Research Article

Formability Characteristics and Penetration Performance of Micro-Jets from Different Materials

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A micro-unmanned aerial vehicle (UAV) swarm has high flexibility and intelligent unmanned flight and stealth capabilities. Moreover, it can attack both single and group targets, which will occupy dominant positions in the future information war. To satisfy the new micro-UAV swarm information combat mode and contribute to the advances in ammunition flexibility, efficiency, miniaturization, and multipurpose applicability, a 10 mm caliber micro-shaped charge warhead was designed in this study. The results indicate that the micro-shaped charge can be assembled with a micro-UAV swarm to efficiently damage the targets without relying on the weapon launch velocity. To realize a lightweight and high-efficiency micro-shaped charge structure, the formability of Teflon, nylon, polycarbonate (polycarb), and metallic copper liners was studied using the finite element analysis. The penetration efficiencies of different micro-jets on gelatin targets were compared and analyzed. It was found that the micro-shaped charge nylon and Teflon jets could pass through the gelatin target and transfer more energy to it compared with copper. The observed penetration aperture was also larger. Although the penetration depth of the polycarb jet to the target was the smallest, the penetration aperture was the largest. The findings of this study can serve as a basis for the development of micro-shaped charge technology.

1. Introduction

Compared with bullets, fragments, and other damage elements that rely on kinetic energy to penetrate armor, the high-temperature, high-pressure, and high-energy density jet formed by the shaped charge warhead demonstrates extremely strong local damage and penetration capacities, is independent of the launch velocity, and has few constraints on the launch environment and conditions. Furthermore, it plays an important role in anti-tank, anti-ship, anti-submarine air defense, and antimissile fields, in addition to oil perforation and controlled explosions in civil engineering [1–4].

The shaped charge is mainly composed of an explosive charge, liner, and shell. To improve the penetration power of shaped charges to armored targets, extensive research has been conducted on shaped charge structures, liner materials, and types of explosive charges [5–8]. Ding et al. studied the penetration performance of shaped charges with different material liners with respect to explosive reactive armor and found that all low-density materials such as float glass, lucite, and plexiglass-shaped jets can effectively detonate explosive reactive armor. The shaped charge caliber used in the study was 60 mm [9]. Through a series of experimental detonations and explosions of shaped charge munitions, Baykara et al. elucidated the microstructural evolution and microstructural features of a metallic copper jet penetrating a steel target, and the warhead caliber used was 66 mm [10]. Ma et al. designed a variable cone angle-shaped charge liner and simulated and compared the penetration capacities of a shaped charge warhead with three different metals—copper, steel, and aluminum. The shaped charge caliber used in the study was 100 mm [11]. Guo et al. studied the reaction characteristic and its application to the shaped charge...
warhead of a novel reactive material. In particular, this polytetrafluoroethylene (PTFE)/Al/Cu/Pb reactive liner-shaped charge exhibited an enhanced penetration behavior for steel targets that incorporated the penetration capability of a high-density and high-ductility jet, in addition to the chemical energy released by PTFE matrix reactive materials; a shaped charge caliber of 100 mm was used [12]. Zhang et al. studied the jet formation and penetration efficiency of a 90 mm caliber active PTFE/Al matrix-shaped charge. The results revealed that an active PTFE/Al jet can efficiently damage light and medium armor targets [13]. Gerami et al. studied the penetration performance of 80 mm caliber-shaped charges with different material liners for a concrete target. It was found that when the front stage-shaped charge of the tandem warhead was made of aluminum, it exhibited a more significant destructive capability than copper [14]. In addition, Yin et al. compared the formability characteristics and penetration performances of steel targets of three material jets—copper, PTFE, and PTFE/copper—and the calibers of all the shaped charges were 40 mm [15, 16]. In the research on micro-shaped charges, Scheffler numerically studied the forming process of damaged elements with three different caliber micro-shaped charges. The three types of shaped charge structures employed were conical liner micro-shaped charges with diameters of 10.41 mm and 25.65 mm, which can form an explosively formed projectile, and a conical liner-shaped charge with a diameter of 25.65 mm. The results revealed that the first conical-shaped charge formed a jet with a tip velocity of 3.3 km/s at 13 μs, the second-shaped charge warhead formed an explosively formed projectile with a tip velocity of 2.8 km/s, and the third warhead formed a high-velocity jet with a tip velocity of 5.7 km/s [17]. For the efficient damage technology of armed helicopters, Wu designed a micro-shaped charge structure with a 10 mm caliber and then analyzed the effects of the stand-off, cone angle, and wall thickness on the penetration performance of a micro-jet with respect to an armed helicopter. It was found that when the mass of the shaped charge was less than 8 g, the penetration depth exceeded 40 mm, which could efficiently damage the armed helicopter [18].

