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Application of sintered liners for explosively formed projectile charges

Jacek Borkowski[a], Zenon Wilk[b], Piotr Koslik[b], Leszek Szymanczyk[c], Bogdan Zygmunt[d,*]

[a] *Military Institute of Armament Technology, Zielonka 05-220, Poland*
[b] *Institute of Industrial Organic Chemistry, Warsaw 03-236, Poland*
[c] *Faculty of Advanced Technologies and Chemistry, Military University of Technology, Warsaw 00-908, Poland*
[d] *Faculty of Mechatronics and Aerospace, Military University of Technology, Warsaw 00-908, Poland*

ABSTRACT

The paper presents the results of experimental investigations on the formation and penetration efficiency of EFP charges with liners performed by applying a powder metallurgy method. Two types of sintered powder liners were tested: liners of the shape of a spherical surface sector and the conical liners with an open apex angle. Liners were made of copper powder and have a base diameter of 45 mm and a mass of 30 g. Explosive charges with sintered copper liners were examined using X-ray pulse technique and a high-speed digital camera. Dynamic shaping of explosively formed projectiles was recorded and the perforation of a steel barrier was tested. Concluding, liners for EFP charges made using powder metallurgy technology proved to be a fully featured substitute for conventional spherical liners produced with a technologically more complicated manufacturing process.

1. Introduction

Driving metallic liners to hypersonic velocity using detonation phenomena is performed in two basic explosive systems: using conical liners with an acute apex angle (<90°) [1] and with an open apex angle (<180°) [2,3]. A special case is a driving system with a spherical liner, which as a rule has the shape of a spherical surface sector.

The basic difference resulting from the construction of the two types of driving systems is the different kind of deformation of the liners caused by the detonation products. A conical liner (classical one) is squeezed symmetrically during detonation of the explosive charge and a cumulative jet is generated from its inner surface. The jet has a diameter of a few millimetres and its front moves with a velocity reaching values of 8–10 km/s. The squeezed liner (the so-called cumulative slug) follows in the same direction with a velocity of about 2 km/s. Because of the monotonic decrease in the velocity of the jet elements, starting from its front, the cumulative jet undergoes elongation during its free flight in air till the moment of its continuity breaking and disintegration into small fragments that cannot penetrate hard barriers. The penetration effect of a jet produced from the conical liner with an acute apex angle is limited to a distance equal to about 10 calibres of the charge, i.e., to the diameter of the liner's base.

These mechanisms differ from the interaction of detonation products with an open-angle conical liner or with a spherical one. The whole liner, driven to 2 km/s velocity, creates an explosively formed projectile (EFP) which reaches a significant distance, quickly losing velocity because of its aerodynamic drag [4]. Penetration into metal barriers of an EFP produced from a spherical liner is observed at significant distances of about a few hundred calibres of the charge liner.

The optimal materials for cumulative liners are high-density metals that have good plastic properties [5–7]. Classical cumulative liners (acute-angle ones) are made of copper, iron, or tungsten. Spherical liners for efficient EFP are made of uranium, tantalum, copper, or Armco iron. Over the last decade, there have been reports on the possibility of producing cumulative liners by applying the powder metallurgy method. Such a method allows for the production of liners sintered from a mixture of powders of various metals, e.g., copper with tungsten with densities close to 15 g/cm^3 [8–10]. The efficiency of cumulative charges with sintered powder liners is similar to those with compact metal liners.

The paper presents the results of experimental investigations on the formation and penetration efficiency of EFP charges with liners that were produced by powder metallurgy method. The authors have not found such an approach to EFP charges design and fabrication work in the literature.

2. Manufacture technology of powder liners

The spherical liners used in the EFP charges investigated herein were manufactured by the matrix press moulding of electrolytic copper

* Corresponding author.
E-mail address: Bogdan.zygmunt@wat.edu.pl (B. Zygmunt).

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Fig. 1. Spherical liners made of different metal powders and EFP charges (at the top) with different sintered metallic powder liners.

