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The application of 3D–printing technology in the manufacture of shaped charge liners
Zastosowanie technologii druku 3D do wytwarzania wkładek kumulacyjnych

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Abstract: *The paper describes the possibilities of using 3D–printing technology for the production of shaped charge liners. For this purpose, fused deposition modelling (FDM) technology was used, which is designed for mass production in terms of cost, efficiency, and quality of individual components. Additive technology allows the production of elements made of various materials (i.e. metals, plastics and ceramics) to an unusually high precision. Additionally, it is possible to obtain almost any geometry (of developed, produced, planned) elements. The presented technology overcomes several disadvantages of the drawbacks associated with standard shaped charge liner manufacturing methods, including their large weight, which limits their use in special loads.*

Streszczenie: *W artykule opisano możliwość wykorzystania technologii druku 3D do produkcji wkładek kumulacyjnych. W tym celu wykorzystano technologię osadzania stopionego materiału (FDM), która jest przeznaczona do produkcji masowej zarówno pod względem kosztów, samej wydajności jak i jakości wykonania poszczególnych elementów. Technologie addytywne pozwalają na wytwarzanie elementów z różnych materiałów (tj. metali, tworzyw sztucznych i ceramiki) z niezwykle wysoką precyzją. Dodatkowo możliwe jest uzyskanie niemal dowolnej geometrii (opracowanych, wytworzonych, planowanych) elementów. Przedstawiona technologia eliminuje szereg wad związanych ze standardowymi metodami produkcji wkładek kumulacyjnych, w tym ich dużą masę, która ogranicza ich zastosowanie w ładunkach specjalnych.*

Keywords: *3D–printing, additive manufacturing technology, liner of a shaped charge, LSC*
Słowa kluczowe: *druk 3D, techniki addytywne, wkładka do ładunku kumulacyjnego*

1. Introduction

The origins of the shaped charge (cumulative) effect can be traced back to the second half of the 19th century. The earliest reference to a hollow charges dates to 1792, when German engineer Franz Xaver von Baader suggested incorporating a conical indentation at the forward end of the charge to enhance its effect and reduce powder consumption [1]. The first full effect of the hollow charge was achieved in 1883 by Max von Foerster (head of the Wolff & Co. nitrocellulose factory in Walsrode, Germany) [2, 3]. In 1886, German Gustav Bloem filed a US patent [4] for detonators with hemispherical cavities designed to concentrate the explosive energy along the axis. The idea of a shaped charge was first discovered and documented by Charles E. Munroe in 1888 [5]. The experiment involved detonating a block of guncotton embossed with the manufacturer's name, which was in contact with steel plates. The explosive charge was marked with the initials U.S.N. (United States Navy) engraved opposite the point of initiation, which were reproduced in a steel plate. Parallel research in Germany by Egon Neumann led to the introduction of a metallic liner into the shaped charge, significantly enhancing its directional effect [6, 7]. Based on the research conducted, the cumulative effect is called the Munroe effect (USA) or the Neumann effect (Germany) and refers to the focusing of explosive energy through a hollow or cavity formed on the surface of the explosive. Furthermore, in 1894 Munroe advanced the concept by developing one of the earliest shaped charges with a metal liner [8-10].

Shaped charges operate by directing and concentrating the energy released from an explosive through a hollow cavity, resulting in an intense, localized force [11, 12]. This hollow cavity effect enables the formation of a high-velocity jet (typically 9-12 km/s), which can be precisely directed against a target [13]. A typical shaped charge includes a casing, a high explosive, and a concave metallic liner – usually hemispherical or conical in shape. The explosive is located between the casing and the liner. Upon initiation by the detonator, the explosive generates a shock wave which collapses the liner, forming a high–velocity metallic jet [14, 15]. During detonation, the liner partially transforms into a high–speed jet, while the remaining part forms a slower–moving slug [16-18]. The ductility of the liner material largely influences the length of the jet produced. Therefore, both the selection of materials and the manufacturing process play a crucial role in shaping the microstructure, which in turn affects ductility [13, 19]. Common methods for producing low-density liners include turning, hot pressing, twin–screw extrusion and cold-press sintering. These methods have significant limitations, such as high costs, low processing accuracy and low yield of finished parts [20, 21]. 3D-printing technology, which uses advanced design and the potential of additive manufacturing (AM) to produce liners of shaped charge, is becoming increasingly popular [15, 22-25].