The current research on shaped charges is mainly focused on calibers above 20 mm, and limited research has been conducted on micro-shaped charges with calibers below 12 mm. However, shaped charges with calibers of 12 mm or lower (e.g., a size of approximately 10 mm) are required. Micro-shaped charges are mainly applied to hard-armored targets, and the research on gelatin targets is incomplete. Moreover, with the advancement of information-based intelligent warfare, the design and study of high-energy warheads that can be equipped with micro-UAVs have received significant research attention worldwide [19, 20]. Therefore, if a micro-shaped charge is assembled with a micro-UAV swarm, it can overcome the shortcomings of traditional bullets and fragments that require high kinetic energy of the launch weapon and more efficiently achieve accurate attacks on bunkers, light armor, and UAVs. In summary, the micro-shaped charge can satisfy the development requirements for miniaturization and multipurpose ammunition.

In this study, a micro-shaped charge warhead with a caliber of 10 mm was designed to improve the combat capability of micro-UAVs. In addition, to realize lightweight and efficient shaped charge structures, the formability of different low-density material jets and differences in their penetration performance for gelatin targets were compared and analyzed. This study can serve as a basis for the structural design of micro-shaped charges in the future.

The novelty and main contributions of this study are as follows. First, a micro-shaped warhead structure equipped with a swarm of miniature drones was designed, which demonstrated an improved damage effect. Second, for the gelatin target plate, the miniature warhead structure was optimized, and a lightweight and efficient charge structure was obtained. Third, the findings of the research conducted on a 10 mm caliber micro-shaped charge can serve as a basis for research on miniaturized, dexterous, multifunctional, and high-efficiency ammunition.

2. Numerical Simulation

In this study, numerical simulation and theoretical analysis were conducted to study the formability characteristics and penetration performances of micro-jets with different materials. Numerical simulations were carried out using the Autodyn package (Century Dynamics, Fort Worth, TX, USA), which is an interactive nonlinear explicit dynamic analysis software that is widely used in simulating detonations, impacts, armor piercing, and ballistics. In the numerical simulations, there were three main research steps. First, the geometric model of the problem to be analyzed was created in the Autodyne software environment. Second, the geometric model was meshed, and a finite element (FE) model was created to provide material parameters, initial conditions, and boundary conditions. Third, a solution calculation was performed. In addition, the accuracy of the numerical simulation was verified based on the theoretical analysis. All detailed research steps would be presented one by one below.

2.1. Structural Design of Micro-Shaped Charge. The structure of the micro-shaped charge designed is shown in Figure 1. It is mainly composed of two parts: explosive charge and shaped charge liner. Since the cone-shaped charge liner has the advantages of stable jet formation, high speed, high quality, high armor-breaking power, and simple processing, the micro-shaped charge liner was designed as a conical shape, with a cone angle of 60° and a wall thickness of 0.4 mm. The explosive charge adopted the traditional cylindrical charge structure, with a charge diameter of 10 mm and a charge height of 15 mm.

2.2. Finite Element Model. The finite element model of the micro-shaped charge structure penetrating the gelatin target included four parts, namely air, explosive charge, shaped charge liner, and gelatin target. The gelatin target had a length and width of 9 cm and 4 cm, respectively [21]. The finite element model was axisymmetric, and to reduce
computational time, a 1/2 finite element model was created in Autodyn. The FE model is shown in Figure 2.

