Structure of copper shaped charge liner evolution law based on die forging process

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Abstract. Numerous studies have addressed the effect of grain size of materials on the overall penetrating performance of warheads. However, the use of the forging process to illustrate the grain heat-treatment refining technology has not been reported. In this experiment, the grain size of copper was observed and evaluated during the main processes of preparing copper shaped charge liners using the die forging process. Through this study, the evolution law for the structure of copper shaped charge liners was examined. In the as-cast condition, the grains of the copper ingots were mostly evenly distributed large flaky equiaxed crystal. Pre-forging and die forging make the grains appear more like strips. After the recrystallization heat treatment, the grain size of the copper shaped charge liner was refined and more uniform. Using these results, this study presents an evolution curve for copper shaped charge liners prepared using the forging process. The results can be used as a technical reference to solve the problem of grain size deviation in the production process of copper shaped charge liners.

1. The introduction
With the diversification of current armored target types and the rapid increase in new armored targets, the protective performance of armored vehicles has significantly improved. Consequently, methods to improve the penetrating power of the warhead are necessitated, which is an important problem for scholars. As the core component of molding technology, the performance parameters of a shaped charge liner will directly affect the shape of metal jets and other related indicators. Domestic and foreign scholars have conducted substantial research on the shape, size accuracy, application of new materials, and grain refinement of materials. Some have concluded that there is a linear relationship between the penetration power of the coating and the reciprocal grain size [1].

Thus far, majority of the research has been focused on the influence of grain size on jet ductility, fracture time, and jet superplastic deformation. Bourne et al. [2] studied the effect of grain size and crystal texture on the properties of hollow charging shells and determined that fine crystal and homogeneous hollow charging shells could significantly improve penetration properties and reduce damage. Lichtenberger et al. [3] studied the effect of the crystal structure of copper, brass, zinc-aluminum alloy, and nickel base coatings on jet stability. Cowan et al. [4] used the Z-A model to predict the formation and fracture of the jet and calculated the length and fracture time of the jet under different grain sizes. Wang Tiefu [5] studied the effect of the grain size of the copper shaped charge liner on the fracture of the concentrated energy jet using a static armor-breaking test.
It is well known that traditional plastic deformation, such as rolling, extrusion, and drawing, can refine the grain size of materials; further, equal channel angular pressing (ECAP), which is a fast-paced research field, presents an alternative method to obtain fine crystalline materials. The anisotropy of materials is often caused by traditional rolling and extrusion technology, which renders the properties unstable. Although the application of equal-diameter angular extrusion technology to warhead coatings has not been reported, the material grain can attain the nanometer level using this method.

Based on the existing mature forging process, this study investigates the change in grain size during the forming process of medicine mold covers and reprocesses medicine mold covers using the phenomenon of grain overshoot; these investigations are aimed at elucidating the grain heat-treatment refining technology.

2. Test method
The copper ingots for the test were prepared in a 50 kg vacuum melting furnace. The hammer forging process was carried out on a 750 kg forging machine. The heat treatment was carried out in a box furnace. The test was cut with an electrical discharge machining wire cutting machine. The low-power tissue was observed on an Axiocam105 color microscope camera, and the grain size was observed under an Axio Observer A1m microscope manufactured by Zeiss.

The forging process for the copper type cover requires the following: smelting, copper ingot forging, extrusion, preforging, die forging, and heat treatment. The billets were forged into copper rods by casting copper ingots. The copper rods were extruded into blanks. After preforging and die forging, the blanks were formed into shaped charge liners. The final heat treatment recrystallized the grains of the copper mask, which refined the grains.

3. Results and analysis

3.1. Copper ingot low grain
As shown in figure 1:

![Figure 1](image)

*Figure. 1 Grain size of copper ingot and copper ingot.*

a Copper ingot prepared by vacuum smelting.  

b Copper ingot of grain.