3D printing technology, also known as additive manufacturing (AM), is a modern method for producing solid parts directly from a digital model using a layer-by-layer material build-up approach [26, 27]. This method ensures precise, rapid, controllable and safe processing. Moreover, precise control over the printing process simplifies production compared to traditional methods and accelerates rapid prototyping [28-32]. One of the molding processes included in 3D printing technology is fused deposition modelling (FDM) [33]. The FDM method uses thermoplastic polymers which are extruded layer by layer to form the desired structure. The filament is heated in the printer nozzle until it melts, then extruded as a semi–molten polymer onto the build platform, where it solidifies. Once a layer is complete, the nozzle deposits the next one directly on top, following the previous geometry. A computer program is responsible for controlling the printer head, which applies the material, transforming the digital data into an actual printed element until the final stage is reached [34-36].

An example of the 3D printing process using the FDM technique is shown in Figure 1. Additive manufacturing enables the production of parts from a wide range of materials – such as metals, plastics, and ceramics – with extremely high precision. Conventional shaped charge liners are typically made of dense metals such as copper, tungsten, or iron. While these materials offer good performance, their high mass limits their application in specialized charges. As a result, additive manufacturing is gaining popularity in this area [37-40].

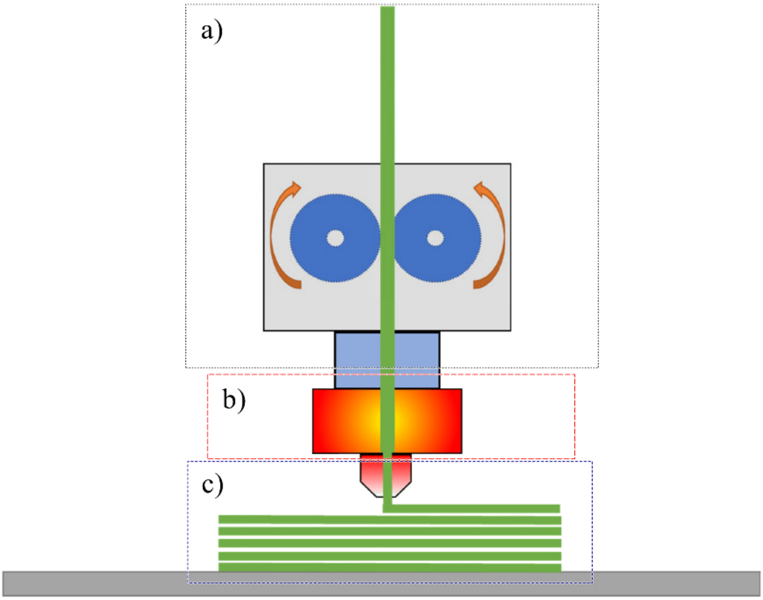

Figure 1. A diagram of FDM technique: a) filament (i.e. thermoplastic or composite material) fed to the extruder nozzle by means of drive rollers, b) the material is heated and extruded through a nozzle, c) extruded filament is deposited on the build platform layer after layer (author's elaboration based on [41])

The main advantage of the FDM method is the low cost of the raw material and the 3D printers themselves. This technology is dedicated to mass production in terms of costs, efficiency and the quality of individual components [42-46]. Thanks to the design flexibility of additive manufacturing, liners with complex geometries can be produced quickly and cost–effectively, without the need for tooling or generating significant material waste. The manufactured liners are characterized by high precision [47, 48].