As the crushing and forming process of the micro-shaped charge liner has a high strain rate, the Euler algorithm was used to simulate the large deformation behavior of the liner under a detonation load. Moreover, the Euler algorithm was used to describe the dynamic behavior of the explosives and air. In addition, the gelatin target is more suitable for simulation using the Lagrange algorithm owing to its ability to accurately capture the material deformation boundary. Therefore, the entire penetration process of the micro-shaped jet into the gelatin target was simulated using the Euler and Lagrange coupling algorithm. The Lagrange and Euler parts were set to automatically contact each other, and the flow-out boundary condition was set around the air to eliminate boundary effects, such that the air and explosive gas could flow out normally when they reached the boundaries of the calculation domain.

2.3. Modeling Material. In this study, CompB was used as the explosive charge material. The charge liner materials were copper, Teflon, nylon, and polycarb; the target material was gelatin. In the numerical simulation, the material parameters of the explosive and liner were selected from the Autodyn material library; the gelatin material properties in [22, 23] were used. The material models and main parameters of the various materials used in this study are as follows.

2.3.1. Air Material Model. The equation of state of the ideal gas was applied to the air, and its main parameters were defined as follows: air density $\rho = 1.293 \times 10^{-3}$ g/cm$^3$, sonic speed in air $C = 340$ m/s, and initial relative volume $V_0 = 1.0$, and the model needs to be given an initial temperature of 15°C and an initial internal energy of $2.068 \times 10^5$ kJ·kg$^{-1}$.

$$P = \rho (\gamma - 1)E,$$

$$\gamma = \frac{C_p}{C_v},$$

$$E = C_vT,$$

where $P$, $\gamma$, and $\rho$ are the pressure, density, and polytropic index of the gas, respectively, $C_p$ and $C_v$ are the specific heat at constant pressure and specific heat at constant volume, $T$ is the temperature, and $E$ is the internal energy of gas.

2.3.2. Explosive Charge Material Model. The explosive charge was high-energy CompB explosive, and the JWL equation of state was used to describe the explosive detonation and explosive gas expansion process after the charge was detonated. The expression is as follows:

$$P = A\left(1 - \frac{\omega}{R_1V}\right)e^{\frac{-R_1V}{R_1V}} + B\left(1 - \frac{\omega}{R_2V}\right)e^{\frac{-R_2V}{R_2V}} + \frac{\omega E_0}{V},$$

where $A$, $B$, $R_1$, $R_2$, and $\omega$ are material constants; $V$ is the initial relative volume; $E_0$ is the initial specific internal energy; and $P$ is the detonation pressure. The main material parameters for CompB are shown in Table 1.

2.3.3. Material Model of Liner and Gelatin Target. The shock dynamic response behaviors of the charge liner and gelatin target under the action of explosive detonation products are described by the shock equation of state, which can be used
to calculate the material compressible fluidity behavior under a strong shock load based on the Gruneisen equation of state of the Huguenot curve:

$$P = \frac{\rho_0 c_0^2 \eta^2}{(1 - s \eta)} \left( 1 - \frac{\eta \rho_0}{\rho} \right) + \gamma_0 \rho_0 E_m,$$

where $c_0$ and $s$ are the parameters of the material shock adiabatic line; $\eta = 1 - \rho_0/\rho$ is the positive volume strain; and $\gamma_0$ is the Gruneisen coefficient. The main equation of state parameters of the different material liners and gelatin target is shown in Table 2.

### 3. Results and Discussion

#### 3.1. Formability Comparison of Different Material Micro-Shaped Jets

The forming processes of different material micro-jets were numerically simulated using the finite element software Autodyn. Since all jet forming processes are similar, taking copper jet as an example, the crushing process of copper liner is shown in Figure 3. When the main charge was detonated at 0 $\mu$s, the explosive produced high-temperature and high-pressure detonation products. At 1.5 $\mu$s, the detonation wave was transmitted to the top of the liner, so the huge pressure impulse began to act on the liner, and the top of the liner began to deform greatly. After 1.5 $\mu$s, with the propagation of the detonation products, the top to the low end of the liner were gradually crushed. At the same time, the microelements flowed along the normal direction of the liner surface, closed on the axis, and then moved along the axis. At 6 $\mu$s, the damage element formed by the liner was stable, since the synthesis velocity of the material on the liner inner surface was greater than the crushing velocity, a jet with high energy density was finally formed. The synthesis velocity of the material on the liner outer surface was less than the crushing velocity, so a pestle with low energy density was formed. There has a velocity difference between the tip and tail of the jet, so the jet continues to stretch in the axial direction, and finally, it will break.