Figure 1-a shows a copper ingot prepared by melting grade a copper plate in a 50Kg vacuum melting furnace, with a diameter of 180mm and a weight of 50Kg. Samples were taken along the cross section of the copper ingot and soaked in 30% nitric acid solution for 12 min. The grain morphology can be seen in figure 1-b: the copper grains in the as-cast state are mostly large flake and equiaxed grains, and the slower cooling rate made the grain size and shape more uniform, which was more conducive to the refinement and homogenization of grains during the plastic deformation of hammer forging.
3.2. Grain condition of copper rod

Figure 2 shows the forged copper rod:

Figure 2. A drawn bar of copper.

After repeated hammer forging, a φ188 mm copper ingot was forged into a φ55 mm copper rod according to the calculation formula for the forging ratio of continuous drawing length:

\[ K = F_a / F_b \]

In the formula, \( F_a \) represents the sectional area of the blank before deformation and \( F_b \) stands for the sectional area of the deformed billet.

The forging ratio of copper ingots was 11.68. The larger the forging ratio, the higher the deformation degree of the forging, the larger the grain crushing degree of the material, and the more apparent the influence on the comprehensive properties of the material [6–8].

3.3. Extruder grain size

The extrusion process was conducted by a 500t oil press. The grain size of a copper rod is shown in figure 4:

As shown in figure 3, the grains in the copper rod were smaller than those in the copper ingot. After forging and drawing the rod, the flake grains were "broken" and became small block grains. At the same time, internal stress was stored in the grains, providing a driving force for subsequent tempering recrystallization.
As shown in figure 5, the grains of the copper parts after extrusion were mostly flaky and unevenly distributed. Because of the limited extrusion deformation, the plastic deformation was not evident, so only a small number of strip grains formed by plastic deformation can be seen in the figure.

3.4. Grain condition of copper parts through presegment and die forging
Preforging and die forging were the final process of copper cover forming. The extruding part was put into the mold and repeatedly hammered with the 750 kg forging hammer until it reached the required size for acceptance. The copper parts were sampled after forming and the grain size was observed. The grain in the mouth, middle, and top of the copper cover are shown in figure 5.

Since the deformation amount of the copper cover was relatively large under this process, it can be seen in figure 6 that the grain at the mouth, middle, and top of the copper cover were mostly strip shaped, and a large amount of plastic deformation of the grains under this process provides the driving force required for the refinement and homogenization of the grains during the recrystallization heat treatment.

3.5. Copper mask grain after heat treatment
Recrystallization heat treatment was carried out on the copper cover according to the process documents. The grains after heat treatment are shown in figure 6:
Figure 6. The grains at the top, middle and mouth of the copper cover after heat treatment.
a The grain at the mouth of the copper cover after heat treatment. b The grain in the middle of the copper cover after heat treatment. c The grain at the top of the copper cover after heat treatment.

Using recrystallization heat treatment, the grains of the copper cover became refined and more uniform. The grain size of the copper cover after heat treatment was evaluated according to standard GB/T6394, Method for the Determination of Average Metal Grain Size. After heat treatment, the grain size range of the mouth of the copper cover was 0.015 – 0.025 mm; the grain size range of the middle of the copper cover was 0.015–0.025 mm; and the grain size range of the top of the copper cover is 0.015–0.025 mm.

4. Conclusion
(1) After slow cooling, the grains in the copper ingots in the as-cast state were mostly large and flaky equiaxed crystals, and the grain size and shape were relatively uniform.
(2) After forging and drawing the long copper rods, the flake grain was broken, and the grain shape was in small blocks.
(3) After extrusion, the grains of the copper pieces were mostly flaky and unevenly distributed, and a small amount of strip grains were formed by plastic deformation because of limited extrusion deformation.
(4) The presegment and die forging caused large plastic deformation of the copper cover, and the grains at the mouth, middle, and top of the copper cover were mostly strip shaped.
(5) After the recrystallization heat treatment, the grain size ranges of the mouth, middle, and top of the copper cover were as follows. The mouth was 0.015–0.025 mm; the middle was 0.015–0.025 mm; and the top was 0.015–0.025 mm. The grains were refined and more uniform.

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