The interdisciplinary combination of 3D printing technology with explosives manufacturing helps overcome challenges faced using traditional methods. Modern trends in high-energy materials increasingly involve the use of additive techniques – not only for material preparation and formulation processes, but also for the fabrication of shaped charges [49, 50]. The main advantage of using additive technology to produce liners is that they are produced by adding the raw materials layer by layer, rather than removing or deforming materials as in conventional manufacturing processes. Traditional manufacturing processes require cutting tools, jigs, fixtures, coolant, moulds, punches, patterns, and external supporting equipment. Using additive manufacturing, it is possible to personalize liners to a specific order, provide design flexibility, minimize waste, and create liners from various materials. Moreover, the reduced lead time is also crucial – from the production of the liners to their introduction to the market, as well as the improvement in the quality of the printed liners compared to conventional methods, which is possible thanks to 3D printing [51-53].

2. Experimental part

2.1. Materials and methods

The Bambu Lab X1E 3D printer was selected, and the forming method was FDM. This printer combines high precision with efficient printing speed, making it suitable for producing complex components. The maximum size of the printed specimen can be up to 256×256×256 mm, which allows the designed models studied in this article, to be printed. A model of the shaped charge was first designed in 'SolidWorks' and exported in STEP format. The finished model was then sent to the 3D printer to complete the preparation of the sample.

Before printing, the relevant parameters were configured in the printer software. A grid infill pattern with 15% infill density was selected for this study. The printer nozzle temperature was set to the melting point of the given material. The temperature of the printing support platform was adjusted to the given material to ensure proper pasting to the platform without deformation during the printing process. The fixed parameters of the selected materials for printing are shown in Table 1.

Table 1. Parameters of filaments selected for testing (T_d – temperature of the printer nozzle, T_s – temperature of the support platform, *TS* – tensile strength)

Commercial Name	**Material*)**	**Density [g/cm³]**	**T_d [°C]**	**T_s [°C]**	***TS* [MPa]**
Noctuo PLA	PLA	1.24	200-230	50-60	60
Noctuo PETG	PETG	1.28	235-265	>85	51
Noctuo PA12CF15	PA12CF15	1.06	265-290	>100	125
Prusament PETG Tungsten	PETG/W	4.0	250-270	7090	49
ColorFabb Coperfill	PLA/Cu	4.0	190-210	50-60	25
ColorFabb Steelfill	PLA/Steel	3.13	190-210	50-60	23
ColorFabb Bronzefill	PLA/Bronze	3.9	190-210	50-60	30

*) PLA – Polylactic acid, PETG – Polyethylene terephthalate glycol, PA12CF15 – Polyamide combined with carbon fiber, PETG/W – PETG combined with tungsten powder, PLA/Cu – PLA combined with fine copper powder, PLA/Steel – PLA combined with fine steel powder, PLA/Bronze – PLA combined with fine bronze powder

The performance parameters of a properly designed and manufactured shaped charge are decisively influenced by the appropriate selection of material and printing parameters. The cases, closures, and spacers of the shaped charges were printed using Noctuo PLA and Noctuo PETG filaments. Default printing profiles were applied, with only the build platform temperature, nozzle temperature, and fan speed parameters adjusted as needed. The heights of the prints varied depending on the material used. For samples printed using PLA, the height of the first layer was 0.20 mm and the subsequent layers 0.16 mm. For samples printed using PETG, the height of the first layer was 0.40 mm and the subsequent layers 0.24 mm. However, for samples printed using PA12CF15, the height of the first layer was 0.30 mm with the subsequent layers being 0.18 mm.

The first stage of the research was to select the appropriate size of the printed shaped charges liners. For the purposes of the test, shaped charges were made with three types of liners: hemispherical with a radius equal to 1/2 of the charge diameter, conical with an opening angle of 45° and conical with an opening angle of 30°**.** Figure 2 shows the dimensioned construction designs of the developed liners of shaped charges. The liners of shaped charges for preliminary tests were printed from PLA/Cu material (an example is shown in Figure 3).