In the process of jet forming, the jet tip velocity corresponding to the four material liners is shown in Figure 4. It can be seen from Figure 4 that the jet tip velocity increased sharply from 0 to 2 $\mu$s. After 4 $\mu$s, the micro-jet shaping was basically complete, and the jet tip velocity remained stable. At this time, compared with metal copper, the micro-jet velocity formed by three low-density nonmetallic materials was higher, and the jet tip velocity of different jets was $V_{\text{Nylon}} > V_{\text{Polycarb}} > V_{\text{Teflon}} > V_{\text{Copper}}$. This is because that for the micro-shaped charge structures of different material liners, when the liner volume was the same, since the density relationship of different material liners was $\rho_{\text{Copper}} > \rho_{\text{Teflon}} > \rho_{\text{Polycarb}} > \rho_{\text{Nylon}}$, the mass was $M_{\text{Copper}} > M_{\text{Teflon}} > M_{\text{Polycarb}} > M_{\text{Nylon}}$. Therefore, under the condition of fixed detonation energy, with a decrease in the mass of the liner, the difficulty of obtaining a higher kinetic energy under the action of the detonation wave reduced, such that $V_{\text{Nylon}} > V_{\text{Polycarb}} > V_{\text{Teflon}} > V_{\text{Copper}}$.

Figure 5 is the variation curve of the length with time before jet tensile fracture. Table 3 shows the formability of different material micro-jets at 6 $\mu$s. It can be seen from Figure 5 that at the same time, for the length of different material micro-jets, $L_{\text{Nylon}} > L_{\text{Teflon}} \approx L_{\text{Polycarb}} > L_{\text{Copper}}$. This is because nylon has the best plasticity, but Teflon and polycarb are inferior in plasticity. However, compared with others, the plasticity of metal copper is the worst. Before the jet was broken, the length growth rate of nylon jet was the fastest, the length growth rate of Teflon and polycarb micro-jets is the second, and the length growth rate of copper jet was the slowest. In addition, it can be seen from Figure 5 that the micro-copper jet, Teflon, nylon, and polycarbonate jets were broken at about 14 $\mu$s, 11 $\mu$s, 9 $\mu$s, and 7 $\mu$s, respectively. Before micro-jets broke, $L_{\text{Teflon}} \approx L_{\text{Copper}} > L_{\text{Nylon}} > L_{\text{Polycarb}}$, which showed that among the three low-density materials, Teflon has the best ductility, which is comparable to copper, followed by nylon and polycarb, which are the worst.
Table 2: Main material parameters of liner and gelatin target.

| Material  | ρ (g/cm³) | γ₀    | C₀ (cm/μs) | S₁   | E (GPa) | G (GPa) | D (m/s) | σₛ (GPa) |
|-----------|-----------|-------|------------|------|---------|---------|---------|----------|
| Copper    | 8.93      | 2.02  | 0.394      | 1.489| 117     | 47.7    | 3940    | 0.12     |
| Teflon    | 2.16      | 0.9   | 0.134      | 1.93 | 0.28    | 2.33    | 1340    | 0.05     |
| Nylon     | 1.14      | 0.87  | 0.229      | 1.63 | 1.4     | 3.68    | 2290    | 0.05     |
| Polycarb  | 1.2       | 0.61  | 0.1933     | 2.65 | 2.3     | 1       | 1933    | 0.0806   |
| Gelatin   | 1.03      | 0.17  | 0.1553     | 1.93 | 1.0E-4  | 1.5E-4  | 1553    | 2.2E-4   |

Figure 3: Micro-jet forming process of copper material liner.

