Research Article

Numerical Simulation of Multiple Explosively Formed Projectile Warhead Forming Characteristics considering Various Materials

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To study the influence of different liner structures and materials (copper, steel, and tungsten) on the forming characteristics of multiple explosively formed projectile (MEFP) with integrated liner and shell designs, three types of liners with different structures were designed. LS-DYNA was used for numerical simulation, and the results show that the thickness change at the center of the liner has no obvious influence on the shape of the explosively formed projectile (EFP). However, the curvature radius of the liner has a significant influence on the shape of the EFP. When the liner material is copper and the curvature radius of the liner is greater than 8 mm, the EFP shape approximates an ellipsoidal or hemispherical shape and the EFP forming speed is between 1900 m/s and 2400 m/s. When the material of the liner is steel or tungsten and the curvature radius of the liner is thicker than 8 mm, the liner is not able to form projectiles in the shape of a sphere, ellipsoid, or long rod. By comparing the forming speed from 1#EFP to 4#EFP, it can be said that MEFP with integrated liner and shell design displays a certain pressurization effect. Research results show that, for small-caliber MEFP warheads, subject to the size of the warhead, when the liner is steel or tungsten, the detonation energy generated by the limited charge does not result in the liner forming an effective EFP. However, when the liner material is selected as copper, the EFP forming shape and speed are more appropriate.

1. Introduction

During the Spanish Civil War from 1936 to 1939, the High-Explosive Antitank (HEAT) with a shaped charge effect began to be used. As a type of shaped charge projectile, explosively formed projectiles (EFP) began to appear in the 1970s. Multiple explosively formed projectile (MEFP) began to appear in the 1980s to improve the hit rate and damage probability of the projectile [1]. MEFP, a highly effective damage warhead, was developed based on a single EFP warhead [2]. MEFP warheads can be divided into three types according to their charge structure: integral type, combined type, and cutting type. Among these, the integral-type MEFP has a simple structure that enables the formed projectile to obtain a higher penetration performance, which has become the research focus [3–5]. In terms of MEFP penetration into the target, Zhao et al. [6] studied the penetration of MEFP into a target plate after cross-mesh cutting EFPs using static explosion tests and numerical simulations. Xiang et al. [7, 8]

carried out numerical simulations and experimental verification of grooved MEFP penetrating steel target plates. Fong et al. [9] studied the elimination of threat posed by mines and improvised explosive devices using the MEFP warhead technology. In terms of the initiation mode of the MEFP, Zhao et al. [10] studied the forming characteristics of MEFP under three different initiation modes through numerical simulation and detonation wave action theory. Fan et al. [11] studied the influence of central initiation and three-, four-, and eight-point simultaneous initiation on the molding characteristics of MEFP using numerical simulation. Li et al. [12] and Song et al. [13] analyzed the impact of the detonation mode on the performance of the MEFP warhead by combining a static detonation test with numerical simulation. In terms of the liner parameters of MEFP, Zhang et al. [14] studied the influence of charge spacing, charge, and curvature radius on the forming characteristics of MEFP using numerical simulation. Liang et al. [15, 16] studied the influence of the structural

parameters of the liner and warhead on the forming characteristics of MEFP by simplifying the model and conducting numerical simulations. Yin et al. [17] analyzed the influence of liner parameters (radius of curvature, caliber, and thickness) on the shaping of MEFP using numerical simulation. In terms of the influence of liner material on MEFP forming characteristics, Zhao et al. [18] conducted a numerical simulation of the MEFP forming process with different materials such as copper, aluminum, and iron used as liners and concluded that the projectile speed and radial dispersion angle were reduced by 58% and 56%, respectively, with an increase in the material density of the liner. Yuan et al. [19] studied the forming characteristics of circumferential MEFPs with different materials and shell thicknesses using numerical simulation and concluded that when the thickness of the liner was larger than that of the shell, the MEFP speed increased rapidly, whereas when the thickness of the liner was smaller than that of the shell, the MEFP speed increased slowly.

The research on the forming performance of the MEFP, according to the flying direction of the formed projectile, can be divided into two categories. In the first category, the liner is along the axial direction of the charge arrangement, and the formed projectile is scattered along the axial direction [6–11, 14, 18], that is, an axial MEFP. In the second type, the liners are along the charge circumferential arrangement, forming the projectile along the charging circumferential direction of flying [12, 13, 15–17, 19], that is, circumferential MEFP. In the literature [6–19], whether referring to axial or circumferential MEFP, there are three characteristics of structure: first, the separation design of the liner and shell is adopted; second, the liner is designed with equal wall thickness; third, the charge caliber of the MEFP warhead is between 40 mm and 205 mm. With the exception of the charge caliber of the MEFP warhead in [13] and [19], which are 48 mm and 40 mm, respectively, the MEFP warheads have medium to large calibers. To study the forming performance of the circumferential MEFP with the integrated design of the small-caliber shell and liner, first, three different structural types of MEFP warheads were designed, wherein the thickness of the liner was smaller than, equal to, and larger than that of the shell, respectively. Second, by using the fluid-solid interaction method, a numerical simulation of the MEFP warhead with three different structure types was carried out, and the forming characteristics of the MEFP were analyzed when the material of the liner and shell was copper, steel, and tungsten, and the simulation results were compared and analyzed.

