Penetration Behavior of \( W_p/Zr \)-based Amorphous Matrix Composite

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Abstract. The penetration ability and penetration behavior of 50% \( W_p/Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) amorphous matrix composite were studied through penetration test and microtopography observation. It is concluded that: the composite projectile shows self-sharpening behavior when penetrating 30CrMnMo steel target and 6061 aluminum target, especially after penetration of the aluminum target, the phenomenon of self-hardening is obvious. 50% \( W \) particles added greatly improves the penetration performance of the composite. In the process of high-speed collision between the composite projectile and the target, the high temperature causes the amorphous alloy \( Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) with low melting point to melt and cover on the surface of the crater.

1. Introduction
Zr-based amorphous alloys have good mechanical properties, excellent corrosion resistance, and self-sharpening property[1-6]. The density of the composite increases by addition of \( W \) in \( Zr \)-based amorphous alloy, and the high density and self-sharpness are the primary conditions for \( W/Zr \)-based amorphous matrix composite to meet the requirements of penetration projectile core. At the same time, the composite does not pollute the environment in the way that depleted uranium bombs do. Therefore, \( W/Zr \)-based amorphous matrix composite is considered to be an ideal core material for armor-piercing projectile[7].

At present, the research on penetration performance of \( W/Zr \)-based amorphous matrix composites is mainly focused on \( W_f/Zr \)-based amorphous matrix composite. Huang et al.[8] had a research on \( W_f/Zr \)-based amorphous matrix composite and found that its penetration performance is better than that of the tungsten alloy. Due to the influence of preparation process, now there are few studies on \( W_p/Zr \)-based amorphous matrix composite, and the research on its penetration behavior is rarely reported.

In this paper, the penetration ability and penetration behavior of 50% \( W_p/Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) amorphous matrix composite were studied through penetration test and microtopography observation, and the comparison tests were made with amorphous alloy \( Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) and 35CrMnSi steel.

2. Experiment
There are three kinds of core material: 50% \( W_p/Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) amorphous matrix composite (\( \rho=11.33 \) g/cm\(^3\)), \( Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5} \) amorphous alloy (\( \rho=6.85 \) g/cm\(^3\)), 35CrMnSi Steel (\( \rho=7.49 \) g/cm\(^3\)). The penetrator is a cylinder with size of \( \varnothing 9 \times 15 \) mm, and is fixed with a triple lobe aluminum shell. The target plates are 30CrMnMo steel (603 armored steel) and 6061 aluminum alloy, and the sizes of steel target and aluminum target are 100×100×100 mm and 100×100×150 mm.
The penetration test was carried out in a ballistic laboratory, and the testing apparatus is shown in figure 1. The projectiles are fired with a 14.7 mm musket. In order to obtain a higher initial velocity, the maximum amount of gunpowder was loaded in the test. A total of 8 effective projectiles were fired in the test: 4 projectiles of W<sub>p</sub>/Zr-based amorphous matrix composite were fired, in which 2 for penetrating of steel target and 2 for penetrating of aluminum target; 2 projectiles of amorphous alloy were fired, in which 1 for penetrating of steel target and 1 for penetrating of aluminum target; 2 projectiles of 35CrMnSi steel were fired, in which 1 for penetrating of steel target and 1 for penetrating of aluminum target. After penetration, photos of craters on the surface of the target were taken. The craters were longitudinally cut along the direction of penetration, and the size of the craters was taken and measured. The microtopography of the crater section was analyzed by field emission scanning electron microscope (FESEM) combined with energy dispersive spectrum (EDS).

3. Results and Discussions

3.1. Penetration Performance

After penetration, obvious craters were observed on each target plate, as shown in figure 2, in which picture 1~4 show the macro profile of the craters on the steel targets, and picture 1~2 show the macro profile of craters penetrated by W<sub>p</sub>/Zr-based amorphous matrix composite projectile, picture 3 is for amorphous alloy projectile and picture 4 is for 35CrMnSi steel projectile; picture 5~8 show the macro profile of craters on the aluminum targets, and picture 5~6 show the macro profile of craters penetrated by composite projectile, picture 7 is for amorphous alloy projectile and picture 8 is for 35CrMnSi steel projectile.

The section profiles of the craters are shown in figure 3, it can be found that the diameter of the bottom of the crater formed by the composite is gradually reduced, especially after penetrating the aluminum target, the bottom of the crater becomes very sharp, there is a very sharp self-sharpening. The impact speed of the projectile, the diameter and the depth of the craters are listed in table 1.
Figure 2. Photos of bullet holes on target surface

Figure 3. Profile morphology of penetration pits after different bullets penetrated steel and aluminum targets

The diameter of the craters is listed in table 1. The average diameter of the crater in the steel target after penetration by composite projectile is 15.25 mm, which is obviously smaller than that of the amorphous alloy projectile(23 mm) and the steel projectile(18 mm). Similarly, the average diameter of the crater in the aluminum target after penetration by composite projectile is 14.75 mm, which is obviously smaller than that of the amorphous alloy projectile(21 mm) and the steel projectile(19.5 mm).

