is squeezed out from the interstice of the W skeleton, which can be observed in Fig. 7(a). Fig. 7(b) shows the microstructure of the middle region of the acute penetrator head corresponding to the “part b” on the view of the retrieved penetrator remnant. During the penetration process, this area is under intense pressure. As a result, it can be seen that the deformation layer with average widths of 30–40 μm is formed adjacent to the rim of the remnant. In the deformation layer, the elliptical W particles are formed after impact. In contrast, the W particles outside the deformation layer remain spherical indicating that no obvious plastic deformation occurs to that area. Fig. 7(c) shows the detailed microstructure feature of the “part c” in the view of the penetrator remnant, and Fig. 7(c) shows same microstructure with that of Fig. 7(b), as a result of that the given penetration direction is perpendicular to the targets. It should be noted that, in Fig. 7(a), (b) and (c), the plastic deformation occurs to the surface of the remnant, however, the plastic deformation is not as severe as that of the 90W–7Ni–3Fe

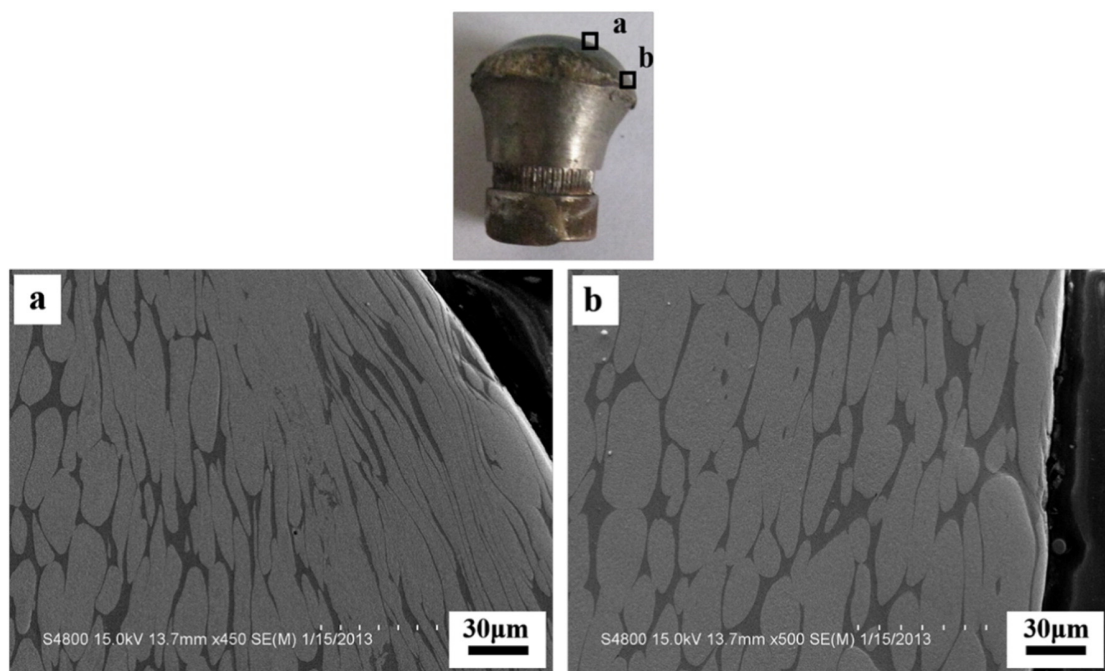


Fig. 6. Photographic view and micrographs in the different regions of the 90W–7Ni–3Fe penetrator remnant. (a) Microstructure of the area corresponding to part a in the photographic view; (b) microstructure of the area corresponding to part b in the photographic view.