In the numerical simulation, firstly, the structured mesh of the designed circumferential MEFP warhead was generated using the ANSYS/ICEM (Integrated Computer Engineering and Manufacturing) meshing tool, and then the unstructured mesh generated by ANSYS/ICEM was generated and imported into HyperMesh for LS-DYNA preprocessing. Finally, it was submitted to the LS-DYNA solver for calculation.

2. Structural Design

To investigate the forming performance of the circumferential MEFP integrated design of the small-caliber shell and liner, the structural parameters of the three different types of MEFP warheads designed are listed in Table 1.

The three-dimensional (3D) model designed by the structural parameters of the MEFP warhead is shown in Table 1, and the structural sketch of the liner is shown in Figure 1.

In the structure (Figure 1), each column is composed of four liners in the axial direction of the charge; each row is composed of 12 liners in the circumferential direction of the charge. Therefore, the circumferential MEFP warhead structure designed in this study had a total of 48 liners, and the liner was centrosymmetric.

3. Numerical Simulation Model

3.1. Finite Element Model. At present, there are many commonly used finite element meshing software, such as HyperMesh, Finite Element Model Builder (FEMB), True Grid, and ANSYS/ICEM. In this study, first, ICEM was used for finite element structured mesh division, then the divided mesh file was imported into HyperMesh for preprocessing of finite element analysis, and finally, the numerical calculation was carried out using LS-DYNA. To reduce the amount of calculation in the numerical simulation, according to the symmetry of the MEFP warhead structure, a quarter finite element model was established, as shown in Figure 2.

3.2. Material Model. The material model of the shell, explosive, and air is the same as that in Section 3.2 of [20], and the material parameters of the liner are shown in Table 2.

ρ is the density of the materials, G is the young's modulus of the materials, A is the yield stress parameters of the materials, B is strain hardening coefficient of the materials, n is the hardening exponent of the materials, C is the strain rate constant of the materials, m is the thermal softening exponent, T_m is the melting point temperature of the materials, T_{room} is the reference temperature (it is usually room temperature), Γ is the Gruneisen coefficient, c_0 is the volume velocities of the materials, and S is the impact adiabatic parameters.

4. Results and Discussion

4.1. Forming Characteristics of Liner and Shell Materials Are Copper

4.1.1. Forming Results. Single-point detonation was adopted in the numerical simulation, and the position of the detonation point is shown in Figure 2. The results are shown in Figure 3, where the material of the integral circumferential MEFP warhead shell and liner is copper.

TABLE 1: MEFP warhead structure parameters of three different structure types.

Parameters	Liner center thickness (Δt)/mm	Inner wall curvature radius of liner ($R1$)/mm	Outer wall curvature radius of liner ($R2$)/mm
Charge height: 52 mm, charge diameter: 37.6 mm, shell thickness: 1.2 mm ($t = 1.2$ mm), and liner diameter: 9 mm	1.1	8	8
		9	9
		10	10
		11	11
	1.2	8	8
		9	9
		10	10
		11	11
	1.3	8	8
		9	9
		10	10
		11	11

FIGURE 1: Three-dimensional structure of MEFP warhead.

FIGURE 2: Finite element model.

TABLE 2: Materials parameters of liner.

Material	ρ (g/cm ³)	G (GPa)	A (MPa)	B (MPa)	n	C	m	T_m (K)	T_{room} (K)	Γ	c_0 (cm/ μ s)	S
Copper	8.93	46.5	90	292	0.31	0.025	1.09	1356	293	2.02	0.39	1.49
Steel	7.8	79	813	601	0.28	0.014	1.04	1723	293	1.67	0.46	1.33
Tungsten	17.7	160	631	1258	0.092	0.014	0.94	1723	293	1.54	0.4	1.24

Because the structure of the monolithic circumferential MEFP warhead designed in this study is center-symmetrical and the detonation point is on the symmetrical centerline, each row of the formed projectiles of the circumferential MEFP warhead has similar characteristics. Therefore, a column of formed projectiles was selected as the research object and labeled as 1#EFP, 2#EFP, 3#EFP, and 4#EFP, respectively.