As shown in table 1, the average penetration depth of the composite projectile is 14.2 mm, which is much larger than that of the amorphous alloy projectile(5.2 mm) and the steel projectile(10.4 mm). Similarly, the average penetration depth by the composite projectile is 47.3 mm, which is far greater than that of the amorphous alloy projectile(14.1 mm) and the steel projectile(29.5 mm).

The impact kinetic energy is listed in Table 1. The average impact kinetic energy of the composite projectile with an impact speed of 762 m/s before penetrating of steel target is 3.17 kJ, which is lower than that of the amorphous alloy projectile with an impact speed of 1262 m/s (5.12 kJ), but the average penetration depth is 14.2 mm, which is about 173% higher than that of the amorphous alloy(5.2 mm); At the same time, the impact kinetic energy of the steel projectile with an impact speed of 988 m/s is 3.75 kJ, which is higher than that of the composite, while the penetration depth of the composite projectile is about 36.5% higher than that of the steel projectile(10.4 mm).
Table 1. Comparison of experimental datas of three samples

| Sample | Material of bullet core | Mass of bullet core (g) | Target | Impact speed(m/s) | Impact kinetic energy speed(kJ) | Depth of crater (mm) | Diameter of crater(mm) |
|--------|-------------------------|-------------------------|--------|------------------|-------------------------------|---------------------|------------------------|
| 1      | Wp/Zr-based amorphous matrix composite | 11.05 | Steel target | 735 | 2.98 | 15.8 | 15 |
| 2      | Wp/Zr-based amorphous matrix composite | 10.81 | Steel target | 789 | 3.36 | 12.6 | 15.5 |
| 3      | Zr$_{41.2}$Ti$_{13.8}$Cu$_{12.5}$Ni$_{10}$Be$_{22.5}$ | 6.47 | Steel target | 1262 | 5.12 | 5.2 | 23 |
| 4      | 35CrMnSi steel | 7.68 | Steel target | 988 | 3.75 | 10.4 | 18 |
| 5      | Wp/Zr-based amorphous matrix composite | 10.59 | Aluminum target | 703 | 2.62 | 45.2 | 16 |
| 6      | Wp/Zr-based amorphous matrix composite | 10.42 | Aluminum target | 720 | 2.70 | 49.4 | 13.5 |
| 7      | Zr$_{41.2}$Ti$_{13.8}$Cu$_{12.5}$Ni$_{10}$Be$_{22.5}$ | 6.53 | Aluminum target | 1203 | 4.73 | 14.1 | 21 |
| 8      | 35CrMnSi steel | 7.49 | Aluminum target | 1002 | 3.76 | 29.5 | 19.5 |

The average impact kinetic energy of the composite projectile with an impact speed of 711 m/s before penetration of aluminum target is 2.66 kJ, which is lower than that of the amorphous alloy projectile with an impact speed of 1203 m/s (4.73 kJ), but the average penetration depth is 47.3 mm, which is about 235% higher than that of the amorphous alloy projectile (14.1 mm); At the same time, the impact kinetic energy of the steel projectile with an impact speed of 1002 m/s is 3.76 kJ, which is higher than that of the composite, while the penetration depth of the composite projectile is about 60.3% higher than that of the steel projectile(29.5 mm).

As a result, the penetration ability of Wp/Zr-based amorphous matrix composite projectile is obviously better than that of the steel projectile, and far higher than that of the amorphous alloy projectile. It shows that 50% W particles added greatly improves the penetration ability of the amorphous matrix composite, and the penetration ability of the composite to the aluminum target has been greatly improved.

3.2. Penetration Behavior

3.2.1 Penetration behavior on steel target. In Figure 2, picture 1~4 show the macro profile of craters on steel target after penetration by different projectiles. It can be found that the surface of the crater is black, similar to "smoky". Analysis shows that: under the action of huge kinetic energy of projectile and the resistance of high strength steel target, the projectile and the target have intense friction and erosion, and the kinetic energy of the projectile is gradually reduced into the internal energy, which causes the temperature of the projectile and the target plate around the crater to rise sharply. The penetration rate of the composite projectile is relatively low, so the friction and erosion of the target are also relatively reduced, and the color of the crater is relatively light.
Figure 4. SEM morphology and EDS of crater profile for steel target after penetration by projectile of W₆/Zr-based metallic glass matrix composite