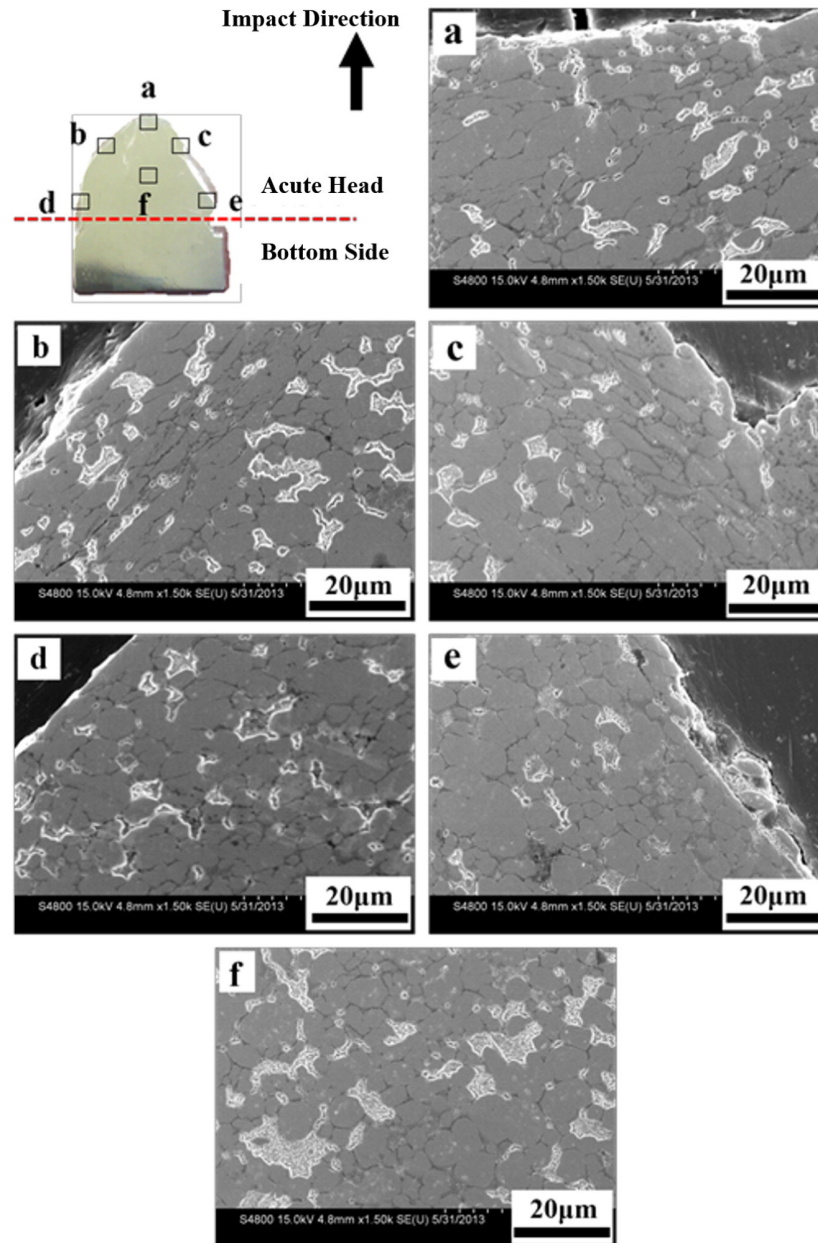


Fig. 7. Photographic view and micrographs in the different regions of the 80W–14Cu–6Zn penetrator remnant. The arrow depicts penetration direction. (a) Microstructure of the region at the top of the remnant head; (b) and (c) microstructure of the middle region of the acute penetrator head; (d) and (e) microstructure of the boundary between the acute head and the bottom side of the penetrator remnant; (f) microstructure of the central region of the penetrator remnant.

penetrator as shown in Fig. 6, which is caused by the high strength and proper critical failure strain of the 80W–14Cu–6Zn alloy. Fig. 7(d) and (e) shows the microstructure of the boundary between the acute head and the bottom side of the penetrator remnant. It can be observed that the W particles are tightly compacted but remain spherical shape, indicating that impact between the penetrator and the target plates mainly concentrates on the surficial layer of the penetrator. Fig. 7(f) displays the SEM micrograph of the central region of the remnant where the original microstructure is maintained, only parts of the W particles connect together, indicating a slight deformation. To sum up, the 80W–14Cu–6Zn alloy penetrator remnant remains an acute head after ballistic impact. The mechanism of the “self-sharpening” capacity is summarized as followed. When the 80W–14Cu–6Zn alloy penetrator is subjected to

ballistic impact, plastic deformation occurs to the surficial layer of the penetrator head mainly, and deformation layer is formed on the surface of the penetrator. When the plastic deformation of the surficial layer of the penetrator reaches the limit of the critical failure strain, the deformed parts will fall off in a timely fashion resulting in the formation of the acute head of the penetrator. Owing to the high strength and proper critical failure strain, the 80W–14Cu–6Zn penetrator exhibits excellent “self-sharpening” capacity. Moreover, the melting Cu–Zn matrix lubricates the penetrator and decreases the transverse effect area of the target plate, which is beneficial to promoting the “self-sharpening” capacity of the 80W–14Cu–6Zn penetrator. As the proper critical shear failure strain and high strength of the alloy is the leading factor of “self-sharpening” behavior, the “sharpening” behavior induced by the proper critical failure

strain and high strength of the 80W–14Cu–6Zn alloy is mainly responsible for the improvement of the penetration performance.

4. Conclusion

The penetration performance of the 80W–14Cu–6Zn, 90W–7Ni–3Fe and 35CrMnSiA penetrators has been investigated systematically. Under the same experimental condition, the 80W–14Cu–6Zn penetrator exhibits the best penetration performance with the penetration depth of 30.35 mm which increases by 29.9% and 99.0% respectively compared with the penetrators made of 90W–7Ni–3Fe and 35CrMnSiA. Meanwhile the shot hole diameter of the 80W–14Cu–6Zn penetrator is 18.32 mm, which is smaller than that of the other two penetrators. Besides the 80W–14Cu–6Zn penetrator shows excellent “self-sharpening” capacity and the remnant of the penetrator maintains an acute head after ballistic impact, while the mushroom-like heads are formed on the remnants of the 90W–7Ni–3Fe and 35CrMnSiA penetrators.

Based on the microstructure analysis, the high strength and proper critical failure strain are responsible for the “self-sharpening” capacity of the 80W–14Cu–6Zn penetrator. When the 80W–14Cu–6Zn alloy penetrator is subjected to ballistic impact, plastic deformation occurs to the head of the penetrator mainly and deformation layer is formed on the surface of the penetrator. When the plastic deformation of the surficial layer of the penetrator reaches the limit of the critical failure strain, the deformed parts will fall off in timely fashion leading to the formation of the acute head of the penetrator. Thus the 80W–14Cu–6Zn penetrator shows desirable “self-sharpening” capacity, which is desirable for the improvement of the penetration behavior. Moreover, during the penetration process, Cu–Zn matrix is melting and squeezed out from the penetrator, which lubricates the penetrator and decreases the transverse effect area of the target plate, which is beneficial to promoting the “self-sharpening” capacity of the 80W–14Cu–6Zn penetrator.

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