Figure 3 shows that when the liner and shell material is copper, the slender forming shape of the projectile gradually flattened with an increase in the liner curvature radius. Due

to the single-point initiation and the selection of initiation position, the pressure of detonation waves front increased gradually with the detonation process, the different positions of detonation wave front acting on the liner lead to the shape difference in 1#EFP, 2#EFP, 3#EFP, and 4#EFP, and the direction of the 2#EFP, 3#EFP, and 4#EFP projectile heads deflects to the direction of detonation wave front propagation. When the radius of curvature of the liner is 8 mm, the shape approximates a rod, and when the radius of curvature of the liner is between 9 mm and 11 mm, the shape is similar to an ellipsoid.

FIGURE 3: Forming results: (a) The thickness of liner is less than the shell thickness. (b) Equal thickness of shell and liner. (c) The thickness of shell is less than the liner thickness.

4.1.2. Forming Speed.

The forming speed is shown in Table 3. From Table 3, it can be observed that, with the increase in the liner curvature radius, the forming speed contrast diagram of the MEFP warhead at $t = \Delta t$, $t > \Delta t$, and $t < \Delta t$ is shown in Figure 4.

As shown in Figure 4, when $t > \Delta t$ and $t = \Delta t$, the velocity of 1#EFP decreases from 2077 m/s and 2097 m/s to 2042 m/s and 2072 m/s, respectively, and then increases to 2085 m/s and 2135 m/s, respectively, resulting in an increase of 1.68% and 1.68% and decrease of 2.1% and 1.68%, respectively. The velocity of 2#EFP decreased from 2205 m/s and 2197 m/s to 2134 m/s and 2131 m/s, respectively, and then increases to 2186 m/s and 2141 m/s, resulting in an increase of 3.21% and 3% and decrease of 2.44% and 0.47%, respectively. The velocity of 3#EFP decreases from 2358 m/s and 2334 m/s to 2358 m/s and 2164 m/s, respectively, and then increases to 2189 m/s and 2175 m/s, respectively, resulting in an increase of 7.38% and 7.28% and decrease of 0.23% and 0.51%, respectively. The velocity of 4#EFP decreases from 2273 m/s and 2257 m/s to 2138 m/s and 2130 m/s, respectively, and then increases to 2138 m/s and 2130 m/s, respectively, resulting in an increase of 5.94% and 5.63% and decrease of 1.82% and 0.05%, respectively. When $t < \Delta t$, the velocity of 1#EFP decreases from 2067 m/s to 1997 m/s and

then increases to 2034 m/s, resulting in an increase of 3.39% and decrease of 1.85%, respectively, and the velocity of 1#EFP–4#EFP decreases from 2165 m/s, 2329 m/s, and 2241 m/s to 2165 m/s, 2329 m/s, and 2241 m/s, respectively, resulting in decreases of 3.14%, 8.93%, and 7.1%, respectively. It can be seen from the above data that when $t > \Delta t$ and $t = \Delta t$, the forming speed first decreases and then increases with the increase in the liner curvature radius, the speed reduction range is between 1.5% and 8%, and the speed increase reduction range is between 0.05% and 2%. When $t < \Delta t$, the forming speed gradually decreases with the increase in the liner curvature radius, and the reduction is between 3% and 9%.

From Table 3, the speed change curve of 1#EFP to 4#EFP can be obtained, as shown in Figure 5.

As shown in Figure 5, when the liner curvature radius with three different structures is less than 11 mm, with the detonation process of the main charge and the pressurization effect of the integrated design of the liner and the shell on the detonation energy, the speed of 1#EFP to 3#EFP gradually ascends. With the detonation, the material of the shell breaks, and the pressurization effect of the integrated design of the liner and shell on the detonation energy of the explosive disappears; therefore, the speed from 3#EFP to

TABLE 3: Forming speed when the material of the liner and shell is copper.

	EFP no.	$R1 = R2 = 8 \text{ mm}$	$R1 = R2 = 9 \text{ mm}$	$R1 = R2 = 10 \text{ mm}$	$R1 = R2 = 11 \text{ mm}$
$t > \Delta t$	1#EFP	2097 m/s	2085 m/s	2072 m/s	2135 m/s
	2#EFP	2205 m/s	2151 m/s	2134 m/s	2186 m/s
	3#EFP	2358 m/s	2264 m/s	2184 m/s	2189 m/s
	4#EFP	2273 m/s	2176 m/s	2138 m/s	2177 m/s
$t = \Delta t$	1#EFP	2077 m/s	2051 m/s	2042 m/s	2085 m/s
	2#EFP	2197 m/s	2140 m/s	2131 m/s	2141 m/s
	3#EFP	2334 m/s	2230 m/s	2164 m/s	2175 m/s
	4#EFP	2257 m/s	2145 m/s	2130 m/s	2131 m/s
$t < \Delta t$	1#EFP	2067 m/s	2005 m/s	1997 m/s	2034 m/s
	2#EFP	2165 m/s	2126 m/s	2115 m/s	2097 m/s
	3#EFP	2329 m/s	2192 m/s	2136 m/s	2121 m/s
	4#EFP	2241 m/s	2139 m/s	2090 m/s	2082 m/s