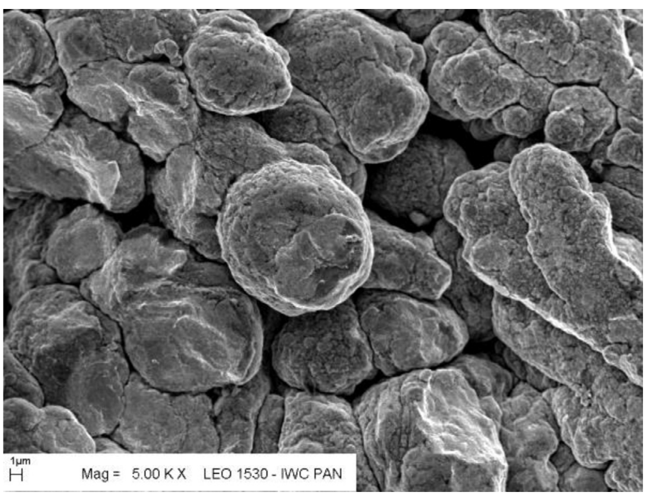

Fig. 2. SEM photo of the fracture surface of a sintered liner made of a copper powder.

powder (ECu). Depending on the input requirements, the spherical liners obtained were subjected to further processing, such as thermal sintering and machining. The precision of the final product shape is determined by the manufacture accuracy of the matrices and the technological process parameters. To obtain liners of required shape accuracy, especially as regards axial symmetry or thickness and local density of the liner, the feeding method of metal powder is particularly important.

The final operation is the temperature sintering of liners in a protective atmosphere (argon). The symmetry and homogeneity of powder liners was assessed on a spinning table workstation and by measuring the liner's wall thickness at pre-determined measurement points. Fig. 1 shows the spherical liners manufactured for the investigation and EFP charges with sintered copper powder liners.

The technology for the production of powder spherical liners is significantly simpler than the production of spherical liners of solid metal. It consists of the matrix moulding of commercial powder, e.g., copper powder, followed by thermal treatment of the moulded liners. For the production of spherical liners of solid copper, a specially prepared copper rod is required with a diameter at least equal to the liner diameter. Such a copper rod should have a fine crystalline structure and high plasticity. The slices of heights higher than the liner height are cut and the internal, external and lateral surfaces of the liner are then "sculpted". Although the mechanical treatment is simple, it is difficult to form a thick copper rod of uniform and fine crystalline structure and high plasticity. EFP liners of different metal structures undergo fragmentation during explosive product interactions what affects negatively armour penetration capability. Metal powders (e.g., copper powder) of any microstructure are significantly cheaper than metal rods of the required microstructure. On this basis, the authors estimate that powder liners are easier to make and cheaper for mass production.

Microscopic examination of the structure of manufactured powder liners has been performed. Fig. 2 show a photogram, made with a scanning electron microscope (SEM), of the fracture surface of a sintered powder liner. The Figure displays the structure of a liner produced from electrolytic copper powder (ECu). Tightly compressed individual copper grains and sharp boundaries between the grains are clearly visible. The diameter of the spherical copper grains is in the order of 10 µm.

3. Elaboration of EFP charges

In order to investigate the process of shaping EFP projectiles from

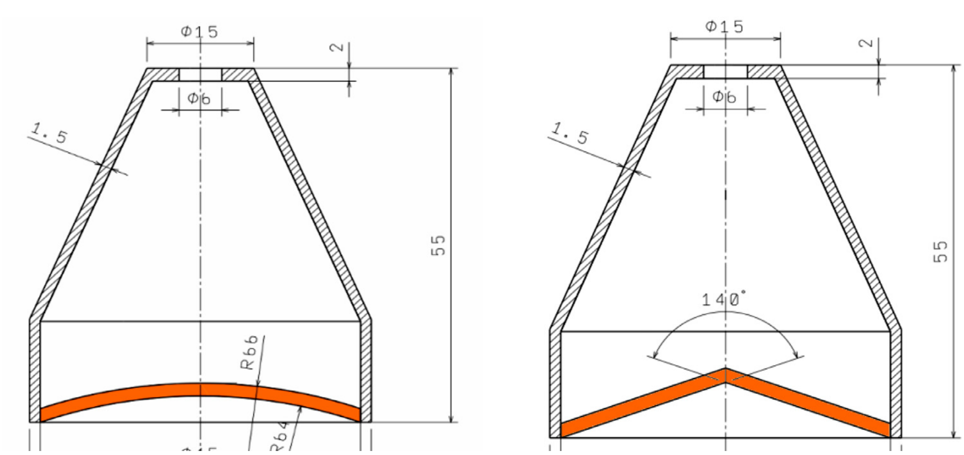

Fig. 3. Sketch of EFP charges with two types of powder liners. Dimensions are expressed in millimeters.