Figure 4: Jet tip velocity corresponding to the four different material liners.
On the other hand, during the forming process of micro-jets, the liner density also changes, which is mainly divided into three stages. Firstly, at the beginning of the detonation products acting on the liner, the huge pressure impulse makes the microelements of the liner quickly compressed and closed, so the liner density increases sharply. Then, since the closed liner has a certain tip-tail velocity difference, the liner microelements stretch forward in the axial direction and gradually form a jet. At this stage, the liner density decreases gradually. The greater the stretching velocity, the smaller the density of the jet microelements becomes. Finally, when the jet formation is stable, the jet stretching velocity gradually decreases to a fixed value, and the jet tip velocity remains basically unchanged. When the micro-jet is at the distance of 2.5CD (where CD is the abbreviation for the charge diameter), the density distribution of the different material micro-jets is shown in Figures 6 and 7. At this time, the jet tip density was $\rho_{\text{Copper}} > \rho_{\text{Teflon}} > \rho_{\text{Polycarb}} > \rho_{\text{Nylon}}$. Among four material liners, the copper jet density decreased by at least only 25.72%, followed by nylon, which decreased by 35.26%, and the density of Teflon and polycarbonate jet decreased more, which were 42.36% and 40.33%, respectively.

3.2. Penetration Performance of Micro-Jets of Different Material Liners on Gelatin Targets. Figure 8 presents a schematic of the micro-shaped jet penetrating the gelatin target. The
target penetration depth and jet tip velocity variation curves are shown in Figure 9. As is evident from Figure 9, the copper, Teflon, and nylon jets could all pass through the 9 cm gelatin target. Among them, the copper jet required the shortest time (65 μs) to pass through the gelatin target, whereas the Teflon jet required 75 μs, and the nylon jet required 140 μs. Compared with the other three materials, the penetration depth of the polycarb jet to the target was the smallest at approximately 7.4 cm. As can be seen from Figure 9, at the initial instant when the jet was in contact with the target, the jet tip velocities were \( V_{\text{Nylon}} > V_{\text{Polycarb}} > V_{\text{Teflon}} > V_{\text{Copper}} \). However, at the end of the jet penetration, \( V'_{\text{Copper}} > V'_{\text{Teflon}} > V'_{\text{Nylon}} > V'_{\text{Polycarb}} \). The time required to penetrate the target of fixed thickness was \( T_{\text{Polycarb}} > T_{\text{Nylon}} > T_{\text{Teflon}} > T_{\text{Copper}} \) according to the jet energy, \( E_K = \frac{1}{2} m v^2 = \frac{1}{2} \rho v^2 \). As the jet mass was \( \rho_{\text{Copper}} > \rho_{\text{Teflon}} > \rho_{\text{Polycarb}} > \rho_{\text{Nylon}} \), the initial volume of the jet was \( v_{\text{Copper}} > v_{\text{Teflon}} > v_{\text{Polycarb}} > v_{\text{Nylon}} \). The jet velocity was not directly proportional to the penetration performance. This is because if the jet density is significantly low, the kinetic energy is low, and the penetration power is limited. Therefore, to realize a micro-jet with a high performance, a greater density and higher velocity should be considered.

In addition, according to the continuous jet penetration theory [20], the jet penetration depth to the target is as follows:
where $L_{\text{max}}$ represents the maximum depth of jet penetration into the target plate, $H_0$ is the distance from the virtual origin of the shaped charge to the target surface, $V_j$ is the jet tip velocity, $V_{j\min}$ is the minimum efficient jet penetration velocity, and $\rho_j$ and $\rho_t$ are the jet and target density, respectively. Geometry and notations are displayed in Figure 10.

When the stand-off is 2.5 times the charge diameter,

$$H_0 = \frac{2h}{3} + 2.5\text{CD},$$

where $h$ is the summed value of the distance from the base of the liner to the target and two-thirds of the cone height.

Considering the polycarb jet as an example, the jet tip velocity was 8654.4 m/s, the tail velocity was 1804 m/s, and the jet density was 0.716 g/cm$^3$ at a distance of 2.5CD. Substituting this in Equation (4) yielded a penetration depth of 8.02 cm; the numerical simulation result was 7.4 cm, and the error was 7%. This suggests that the numerical simulation was reliable. The penetration depths of the copper, Teflon, and nylon jets into the wireless target were calculated on this basis, which were all greater than the thickness of the target by 9 cm. This shows that they can pass through the target, as indicated by the numerical simulation results.