FIGURE 4: Comparison of forming speed of different structure types: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

4#EFP reduces. In Figure 5, when $t > \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2097 m/s, 2085 m/s, 2072 m/s, and 2135 m/s to 2358 m/s, 2264 m/s, 2184 m/s, and 2189 m/s, respectively, and then decreases to 2273 m/s, 2176 m/s, 2138 m/s, and 2177 m/s, respectively, resulting in an increase of 12.4%, 8.6%, 5.4%, and 2.5% and decrease of 3.6%, 3.9%, 2.1%, and 0.5%, respectively. When $t = \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2077 m/s, 2051 m/s, 2042 m/s, and 2085 m/s to 2334 m/s, 2230 m/s, 2164 m/s, and 2175 m/s, respectively, and then decreases to 2257 m/s,

2145 m/s, 2138 m/s, and 2131 m/s, respectively, resulting in an increase of 12.4%, 8.7%, 5.9%, and 4.3% and decrease of 3.3%, 3.8%, 1.6%, and 2%, respectively. When $t < \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2067 m/s, 2005 m/s, 1997 m/s, and 2034 m/s to 2329 m/s, 2192 m/s, 2136 m/s, and 2121 m/s, respectively, and then decreases to 2241 m/s, 2139 m/s, 2090 m/s, and 2082 m/s, respectively, resulting in an increase of 12.7%, 9.3%, 6.9%, and 4.3% and decrease of 3.8%, 2.4%, 2.2%, and 1.8%, respectively. It can be seen from the above data that the speed increase range of

FIGURE 5: Comparison of forming speed of different structure types: (a) comparison of forming speed of $R_1 = R_2 = 8$ mm; (b) comparison of forming speed of $R_1 = R_2 = 9$ mm; (c) comparison of forming speed of $R_1 = R_2 = 10$ mm; (d) comparison of forming speed of $R_1 = R_2 = 11$ mm.

1#EFP to 3#EFP is between 4% and 12.5%, the increase gradually decreases with the curvature radius of the liner increases, the speed reduction range of 3#EFP to 4#EFP is between 0.5% and 4%, and the reduction rate gradually decreases.

When the shell thickness of the integral MEFP warhead remains unchanged and the curvature radius of the liner remains unchanged, only the thickness at the center changes for three different types of MEFP warheads. Therefore, the influence of thickness change at the center on the change of forming speed can be obtained from the forming speed list shown in Table 3, as shown in Figure 6.

As shown in Figure 6, when the thickness at the center of the liner increases from 1.1 mm to 1.3 mm, the speed of the projectile gradually decreases. In Figure 6, when the curvature radius is different, the velocity of 1#EFP decreases from 2097 m/s, 2085 m/s, 2072 m/s, and 2135 m/s to 2067 m/s, 2005 m/s, 1997 m/s, and 2034 m/s, respectively, resulting in a decrease of 1.4%, 3.8%, 3.6%, and 4.7%, respectively. The velocity of 2#EFP decreases from 2205 m/s, 2151 m/s, 2134 m/s, and 2189 m/s to 2165 m/s, 2126 m/s, 2115 m/s, and 2097 m/s, respectively, resulting in a decrease of 1.8%, 1.2%, 0.9%, and 4.2%, respectively. The velocity of 3#EFP decreases from 2358 m/s, 2264 m/s, 2184 m/s, and 2186 m/s to 2329 m/s, 2192 m/s, 2136 m/s,

and 2121 m/s, respectively, resulting in a decrease of 1.2%, 3.2%, 2.2%, and 3%, respectively. The velocity of 4#EFP decreases from 2273 m/s, 2176 m/s, 2138 m/s, and 2177 m/s to 2241 m/s, 2139 m/s, 2090 m/s, and 2082 m/s, respectively, resulting in a decrease of 1.4%, 1.7%, 2.2%, and 4.3%, respectively. It can be seen from the above data that the speed of the formed projectile decreases by 1%–5% with the increase of the thickness at the center of the liner.

4.2. Forming Characteristics of Liner and Shell Materials Are Steel

4.2.1. Forming Results. The material in the finite element model of the MEFP warhead established in the third part was chosen as steel, and the remaining boundary conditions of the numerical simulation were set to be the same as for Section 4.1. The resulting forming result is shown in Figure 7.

In Figure 7, when the material of the liner and the shell is steel, the shape of the EFP starts to deteriorate with the increase in the liner curvature radius, and even the shape of a sphere, an ellipsoid, and a long rod cannot be formed. When the liner curvature radius is 8 mm, 1#EFP, 2#EFP, 3#EFP, and 4#EFP can form an approximate ellipsoidal projectile. When the liner curvature radius is 9 mm, 3#EFP and 4#EFP

FIGURE 6: Comparison of forming speed of different thickness of liner center: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

will be able to form an ellipsoid projectile; when the liner curvature radius is greater than 9 mm, 1#EFP, 2#EFP, 3#EFP, and 4#EFP will be unable to form projectiles in the shape of spheres, ellipsoids, or long rods. When the shell thickness of the MEFP warhead and the liner curvature radius is constant, the shape does not change significantly with an increase in the thickness at the center. In addition, the forming results of the three structure types are similar.