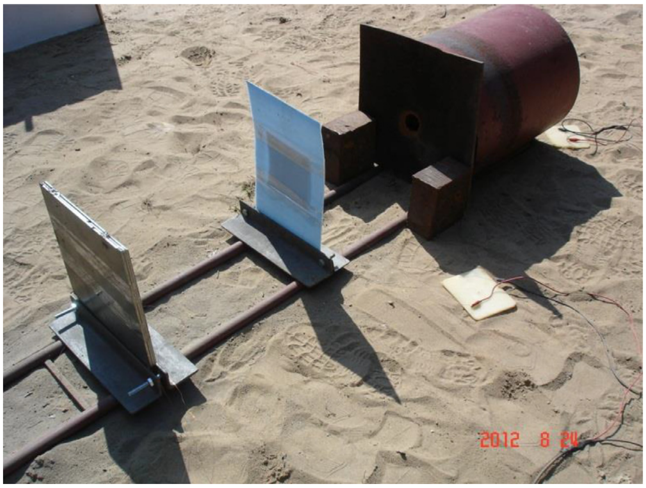

Fig. 4. The stand for powder EFP's flight registration and testing of their perforation ability.

sintered powder liners, two series of liners of the same mass equal to 30 g were fabricated: conical open-angle liners and spherical ones. The thickness of both types of liners was about 2 mm. The construction of liners of various geometries is shown in Fig. 3. The liners were made by applying powder metallurgy technology. Pure electrolytic copper powder was used (ECu 0.160) and then pressed in matrices. The powder compaction pressure was 400 MPa. The raw liners produced were subjected to a few hours sintering in an argon-atmosphere furnace at the temperature of 800 °C. Next, the liners were pressed again in order to correct their symmetry (the so-called calibration process). The average density of the liners was 8.6 g/cm^3. The porosity of liners amounts to 3–4%.

EFP charges were formed by pressing a high explosive on a powder liner placed in a plastic thin-walled casing. 70 g of RDX with addition of fluoropolymer (4% PTFE) as a binder was used. The explosive's density was 1.80 g/cm^3. The EFP charge was detonated with a blasting cap.

4. Registration of the sintered powder EFP flight

The test stand for the projectiles' flight registration and testing of the penetration of different EFP charges is shown in Fig. 4. The examined EFP charges with sintered spherical or conical liners were placed in a steel pipe with a diameter of 400 mm. The pipe was closed with a steel plate having a hole from which the EFP flew away. This system limited the penetration of detonation gases in the direction of the flying projectile, which could have disturbed the observation field. At the distance of 1 m (22 calibres) from the charge, on the projectile path, a steel barrier with a total thickness of 15 mm (3 × 5 mm) was placed. At half of the distance, there was a thin trigger foil used for measurement of the projectile velocity on its path. For the registration

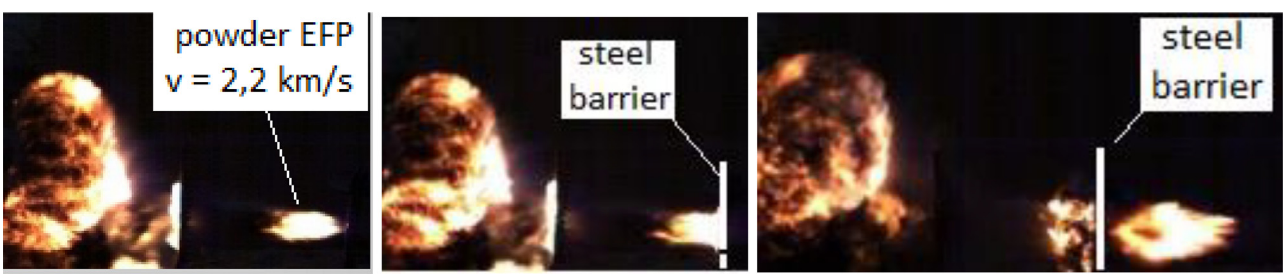

Fig. 5. Images taken with high-speed camera show EFP in flight after time 250 µs (first image), at the moment of hiting a steel barrier after 300 µs (second) and after penetration of a barrier (400 µs). Time is counted from a moment of a cap detonation.