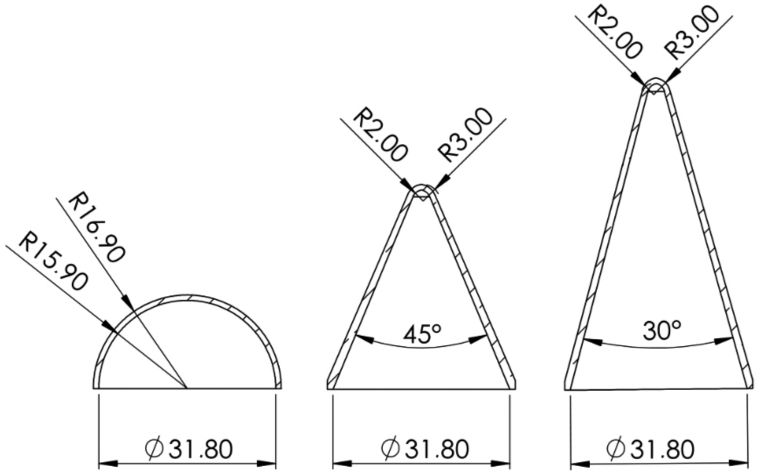

Figure 2. Diagram of the liners of shaped charges

a) b)

Figure 3. Printouts of liners of shaped charges made of PLA/Cu: a – conical, b – hemispherical

Preliminary tests were conducted to evaluate the penetration performance of shaped charges equipped with 3D-printed liners of varying geometries. On this basis, conical liners of shaped charges with an opening angle of 45° were selected for further testing. In the next stage of the study, shaped charges with 45° conical liners printed from different composite materials – PLA/Steel, PLA/Bronze, PETG/W, and PA12CF15 – were prepared. Figure 4 shows examples of printed liners of shaped charges.

a) b) c)

Figure 4. Examples of printouts of liners of shaped charges made of: a – PLA/Steel, b – PETG/W, c – PA12CF15

The explosive used in the tests was MWP-14, a plastic-bonded explosive (PBX), which was evaluated for sensitivity to mechanical initiation stimuli. The friction sensitivity test was conducted using a Peter's apparatus in accordance with the standard [54]. The impact sensitivity test was carried out with a BAM Fallhammer Apparatus in accordance with the standard [55].

The penetration tests were aimed at determining the effectiveness of charges using the printed liners of shaped charges. Shaped charge jets have an excellent penetration capability against a wide range of targets. Therefore, it is necessary to predict the depth of penetration of the shaped charge, which is the key parameter for the assessment of the effect of a shaped charge on a target. The performance of the fabricated shaped charge liners was compared based on their penetration depth into steel plates. The test stand consisted of a set of 6 steel plates, so-called witnesses, each 10 mm thick. The shaped charge was positioned above the top plate at varying stand–off distances using spacers – specifically 1, 2, or 3 charge diameters, depending on the test variant. In some cases, field tests were also carried out for distances equal to 0.5 charge diameter. The diagram of the test stand is shown in Figure 5. Figure 6 shows an actual penetration test site consisting of a set of 6 steel plates (each 10 mm thick, plate dimensions 300×300 mm) and a shaped charge.

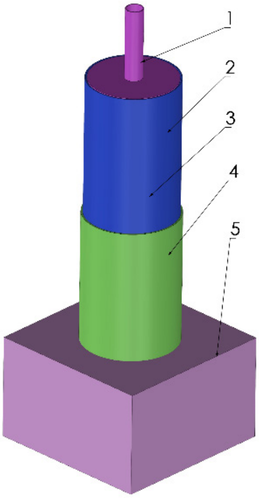

Figure 5. Diagram of the test stand: 1 – closure with detonator socket, 2 – charge case, 3 – internally placed liner of shaped charge, 4 – spacers, 5 – steel plates

Figure 6. Penetration test sites used for testing

2.2. Results and discussion

2.2.1. Friction and impact sensitivity measurements

The friction and impact sensitivity of MWP-14 material was tested. The results are presented in Table 2. According to the manufacturer's data, the MWP-14 explosive used in the research has a density of 1.40-1.50 g/cm^3, a plasticity at +20 °C of 95 ±20 [unit of pressure] and a detonation velocity of >7000 m/s.