4.2.2. Forming Speed. The forming speed is shown in Table 4.

From Table 4, it can be obtained that, with the increase of the liner curvature radius, the forming velocity contrast diagram of the MEFP warhead at $t = \Delta t$, $t > \Delta t$, and $t < \Delta t$ is shown in Figure 8.

In Figure 8, the velocity of 1#EFP increases from 2327 m/s, 2283 m/s, and 2255 m/s to 2374 m/s, 2341 m/s, and 2308 m/s, respectively, resulting in an increase of 2%, 2.5%, and 2.8%, respectively. The velocity of 2#EFP increases from 2409 m/s, 2391 m/s, and 2334 m/s to 2506 m/s, 2475 m/s, and 2442 m/s, respectively, resulting in an increase of 4%, 3.5%, and 4.6%, respectively. The velocity of 3#EFP increases from 2375 m/s, 2365 m/s, and 2320 m/s to 2521 m/s, 2494 m/s, and 2461 m/s, respectively, resulting in an increase of 6.1%, 5.5%, and 6.1%, respectively. The velocity of 4#EFP increases from 2315 m/s, 2301 m/s, and 2267 m/s to 2455 m/s, 2428 m/s, and

2399 m/s, respectively, increasing by 6%, 5.5%, and 5.8%, respectively. It can be seen from the above data that when the material of the liner and shell is steel, the speed increase range of the formed projectile is between 2% and 6.5% with the increases of the liner curvature radius.

From Table 4, the speed change curve from 1#EFP to 4#EFP can be obtained, as shown in Figure 9.

In Figure 9, when $t > \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2327 m/s, 2352 m/s, 2362 m/s, and 2374 m/s to 2409 m/s, 2455 m/s, 2496 m/s, and 2521 m/s, respectively, and then decreases to 2315 m/s, 2393 m/s, 2432 m/s, and 2455 m/s, respectively, resulting in an increase of 3.5%, 4.4%, 4.5%, and 6.2% and decrease of 3.9%, 2.5%, 2.6%, and 2.6%, respectively. When $t = \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2283 m/s, 2309 m/s, 2333 m/s, and 2341 m/s to 2391 m/s, 2422 m/s, 2466 m/s, and 2494 m/s, respectively, and then decreases to 2301 m/s, 2362 m/s, 2407 m/s, and 2428 m/s, respectively, resulting in an increase of 4.7%, 4.9%, 5.7%, and 6.5% and decrease of 3.8%, 2.5%, 2.4%, and 2.6%, respectively. When $t < \Delta t$, the velocity from 1#EFP to 4#EFP increases from 2255 m/s, 2270 m/s, 2294 m/s, and 2308 m/s to 2334 m/s, 2389 m/s, 2434 m/s, and 2461 m/s, respectively, and then decreases to 2267 m/s, 2362 m/s, 2376 m/s, and 2399 m/s, respectively, resulting in an increase of 3.5%, 5.2%, 6.1%, and 6.6% and decrease of 2.9%, 2.2%, 2.4%, and 2.5%, respectively. It can be seen from the above data that the speed increase range of the formed projectile is

FIGURE 7: Formed results: (a) the thickness of the liner is less than the shell thickness; (b) equal thickness of shell and line; (c) the thickness of shell is less than the liner thickness.

TABLE 4: Forming speed when the material of the liner and shell is steel.

	EFP no.	$R1 = R2 = 8 \text{ mm}$	$R1 = R2 = 9 \text{ mm}$	$R1 = R2 = 10 \text{ mm}$	$R1 = R2 = 11 \text{ mm}$
$t > \Delta t$	1#EFP	2327 m/s	2352 m/s	2362 m/s	2374 m/s
	2#EFP	2409 m/s	2454 m/s	2484 m/s	2506 m/s
	3#EFP	2375 m/s	2455 m/s	2496 m/s	2521 m/s
	4#EFP	2315 m/s	2393 m/s	2432 m/s	2455 m/s
$t = \Delta t$	1#EFP	2283 m/s	2309 m/s	2333 m/s	2341 m/s
	2#EFP	2391 m/s	2422 m/s	2451 m/s	2475 m/s
	3#EFP	2365 m/s	2421 m/s	2466 m/s	2494 m/s
	4#EFP	2301 m/s	2362 m/s	2407 m/s	2428 m/s
$t < \Delta t$	1#EFP	2255 m/s	2270 m/s	2294 m/s	2308 m/s
	2#EFP	2334 m/s	2383 m/s	2418 m/s	2442 m/s
	3#EFP	2320 m/s	2389 m/s	2434 m/s	2461 m/s
	4#EFP	2267 m/s	2337 m/s	2376 m/s	2399 m/s

between 2% and 7%, and the speed reduction range of the formed projectile is between 2% and 3%.