Fig. 6. Pictures showing a 15 mm (3 ×5 mm) thick steel barrier penetrated by a copper powder EFP that was initiated at a distance of 1 m. Inlet of a projectile (left) and outlet (right).

Table 1
Penetration of EFP in a steel barrier.

Type of EFP liner	Distance, m	Penetration, mm
Spherical (Fig. 3, left)	0.5	30
	2.5	30
	5	25
	10	20
Conical (Fig. 3, right)	0.5	50
	2.5	50
	5	45
	10	40

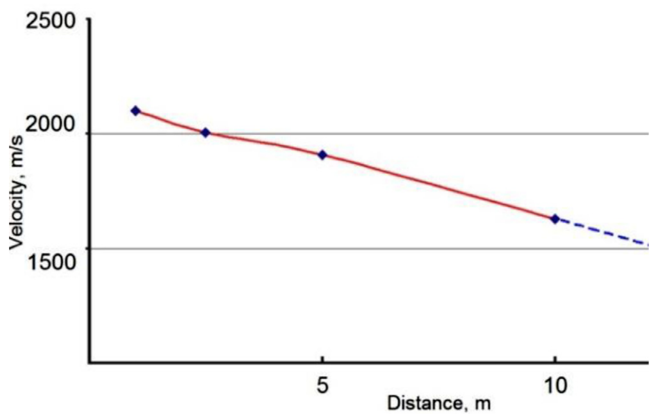

Fig. 7. EFP velocity vs. distance for charges with a spherical powder liner.

process, a fast digital high-speed camera Phantom V210 was used, placed at a distance of 20 m from the projectile trajectory. The recording speed was 20,000 frames per second, which means an image was created every 50 µs.

Fig. 5 shows images of the flying projectile that was created after detonation of the EFP charges with the spherical sintered liner. In the second image, the projectile hits the 15 mm thick steel barrier. It then penetrates the barrier and fragments behind the barrier (third image). Determination of the shape of the flying projectile in this experiment is not possible because of the intensive illumination of the air around the projectile that moves with a hypersonic velocity equal to 2.2 km/s (6.5 Mach). Fig. 6 presents the pictures of the inlet and outlet of the EFP projectile in the punched 15 mm thick steel plate, in that experiment.

Field experiments aimed at measuring the hemispherical EFP projectile velocity as a function of distance were performed. Simultaneously, the maximal (ultimate) penetration depth into a steel barrier was determined (Table 1). The projectile velocity at a given distance was calculated from the measured flight time between two sensors placed at a distance of 1 m from each other. On a diagram (Fig. 7) one can see a fast decrease of the velocity of the EFP projectile formed from spherical liner with increasing distance. The observed velocity decrease is significantly faster than that presented in reference [4]. This can be caused by the smaller EFP mass (30 g) in comparison with the projectile's mass in reference [4] which equals 70 g.

5. X-ray study of powder EFP dynamic formation by a pulse X-ray method

The dynamic process of EFP's formation from the liners made of a copper powder was registered by means of a pulse X-ray system of the SKAND-FLASH 450 type [9]. Thanks to the research methodology used, it was possible to acquire the following data for each EFP charge fired: projectile length and symmetry assessment at specified time points, determination of projectile tip velocity, determination of projectile formation and fragmentation nature and the characteristics of projectile stretching.