Table 2. Friction and impact sensitivity of MWP-14

Explosive	Friction sensitivity [N]	Impact sensitivity [J]
MWP-14	360	15

2.2.2. The shaped charge penetration testing

The average penetration depths of the steel plates for the shaped charges with PLA/Cu printed liners tested are presented in Table 3. The results are the average of 5 measurements for each test.

Table 3. Average penetration depths obtained during penetration tests for PLA/Cu shaped liners

Spacer [charge diameter]	**Average penetration depth [mm]**
1	20.19 **±2.96**
1	18.83 **±1.86**
1	18.55 **±2.28**
2	7.96 **±2.14**
2	2.17 **±0.67**
2	5.53 **±1.12**
NS	26.71 ±2.68
NS	28.92 **±1.98**

In the case of tests with a 1-charge diameter spacer, the generated jet caused penetration of the steel plates but was deviated from the axis of symmetry of the shaped charge, which had an impact on a reduction in penetration. Tests with a 2-charge diameter, the generated jet did not penetrate a steel plate. As part of the research, tests were carried out for shaped charges without spacers. It can be stated that the lack of spacer elements produced the best penetration effect of the created shaped charges.

In summary, increasing the stand-off distance resulted in a decrease in penetration depth for shaped charges with PLA/Cu liners. The highest penetration performance was observed for charges tested without spacers. Visual inspection focused on evaluating the entry holes formed by the shaped charge jet on the surface of the steel plates. An example of a penetrated plate is shown in Figure 7.

Figure 7. Examples of results of the entry openings after a shot with a shaped charge during steel plate penetration tests

Table 4 summarizes the average penetration depths achieved by shaped charges with 45° conical liners printed from different composite materials – PLA/Steel, PLA/Bronze, PETG/W and PA12CF15. The results are the average of 5 measurements for each test.

Table 4. Average penetration depths [mm] obtained during penetration tests for liners of shaped charges

Attempt number	**Spacer [charge diameter]**	**Liner material**			
		PLA/Steel	**PETG/W**	**PLA/Bronze**	**PA12CF15**
1	1	25.37 **±3.19**	34.42 **±1.51**	29.85 **±1.94**	31.19 **±0.49**
2	1	35.32 **±3.03**	25.56 **±0.84**	16.91 ±0.73	25.36 **±1.66**
3	1	35.88 **±2.90**	39.21 **±1.71**	15.73 **±1.81**	21.57 **±0.96**
4	1	29.11 **±1.20**	29.98 **±1.93**	17.44 **±0.97**	31.43 **±0.93**
5	1	30.78 **±0.96**	42.57 **±0.40**	27.14 **±0.99**	27.74 **±2.15**
1	2	26.11 **±0.90**	4.09 **±1.32**	NP*⁾	15.84 **±1.18**
2	2	23.17 **±2.38**	19.01 **±0.99**	6.71 **±0.60**	19.77 **±1.14**
3	2	22.67 **±2.13**	7.33 **±1.52**	11.32 **±0.62**	20.08 **±0.75**
4	2	22.96 **±0.72**	9.05 **±0.84**	5.29 **±0.62**	26.91 **±0.84**
5	2	13.00 **±1.44**	18.18 **±1.56**	3.79 **±0.31**	18.84 **±1.49**
1	3	17.25 **±0.29**	2.16 **±0.51**	NP	8.22 **±2.04**
2	3	17.79 **±2.23**	2.30 **±0.78**	NP	12.22 **±1.34**
1	0.5	43.33 **±0.84**	36.23 **±2.57**	30.10 **±1.89**	25.78 **±1.30**
2	0.5	35.11 **±0.39**	46.06 **±2.26**	37.78 **±1.43**	27.68 **±0.48**
3	0.5	47.11 **±0.25**	49.60 **±1.02**	32.98 **±1.75**	29.56 **±2.00**

*⁾ NP – No penetration

Considering the results obtained for the PLA/Steel, PETG/W and PLA/Bronze liners, it can be stated that the worst penetration effects were obtained for the shaped charges with a 3-caliber spacer. However, the best results were obtained for the shaped charges with a 0.5-caliber spacer, where a jet characterized by the greatest symmetry of the perforated hole was obtained.