The energy curve of the gelatin target during the penetration of the micro-jet is shown in Figure 11. As the jet (with a high temperature, high pressure, and high energy density) penetrated the gelatin target, the target was suddenly impacted and rapidly absorbed the high energy of the jet, and the total energy abruptly increased. With an increase in the penetration depth, the jet energy gradually changed, its velocity gradually decreased, and the penetration energy also decreased. Therefore, the total energy of the target decreased. As can be seen from Figure 11, the total energies
Figure 10: Theoretical calculation model of continuous jet penetrating target.

Figure 11: Continued.
Figure 11: Energy absorption curve of gelatin target during micro-jet penetration: (a) copper jet; (b) Teflon jet, (c) nylon jet; and (d) polycarb jet.

Table 4: Stress and strain distributions of gelatin target at the end of penetration by different micro-jets.

| Jet material | Equivalent stress | A-A section equivalent stress | Effective plastic strain |
|--------------|-------------------|-------------------------------|--------------------------|
| Copper       | MIS.STRESS (Mbar) |                             |                          |
| Teflon       | MIS.STRESS (Mbar) |                             |                          |
| Nylon        | MIS.STRESS (Mbar) |                             |                          |
transmitted by different micro-jets to the target at the end of the penetration were $E_{\text{Nylon}} > E_{\text{Teflon}} > E_{\text{Polycarb}} > E_{\text{Copper}}$, the internal energies were $E_{\text{Teflon}} > E_{\text{Polycarb}} > E_{\text{Nylon}} > E_{\text{Copper}}$, and the kinetic energies were $E_{k_{\text{Nylon}}} > E_{k_{\text{Polycarb}}} > E_{k_{\text{Teflon}}} > E_{k_{\text{Copper}}}$. This indicates that compared with copper, nonmetallic material jets can transfer more energy to the target. Furthermore, the nylon jet transferred the highest energy to the gelatin target, followed by Teflon. Although the polycarb jet did not completely pass through the target, it transferred a certain amount of energy to the target. By contrast, the copper jet did not rapidly pass through the gelatin target and transferred the least energy.

Table 4 presents the equivalent stress distribution, equivalent stress, and effective plastic strain distribution of the gelatin target at the end of the micro-jet penetration. Figure 12 presents a schematic of the strain-area distribution in the gelatin target. As can be seen from Table 4, during the penetration of the micro-jet, the gelatin target was destroyed, and an instantaneous cavity area was gradually formed in the target. As shown in Table 5, the penetration diameters $D$ of the target were $D_{\text{Polycarb}} > D_{\text{Nylon}} > D_{\text{Teflon}} > D_{\text{Copper}}$, and the penetration diameter of the low-density nonmetallic jets into the gelatin target was larger than that of the metallic copper jet. Moreover, based on the maximum distortion energy theory, the von Mises stress (equivalent stress) was used to determine the yield point of the material, namely

$$
\sigma_{eq} = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 / 2},
$$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses at the research point. When the equivalent stress of the impacted gelatin material exceeded the yield stress of gelatin by 2.2 MPa, the target underwent irreversible plastic deformation. However, the influence of the jet diminished with distance from the impact point in the gelatin target material and caused only elastic deformation.

It is evident from Figure 5 that compared with the copper and Teflon jets, the nylon jet passed through the gelatin target and resulted in the largest plastic strain area, followed by Teflon. Although the copper jet could pass through the target, the plastic strain area was small. Therefore, when designing a micro-shaped charge structure, it is appropriate to use low-density nonmetallic materials as charge liners to achieve high-efficiency damage and meet the development requirements for lightweight weapons.

| Damage element | Maximum diameter (cm) | Minimum diameter (cm) | Penetration depth |
|----------------|-----------------------|-----------------------|------------------|
| Copper jet     | 0.96                  | 0.34                  | Run through      |
| Teflon jet     | 1.95                  | 0.66                  | Run through      |
| Nylon jet      | 3.2                   | 1.32                  | Run through      |
| Polycarb jet   | 3.2                   | 1.37                  | 7.4 cm           |