A sketch of the X-ray setup is presented in Fig. 8. The projectile flight was observed at different time delays: 0, 15, 33, 60 and 150 µs, counting from the time of the cap detonation. A scale (100 mm iron bar) was added to enable the determination of length and diameter of the projectile at the chosen moment of its formation. From the X-ray pictures the shape of projectiles, their diameter and length at all phases of their formation can be evaluated. Based on the projectile position for

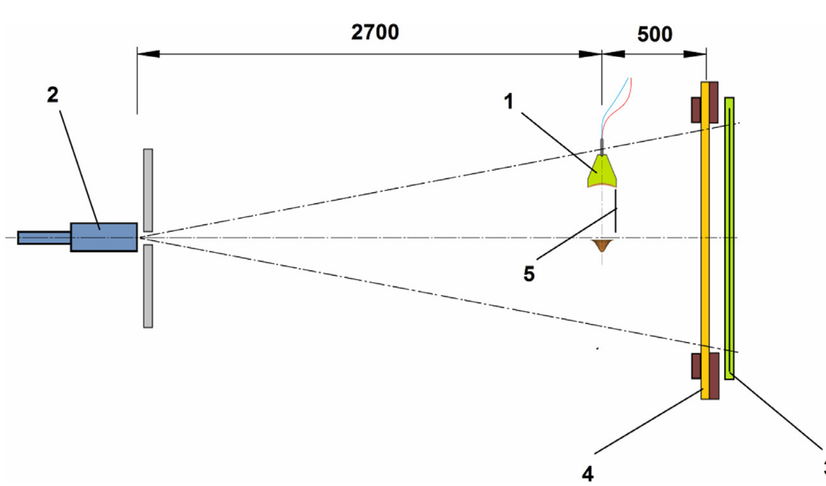

Fig. 8. Sketch of the pulse X-ray setup for investigation of a dynamic formation of EFP. (1) EFP charge, (2) - X-ray generator, (3) - X-ray detector, (4) - splinters shield, 5 – 100 mm iron rod.

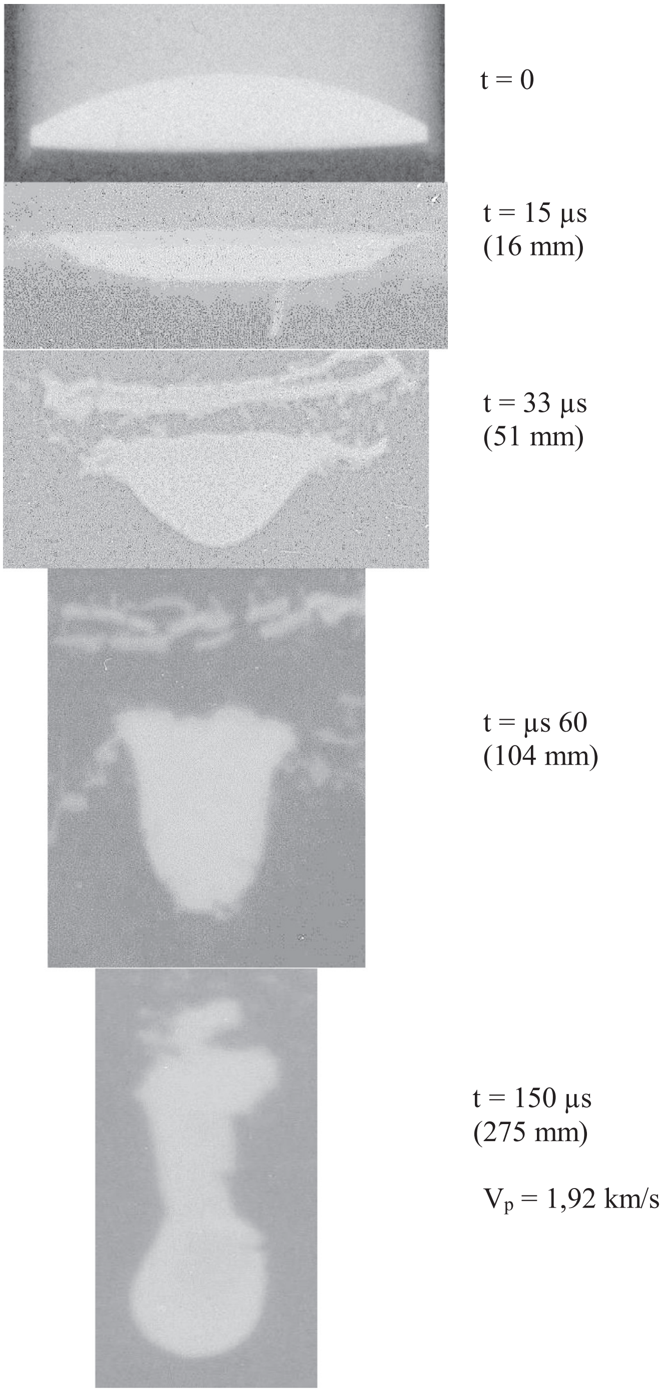

Fig. 9. Formation of a projectile from a sintered copper spherical liner.