When the shell thickness of the integral MEFP warhead remains unchanged and the liner curvature radius remains unchanged, only the thickness at the center changes for three different types of MEFP warheads. Therefore, the influence of thickness change at the center on the change of forming speed can be obtained from the forming speed list shown in Table 4, as shown in Figure 10.

As shown in Figure 10, when the curvature radius is different, the velocity of 1#EFP decreases from 2327 m/s, 2352 m/s, 2362 m/s, and 2374 m/s to 2255 m/s, 2270 m/s, 2294 m/s, and 2308 m/s, respectively, resulting in a decrease of 3.1%, 3.5%, 2.9%, and 2.8%, respectively. The velocity of 2#EFP decreases from 2409 m/s, 2454 m/s, 2484 m/s, and 2506 m/s to 2334 m/s, 2383 m/s, 2418 m/s, and 2442 m/s, respectively, resulting in a decrease of 2.3%, 2.9%, 2.7%, and 2.6%, respectively. The velocity of 3#EFP

FIGURE 8: Comparison of forming speed of different structure types: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

FIGURE 9: Continued.

FIGURE 9: Comparison of forming speed of different structure types: (a) comparison of forming speed of $R1 = R2 = 8$ mm; (b) comparison of forming speed of $R1 = R2 = 9$ mm; (c) comparison of forming speed of $R1 = R2 = 10$ mm; (d) comparison of forming speed of $R1 = R2 = 11$ mm.

FIGURE 10: Comparison of forming speed of different thickness of liner center: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

decreases from 2375 m/s, 2455 m/s, 2496 m/s, and 2521 m/s to 2320 m/s, 2389 m/s, 2434 m/s, and 2461 m/s, respectively, resulting in a decrease of 2.3%, 2.7%, 2.5%, and 2.4%, respectively. The velocity of 4#EFP decreases from 2315 m/s, 2393 m/s, 2432 m/s, and 2455 m/s to 2267 m/s,

2337 m/s, 2376 m/s, and 2399 m/s, respectively, resulting in a decrease of 2.1%, 2.3%, 2.3%, and 2.3%, respectively. From the above data, the speed of the formed projectile decreases by 2%–3.5% with the increase of the thickness at the center of the liner.

4.3. Forming Characteristics of Liner and Shell Materials Are Tungsten

4.3.1. Forming Results. The material in the finite element model of the MEFP warhead established in the third part was chosen as tungsten, and the remaining boundary conditions of the numerical simulation were set to be the same as in Section 4.1. The forming result is shown in Figure 11.

As shown in Figure 11, when the liner and shell material is tungsten and the liner curvature radius is greater than 8 mm, the projectile with a spherical shape, ellipsoid shape, and long rod shape cannot be formed. It is shown in Figures 11(a)–11(c) that the forming results of the three types of MEFP warheads are similar.

4.3.2. Forming Speed. The forming speed is shown in Table 5.

From Table 5, it can be observed that, with the increase in the liner curvature radius, the formed speed contrast diagram of the MEFP warhead at $t = \Delta t$, $t > \Delta t$, and $t < \Delta t$ is shown in Figure 12.

As shown in Figure 12, the velocity of 1#EFP increases from 1569 m/s, 1541 m/s, and 1511 m/s to 1622 m/s, 1597 m/s, and 1571 m/s, respectively, resulting in an increase of 3.4%, 2.5%, and 4%, respectively. The velocity of 2#EFP increases from 1733 m/s, 1694 m/s, and 1658 m/s to 1833 m/s, 1806 m/s, and 1768 m/s, respectively, resulting in an increase of 5.8%, 6.6%, and 6.6%, respectively. The velocity of 3#EFP increases from 1729 m/s, 1682 m/s, and 1660 m/s to 1850 m/s, 1813 m/s, and 1780 m/s, respectively, resulting in an increase of 7%, 7.8%, and 7.2% respectively. The velocity of 4#EFP increases from 1612 m/s, 1585 m/s, and 1559 m/s to 1690 m/s, 1669 m/s, and 1644 m/s, respectively, resulting in an increase of 4.8%, 5.3%, and 5.5%, respectively. It can be seen from the above data that when the material of the liner and shell is steel, the speed increase range of the formed projectile is between 3% and 8% with the increases of the liner curvature radius.

From Table 5, the speed change curve from 1#EFP to 4#EFP can be obtained, as shown in Figure 13.