Figure 5. SEM morphology and EDS of crater profile for steel target after penetration by projectile of metallic glass Zr₄₁₂₂Ti₃₃₆₃Cu₁₂₅₃Ni₁₀₉Be₂₂₅
Figure 4–Figure 6 show the micromorphology and energy spectrum of the crater section in the steel target, respectively. It can be found in figure 4 and figure 5 that there was a gray covering layer different from the target on the crater after penetration by Wp/Zr-based amorphous matrix composite projectile and amorphous alloy projectile, while there is no obvious difference between the crater surface and the target matrix after penetration by steel projectile. In figure 4 the surface coating on crater formed after penetration of the steel target by the composite projectile has a good combination with the target surface, with white particles in the middle. It is detected that the white particles in the gray covering layer are W particles by EDS, and the gray part of the coating is similar to the surface coating on crater after penetration by the amorphous alloy projectile as shown in figure 5, all of them contain Zr, Ni, Cu and other elements, and the composition is basically similar to that of the amorphous alloy Zr41.2Ti13.8Cu12.5Ni10Be22.5. But 30CrMnMo steel does not contain such elements, it is concluded that the coating is caused by the melting of the projectile during penetration and covers the surface of the crater.

A similar situation also be found when Wang et al.[9] studied the penetration behavior of Wp/Zr-based amorphous matrix composite. The melting point of amorphous alloy Zr41.2Ti13.8Cu12.5Ni10Be22.5 is only 937K[10], in the process of high-speed collision between the projectile and the target, the high temperature causes the amorphous alloy to melt and cover on the surface of the crater.

3.2.2 Penetration behavior on aluminum target. In Figure 2, picture 5–8 show the macro profile of craters on aluminum target after penetration by different projectiles. It can be found that the color of the crater remained essentially, but the deformation of the crater is larger than that of the steel target, and obvious cracks are visible to the naked eye, which indicate that the damage of the projectiles to the aluminum target was greater. Analysis shows that: the aluminum target is soft and easy to yield, it will slide with the projectile during the penetration, more kinetic energy will be absorbed by the deformation and
destruction of the aluminum target, and the part converted into thermal energy will be greatly reduced compared with that of the steel target.

Figure 7–Figure 9 show the micromorphology and energy spectrum of the crater’s section in the aluminum target, respectively. It can be found in figure 7 and figure 8 that there was a covering layer different from the target on the crater after penetration by the composite projectile and amorphous alloy projectile. It is similar to that of the steel target, the projectile with low melting point will melt and cover on the surface of the crater during penetration on aluminum target at high speed. In figure 9, No coating was found on the crater’s surface after penetration by steel projectile, and the steel projectile is embedded in the crater.

![Figure 7. SEM morphology and EDS of crater profile for aluminum target after penetration by projectile of Wp/Zr-based metallic glass matrix composite](image)

| Spectrum | Mg  | Al  | Cu  | Zr  | Ag  | W  | Total |
|----------|-----|-----|-----|-----|-----|----|-------|
| Spectrum 1 | 100.00 | 100.00 |
| Spectrum 2 | 74.63 | 5.04 | 20.33 |
| Spectrum 3 | 100.00 | 100.00 |
| Spectrum 4 | 78.05 | 4.75 | 17.20 |
| Spectrum 5 | 66.89 | 7.49 | 12.19 | 13.43 | 100.00 |
| Spectrum 6 | 0.80 | 92.08 | 7.12 | 100.00 |
When the composite projectile and the amorphous alloy projectile penetrate the aluminum target, more kinetic energy is absorbed by the deformation and destruction of the aluminum target because of the large deformation of aluminum alloy target. The relatively low thermal energy makes the surface of the crater and the interface of the molten projectile less permeable than that of the steel target, so the coating on the crater surface is relatively loose after penetration by the composite projectile.
4. Conclusion

(1) The Wp/Zr-based amorphous matrix composite projectile shows self-sharpening behavior in penetration of 30CrMnMo steel target and 6061 aluminum target, especially after penetrating the aluminum target, the phenomenon of self-sharpening is very obvious.

(2) 50% W particles added greatly improves the penetration performance of the composite, the penetration depth of steel target for the composite projectile with an impact speed of 762 m/s is about 173% higher than that of the amorphous alloy with an impact speed of 1262 m/s, and is about 36.5% higher than that of the steel projectile with an impact speed of 988 m/s. For aluminum target, the penetration depth of the composite projectile with an impact speed of 711 m/s is about 235% higher than that of the amorphous alloy with an impact speed of 1203 m/s, and is about 60.3% higher than that of the steel projectile with an impact speed of 1002 m/s.

(3) In the process of high-speed collision between the composite projectile and the target, the high temperature causes the matrix amorphous alloy to melt and cover on the surface of the crater.

5. References

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