distinct times, the average projectile velocity (V_p) was calculated.

Fig. 9 presents X-ray pictures showing the phases of the formation of a hypersonic projectile from a sintered copper spherical liner. In the first section of the flight, the projectile obtains the characteristic streamline drop shape at a distance of about 2 calibres (~100 mm) and undergoes a slight elongation. The average velocity of the projectile's front was 1.92 km/s. At the distance of 500 mm, the investigated powder projectile penetrated a set of steel plates with a thickness of 20 mm (4 × 5 mm). The diameter of the hole was 25 mm.

Fig. 10 shows X-ray pictures of the phases of shaping the hypersonic projectile from a powder conical open-angle liner. During flight, the projectile undergoes stretching and after 150 µs its frontal part is fragmented into separate drops. The average velocity of the projectile's front was 2.7 km/s. A steel barrier with a thickness of 40 mm (5 × 8 mm steel plates) situated at a distance of 500 mm was penetrated. The diameter of the hole was 15 mm.

6. Conclusions

Our results show that powder metallurgy is a useful tool for the production of spherical and conical acute-angle liners for EFP charges. We fabricated sintered liners with a diameter of 45 mm from copper powder and used them for EFP charges. The efficiency of the obtained sintered powder liners was evaluated in laboratory investigations in which the penetration of steel barriers was tested. Generally speaking, the penetration performance is comparable with that of EFP projectiles generated from liners made of compact (non-sintered) copper. The projectiles formed from sintered spherical liners are efficient at a distance of over 200 calibres. The maximal obtained effectiveness of projectiles formed from sintered spherical liners reaches a value of 0,7 (relation of penetration depth to liner diameter). The effectiveness of projectiles formed from sintered conical open-angle liners exceeds the value of 1. Literature data [11–14] indicate that penetration effectiveness of EFP charges with spherical liners made of solid iron or copper amounts the value of 0.6. Reference [11] gives an effectiveness value of at least 0.5 for penetration of an copper EFP into steel targets. Reference [12] mentions effectiveness values of 0.55–0.60 for EFP's with a hemispherical copper liner in a steel barrier, while in reference [13] EFP effectiveness is evaluated as 0.8–1.0. In [14] the EFP effectiveness for steel armor penetration is assessed on 1.0 in the case of spherical tantalum liners and on 0.5 for liners made of solid copper or iron.

Concluding, effectiveness of EFP charges with spherical liners made of copper powder or made of solid copper is comparable.

The process of the formation of projectiles from sintered liners is analogous to that observed for projectiles formed from solid metal. Forming the projectile from a conical open-angle liner shows the features of the formation of a jet from an acute-angle liner, especially the effect of stretching and fragmentation of the frontal part of the jet.

Obviously the porous sintered copper liner has a micro-grain structure that leads to lower mechanical strength in comparison to compact copper. However, as our experiments showed, this factor has only a minor influence on the dynamic formation of the projectile, on the flight with a hypersonic velocity and on the capability to penetrate the steel barrier.

The authors have proved earlier that the replacement of conical solid metallic liners with powder liners in shaped charges results in similar penetration effects [9]. Due to the technology of powder metallurgy, it is also possible to make efficient conical liners from powder mixtures of various metals (e.g., Cu and W), as well as to produce layered liners. Shaped charges with conical powder liners are usually used in oil and gas mining [8] because powder liners do not create a slug that can block the perforated tunnels. Similarly, also liners for EFP charges made using powder metallurgy technology proved to be a fully featured substitute for the technologically more complicated solid spherical liners. By applying the powder technology described here, it should be possible to produce spherical liners from a mixture of relatively inexpensive and available powders, e.g. copper and tungsten, with a density up to 15 g/cm^3 [9].