The results obtained for shaped charges with PA12CF15 liners show that the worst penetration was also achieved by shaped charges with a 3-charge diameter spacer. The best penetration was achieved for shaped charges with a 0.5- and 1-charge diameter spacer.

Comparing the results obtained for all types of liners, in the case of the 0.5 charge diameter spacer used, the best penetration effects were achieved by liners made of PETG/W, which in two tests penetrated more than 4 steel plates. In the case of the 3-charge diameter spacer used, the worst penetration effects were achieved by liners made of PLA/Bronze, which in both tests only slightly deformed the steel plates, without causing any penetration. In order to visually present the obtained results, Figure 8 presents a comparison of the penetration effects for all types of liners of shaped charge. The graph shows the thickness of one steel plate in order to emphasize the penetration effects obtained. With the increase in the length of the spacers used, the penetration capacity of the steel plates decreases for each type of liner of shaped charge used.

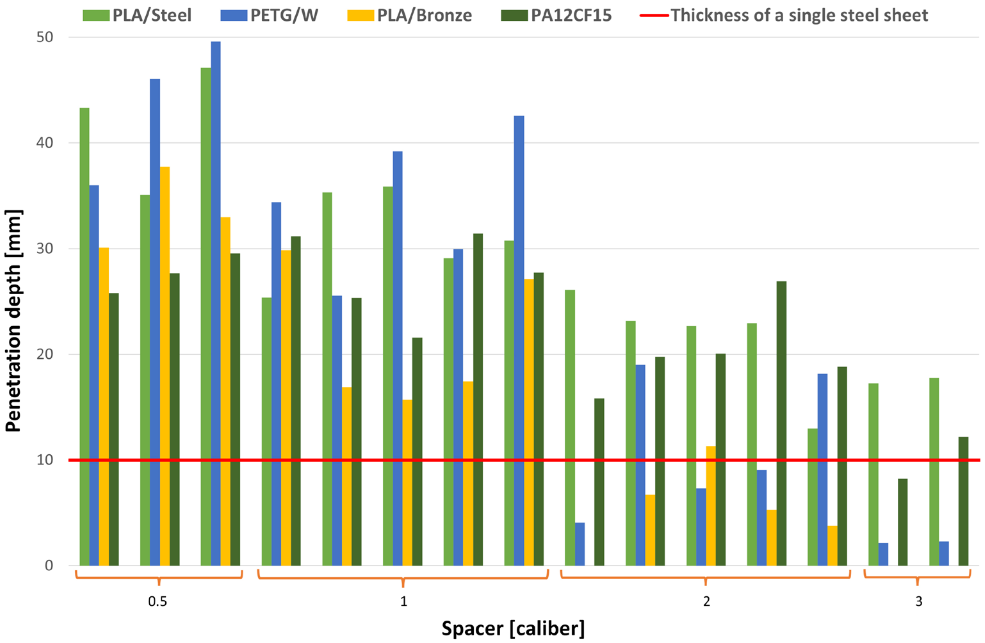

Figure 8. Dependence of penetration depth for liners made of different materials depending on the distance spacer used during testing

3. Conclusions

- 3D printing is a modern manufacturing technique which enables the production of components directly from digital models using a layer–by–layer material deposition approach. The use of the Fused Deposition Modelling (FDM) method allows for the fabrication of shaped charge liners with defined parameters capable of forming a cumulative jet and perforating target materials.
- Experimental results confirmed that, upon detonation, shaped charges equipped with the printed liners generated a coherent jet capable of penetrating the front steel plate.
- Tests of shaped charges directed against steel plates demonstrated that liners of shaped charge printed from PLA/Steel had the best penetration ability, while liners printed from PLA/Bronze had the lowest penetration ability.
- The PLA/Steel liners successfully perforated at least one steel plate in every test. Additionally, the resulting shaped charge jets produced clean, circular entry holes, indicative of symmetrical and well-formed jet behaviour.

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