As shown in Figure 13, when $t > \Delta t$, the velocity from 1#EFP to 4#EFP increases from 1569 m/s, 1595 m/s, 1610 m/s, and 1622 m/s to 1733 m/s, 1787 m/s, 1824 m/s, and 1850 m/s, respectively, and then decreases to 1612 m/s, 1651 m/s, 1679 m/s, and 1690 m/s, respectively, resulting in an increase of 10.5%, 12%, 13.3%, and 14.1% and decrease of 7%, 7.6%, 7.9%, and 8.6%, respectively. When $t = \Delta t$, the velocity from 1#EFP to 4#EFP increases from 1541 m/s, 1568 m/s, 1586 m/s, and 1597 m/s to 1694 m/s, 1752 m/s, 1788 m/s, and 1813 m/s, respectively, and then decreases to 1585 m/s, 1652 m/s, 1653 m/s, and 1669 m/s, respectively, resulting in an increase of 9.9%, 11.7%, 12.7%, and 13.5% and decrease of 6.4%, 7.2%, 7.6%, and 7.9%, respectively. When $t < \Delta t$, the velocity from 1#EFP to 4#EFP increases from 1511 m/s, 1540 m/s, 1558 m/s, and 1571 m/s to 1660 m/s, 1706 m/s, 1748 m/s, and 1780 m/s, respectively, and then decreases to 1559 m/s, 1600 m/s, 1630 m/s, and 1644 m/s, respectively, resulting in an increase of 9.9%, 10.8%, 12.2%,

and 13.3% and decrease of 6.1%, 6.2%, 6.8%, and 7.6%, respectively. It can be seen from the above data that the speed increase range of the formed projectile is between 9.5% and 14.5%, and the speed reduction range of the formed projectile is between 6% and 8%.

When the shell thickness of the integral MEFP warhead remains unchanged and the liner curvature radius remains unchanged, only the thickness at the center changes for three different types of MEFP warheads. Therefore, the influence of thickness change at the center on the change of forming speed can be obtained from the forming speed list shown in Table 5, as shown in Figure 14.

As shown in Figure 14, when the thickness at the center of the liner increases from 1.1 mm to 1.3 mm, the velocity of the projectile gradually decreases. In Figure 14, when the curvature radius is different, the velocity of 1#EFP decreases from 1569 m/s, 1595 m/s, 1610 m/s, and 1622 m/s to 1511 m/s, 1540 m/s, 1558 m/s, and 1571 m/s, respectively, resulting in a decrease of 3.7%, 3.4%, 3.2%, and 3.1%, respectively. The velocity of 2#EFP decreases from 1733 m/s, 1779 m/s, 1812 m/s, and 1833 m/s to 1658 m/s, 1750 m/s, 1738 m/s, and 1768 m/s, respectively, resulting in a decrease of 4.3%, 2.8%, 4.1%, and 3.5%, respectively. The velocity of 3#EFP decreases from 1729 m/s, 1787 m/s, 1824 m/s, and 1850 m/s to 1660 m/s, 1706 m/s, 1748 m/s, and 1780 m/s, respectively, resulting in a decrease of 4%, 2.7%, 4.2%, and 3.8%, respectively. The velocity of 4#EFP decreases from 1612 m/s, 1651 m/s, 1679 m/s, and 1690 m/s to 1559 m/s, 1600 m/s, 1630 m/s, and 1644 m/s, respectively, resulting in a decrease of 3.3%, 3.1%, 2.9%, and 2.7%, respectively. It can be seen from the above data that the speed of the formed projectile decreases by 2%–5% with the ascent of the thickness at the center of the liner.

4.4. The Speed Comparison of Different Materials. From Tables 3–5, it can be observed that, with the increase in the liner radius of curvature, the contrast diagram of the forming speed of the MEFP warhead with different materials of the liner is shown in Figure 15 when the liner curvature radius increases.

In Figure 15, when the material is copper, steel, or tungsten in the liner, the forming speed of EFP is $v_{\text{steel}} > v_{\text{copper}} > v_{\text{tungsten}}$. When the liner material is copper, the forming projectile speed is between 1900 m/s and 2400 m/s, and the formed projectile speed reduces with an increase in the radius of curvature; when the liner material is steel, the forming projectile speed is between 2250 m/s and 2550 m/s, and the speed of formed projectile increases with an increase in the radius of curvature; when the liner material is tungsten, the speed of the formed projectile is between 1500 m/s and 1850 m/s, and the speed of formed projectiles increases with an increase in the radius of curvature.

From Tables 3–5, we can obtain the speed curve of 1#EFP to 4#EFP when the liner is a different material, as shown in Figure 16.

In Figure 16, the speed variation law of 1#EFP to 4#EFP first increases and then decreases. Moreover, when the liner is of a different material, the speed of 4#EFP is greater than

TABLE 5: Forming speed when the material of the liner and shell is tungsten.