Figure 12: Schematic diagram of strain area distribution in gelatin target.
4. Conclusion

In this study, a 10 mm caliber miniature-shaped charge structure was designed, and the effects of the liner material on the micro-jet formation performance and penetration performance were studied using a gelatin target. The main conclusions are as follows:

1. The tip velocities of the damage element formed by the three nonmetallic material liners were larger than that of metallic copper—$V_{\text{Nylo}} > V_{\text{Polycarb}} > V_{\text{Teflon}} > V_{\text{Copper}}$. The lengths of the micro-jets before tensile fracture were $V_{\text{Nylo}} > V_{\text{Polycarb}} > V_{\text{Teflon}} > V_{\text{Copper}}$. Therefore, among the three low-density materials, Teflon exhibited the highest ductility comparable to that of copper followed by nylon and polycarbonate.

2. In terms of the penetration depth into the gelatin target, copper, Teflon, and nylon jets passed through the target. The polycarb jet passed through the target, and the penetration depth of the target plate was only 7.4 cm. Therefore, when designing a miniature shaped charge, the density of the shaped charge liner material should be moderate. This suggests that the use of lightweight materials cannot be blindly pursued. If the density is excessively low, although the jet velocity is higher, the jet quality is significantly lower and its energy is limited.

3. Compared with copper, the three nonmetallic material jets transmitted more energy to the gelatin target during the penetration of the target, and the plastic strain area and the damage and failure areas were larger. The nylon jet transmitted the most energy to the target. Moreover, the penetration aperture of the nylon jet was the largest, followed by Teflon, and that of copper was the smallest. Although the polycarb jet did not pass through the target, it exhibited the largest penetration aperture in the target and transmitted more energy than copper.

In this study, it was found that the three nonmetallic material-shaped charges meet the development requirement for lightweight ammunition and can transmit higher energy to the target compared with the copper liner-shaped charge. Overall, the nylon jet demonstrated the highest penetration efficiency on the gelatin target compared with the copper jet based on the penetration depth and penetration energy, followed by Teflon and polycarb. The penetration efficiency of the target was the lowest. This article can therefore serve as a basis for future research on miniature charges [24].