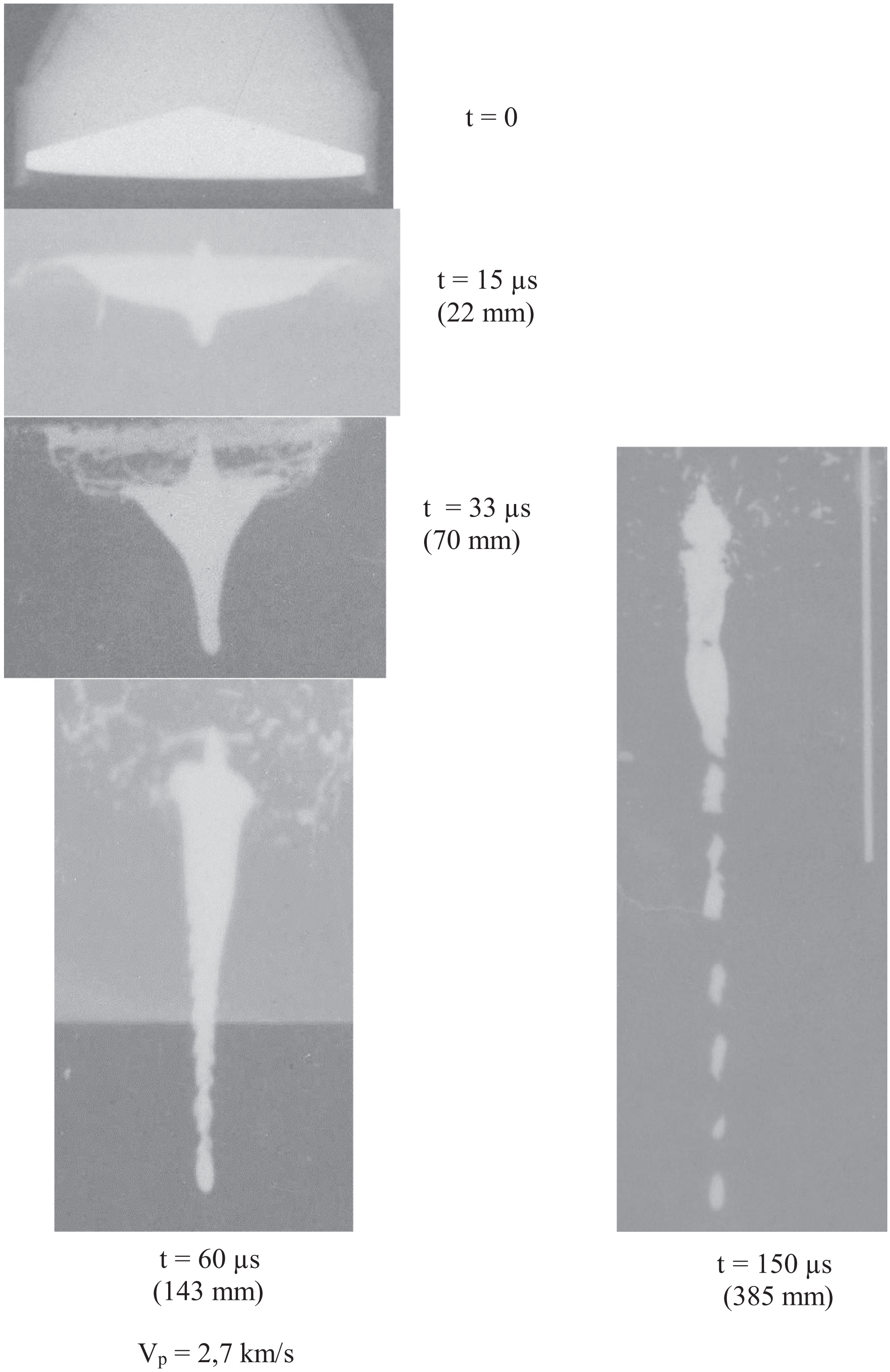

Fig. 10. Formation of a projectile from a sintered copper conical liner.

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