	EFP no.	$R1 = R2 = 8 \text{ mm}$	$R1 = R2 = 9 \text{ mm}$	$R1 = R2 = 10 \text{ mm}$	$R1 = R2 = 11 \text{ mm}$
$t > \Delta t$	1#EFP	1569 m/s	1595 m/s	1610 m/s	1622 m/s
	2#EFP	1733 m/s	1779 m/s	1812 m/s	1833 m/s
	3#EFP	1729 m/s	1787 m/s	1824 m/s	1850 m/s
	4#EFP	1612 m/s	1651 m/s	1679 m/s	1690 m/s
$t = \Delta t$	1#EFP	1541 m/s	1568 m/s	1586 m/s	1597 m/s
	2#EFP	1694 m/s	1745 m/s	1772 m/s	1806 m/s
	3#EFP	1682 m/s	1752 m/s	1788 m/s	1813 m/s
	4#EFP	1585 m/s	1625 m/s	1653 m/s	1669 m/s
$t < \Delta t$	1#EFP	1511 m/s	1540 m/s	1558 m/s	1571 m/s
	2#EFP	1658 m/s	1705 m/s	1738 m/s	1768 m/s
	3#EFP	1660 m/s	1706 m/s	1748 m/s	1780 m/s
	4#EFP	1559 m/s	1600 m/s	1630 m/s	1644 m/s

FIGURE 11: Forming results: (a) the thickness of the liner is less than the shell thickness; (b) equal thickness of shell and line; (c) the thickness of shell is less than the liner thickness.

that of 1#EFP but less than that of 2#EFP and 3#EFP. This indicates that, in addition to the complete detonation of the main charge, the structure of the integrated design of the liner and shell has a certain pressurization effect.

From the forming speed list shown in Tables 3–5, we can determine the influence of the thickness change at the center on the forming speed change when the liner is a different material, as shown in Figure 17.

FIGURE 12: Comparison of forming speed of different structure types: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

FIGURE 13: Continued.

FIGURE 13: Comparison of forming speed of different structure types: (a) comparison of forming speed of $R1 = R2 = 8$ mm; (b) comparison of forming speed of $R1 = R2 = 9$ mm; (c) comparison of forming speed of $R1 = R2 = 10$ mm; (d) comparison of forming speed of $R1 = R2 = 11$ mm.

FIGURE 14: Comparison of forming speed of different thickness of liner center: (a) comparison of forming speed of 1#EFP; (b) comparison of forming speed of 2#EFP; (c) comparison of forming speed of 3#EFP; (d) comparison of forming speed of 4#EFP.

(a)

(b)

FIGURE 15: Continued.

FIGURE 15: Comparison of forming speed of different structure types and different materials: (a) comparison of forming speed of $t > \Delta t$; (b) comparison of forming speed of $t = \Delta t$; (c) comparison of forming speed of $t < \Delta t$.

FIGURE 16: Continued.

FIGURE 16: Comparison of forming speed of different structure types and different materials: (a) comparison of forming speed of $t > \Delta t$; (b) comparison of forming speed of $t = \Delta t$; (c) comparison of forming speed of $t < \Delta t$.

(a)

(b)

FIGURE 17: Continued.

FIGURE 17: Comparison of forming speed of different thickness and different materials of liner center: (a) comparison of forming speed of $R1 = R2 = 8$ mm; (b) comparison of forming speed of $R1 = R2 = 9$ mm; (c) comparison of forming speed of $R1 = R2 = 10$ mm; (d) comparison of forming speed of $R1 = R2 = 11$ mm.

In Figure 17, when the material of the liner is copper, steel, or tungsten, the EFP forming speed gradually decreases with an increase in the liner center thickness.

5. Conclusion

To study the influence of different materials on the forming characteristics of different structural types of circumferential MEFP warheads, three structural types of circumferential MEFP warheads were designed: the warheads in which the thickness of the liner was smaller than that of the shell, those in which the thickness of the liner and the shell was equal, and those in which thickness of the liner was greater than that of the shell. Three materials, copper, steel, and tungsten, were used to simulate the designed circumferential MEFP warhead. The results show that when the material of the liner and shell is copper, the forming effect of EFP worsens with an increase in the curvature radius of the liners. The forming results of the three types of circumferential MEFP warheads are similar, and the forming effect is appropriate when the radius of curvature of the liner is between 9 and 10 mm; when the material of the liner and shell is steel and tungsten, the liner will not be able to form projectiles with spherical, ellipsoidal, or long rod shapes with an increase in the curvature radius (when the diameter is greater than or equal to 8 mm), and the forming results of the three types of circumferential MEFP warheads are similar. For the small-caliber MEFP warhead, if the material of the liner and the shell is selected as copper, the liner curvature radius is between 9 mm and 10 mm; if the material of the liner and the shell is selected as steel and the liner curvature radius is greater than 8 mm, the forming speed of the projectile is large, but the liner cannot form a better-shaped projectile. If the liner and the shell material are selected as tungsten, and the liner curvature radius is greater than 8 mm, the forming speed of the projectiles is slow, and the liners cannot form a better-shaped projectile.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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