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] K. Adam, P. Dariusz, and B. Mirosław, “Metallographic analysis of piercing armor plate by explosively formed projectiles,” Archives of Civil and Mechanical Engineering, vol. 18, no. 4, pp. 1686–1697, 2018.
[2] V. V. Selivanov, S. V. Fedorov, Y. M. Nikolskaya, and S. V. Ladov, “Research of the explosive formation of a compact element for meteoroids fragments and space debris modelling,” Acta Astronautica, vol. 163, pp. 84–90, 2019.
[3] X. Jia, M. Xu, Z. Huang, Q. Xiao, S. Chen, and B. Ma, “Theoretical analysis and experimental study of the performance of shaped charge jet penetration into thick-walled moving target by rocket sled testing method,” International Journal of Impact Engineering, vol. 155, no. 4, Article ID 103894, 2021.
[4] Z. Zhao and W. Jin, “Finite element modeling of the shaped charge jet and design of the reusable perforating gun,” Petroleum Science, vol. 17, pp. 1389–1399, 2020.
[5] C. Wang, J. Ding, and H. T. Zhao, “Numerical simulation on jet formation of shaped charge with different liner materials,” Defence Science Journal, vol. 65, no. 4, pp. 1686–1697, 2015.
[6] W. Q. Guo, J. X. Liu, Y. Xiao, S. Li, Z. Zhao, and J. Cao, “Comparison of penetration performance and penetration mechanism of w-cu shaped charge liner against three kinds of target: pure copper, carbon steel and Ti-6Al-4V alloy,” International Journal of Refractory Metals and Hard Materials, vol. 60, pp. 147–153, 2016.
[7] J. H. Dou, X. Jia, Z. X. Huang et al., “Theoretical and numerical simulation study on jet formation and penetration of different liner structures driven by electromagnetic pressure,” Defence Technology, vol. 17, p. 13, 2021.
[8] M. Sun, C. Li, X. Zhang, X. Hu, X. Hu, and Y. Liu, “Reactivity and penetration performance Ni-Al and Cu-Ni-Al mixtures as shaped charge liner materials,” Materials, vol. 11, pp. 2267–2278, 2018.
[9] L. L. Ding, W. H. Tang, and X. W. Ran, “Simulation study on jet formability and damage characteristics of a low-density liner material,” Materials, vol. 11, pp. 1–17, 2018.
[10] T. Baykara, V. Gu, and A. Demirural, “Structural evolution and microstructural features of the hydrodynamically penetrating copper jet of a shaped charge,” Journal of Materials Engineering and Performance, vol. 30, pp. 1862–1871, 2021.
[11] G. S. Ma and G. L. He, “Numerical simulation and experimental study on shaped charge warhead of guided ammunition,” Shock and Vibration, vol. 2021, Article ID 6658676, 15 pages, 2021.
[12] H. G. Guo, Y. F. Zheng, S. He, Q. B. Yu, C. Ge, and H. F. Wang, “Reaction characteristic of PTFE/Al/Cu/Pb composites and application in shaped charge liner,” Defence Technology, vol. 472, pp. 1–11, 2021.
[13] X. P. Zhang, Z. J. Wang, J. P. Yin, J. Yi, and H. Wang, “Damage mechanism of PTFE/Al reactive charge liner structural parameters on a steel target,” Defence Technology, vol. 14, pp. 3701–3718, 2021.
[14] N. D. Gerami, G. H. Liaghat, G. Moghadas, and N. Khazraiyian, “Analysis of liner effect on shaped charge penetration into thick concrete targets,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 39, 2017.

[15] B. H. Chang, J. P. Yin, and Z. Q. Cui, “Improved dynamic mechanical properties of modified PTFE jet penetrating charge with shell,” *Strength of Materials*, vol. 48, pp. 82–89, 2016.

[16] J. P. Yin, Z. X. Shi, J. Chen, B. H. Chang, and J. Y. Yi, “Smooth particle hydrodynamics-based characteristics of a shaped jet from different materials,” *Strength of Materials*, vol. 51, pp. 85–94, 2019.

[17] D. R. Scheffler, M. S. Burkins, and W. P. Walters, “Characterization of Jets from Exploding Bridge Wire Detonators,” *Army Research Lab Aberdeen Proving Ground Md Weapons And Materials Research Directorate, ARL-TR-3518*, 2005.

[18] C. Wu, Y. Jin, and L. Zhou, “Experimental study on penetration power of miniature armor-piercing projectile,” *Journal of Projectiles, Rockets, Missiles and Guidance*, vol. 51, pp. 82–89, 2002.

[19] C. H. Li, Q. B. Lu, and R. Jin, *What Is the Use of Micro-unmanned Aerial Vehicle*, People’s Liberation Army Daily, Beijing, China, 2020.

[20] S. Y. Liu and S. Shuai, *Application and Enlightenment of UAV in NAKA Conflict*, Ordnance Industry Automation, Ayudh Bhawan, Kolkata, India, 2021.

[21] T. Jing, W. Guo, and X. Lei, “Comparative simulation of penetration efficiency of rifle shells M855 and M855A1,” *Journal of Projectiles, Rockets, Rockets and Guidance*, vol. 3, pp. 45–48+54, 2018.

[22] Y. K. Wen, C. Xu, Y. X. Jin, and R. C. Batra, “Rifle bullet penetration into ballistic gelatin,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 67, pp. 40–50, 2017.

[23] G. H. Yoon, J. S. Mo, K. H. Kim, C. H. Yoon, and N. H. Lim, “Investigation of bullet penetration in ballistic gelatin via finite element simulation and experiment,” *Journal of Mechanical Science and Technology*, vol. 29, pp. 3747–3759, 2015.

[24] M. Held, “Penetration cut off velocities of shaped charge jets,” *Propellants, Explosives, Pyrotechnics*, vol. 13, pp. 111–119, 1988.