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Investigation of the Efficiency of Cumulative Cones Manufactured by Additive Processes from Various Materials

Abstract

There is currently little-known research on low-density cumulative cones, although they can be useful and cost-effective in a number of areas. 3D printing is providing a foundation and cohesion in this area of blasting technology that has been difficult to achieve in the past. Taking advantage of this, I have carried out prototype testing in my study, in total I have been able to create nine cumulative charges using additive manufacturing and test their effectiveness. To get a broader picture, I used several types of 3D printers and several materials for the analytical testing of the three charge types developed. The tests gave me conclusive results on the applicability of the technology and the performance of the different polymers.

Keywords: additive, 3D printing, blasting technology, cumulative, charges

Introduction

Nowadays, military research faces numerous challenges. Navigating the most important research directions is relatively simple.[2] Technical and military theoretical research encompasses the application of modern technologies, such as artificial intelligence[3] and the practical use of autonomous systems,[4] as well as what might be the greatest challenge of our time, climate change, which imposes (or will impose) an enormous

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[2] Boda et al. 2016.

[3] Fazekas 2023.

[4] Tóth–Vég 2022.

burden on all armed forces.[5] Within this broad scope, 3D printing also holds a worthy position, as most armed forces are already applying additive manufacturing technologies at a practical level.

I chose cumulative charges as a concrete research direction, focusing on this area. While cumulative liners usually emphasise high-density materials like copper, I decided to concentrate on low-density materials, specifically polymers and composite polymers. Although these materials significantly lag behind copper in terms of destruction capability, immense perforation is not always required for the target object. In certain explosive ordnance disposal tasks,[6] it can be particularly favourable if the charge only penetrates the anticipated material thickness.

In this study, I will examine cumulative cones formed from different materials and manufactured using various additive manufacturing technologies. Beyond their efficiency, it will be interesting to compare the geometry of the holes created in the target objects to identify potential future development directions. Comparing additive technologies and fundamentally similar materials is inherently intriguing, but examining the same technology with different materials can also provide forward-looking insights. All components of the examined charges have a uniform geometric shape, with only the manufacturing conditions and materials varied.

My goal is to detonate nine charges to investigate the efficiency of three variants of charges. I hypothesise that there will not be significant differences in the results, but the differences between manufacturing technologies will become clearly identifiable.

Additive manufacturing

The first technology to be demonstrated is the Fused Deposition Modelling or Fused Filament Fabrication (FDM/FFF). This is a very widely used method, even for hobby purposes, whereby wound polymers, so-called filaments, can be used as raw material.

These filament materials can be made from a wide variety of polymers and composites. Perhaps the most well-known and commonly purchased material for hobby purposes is polylactic acid (PLA), but there is a broad range of other options available, such as PET,[7] PET-G,[8] ABS,[9] ASA,[10] and PA[11] or nylon. The diameter of the filaments is crucial, as they come in two sizes (1.75 mm and 2.85 mm), and technical equipment (Figure 1) is not capable of handling a different size without significant modification or conversion.

The spooled polymer is pulled or pushed by gears into the print head, which is responsible for melting the material. The resulting melt flows through a nozzle and is deposited onto the build platform within the construction area.[12]

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[5] Földi–Padányi 2022; Padányi 2023.

[6] E.g. some improvised explosive device disposal tasks. Daruka–Kovács 2013.

[7] Polyethylene terephthalate.

[8] Polyethylene terephthalate glycol.

[9] Acrylonitrile butadiene styrene.

[10] Acrylonitrile styrene acrylate.

[11] Polyamid.

[12] Gál–Németh 2019: 233.

The main principle of the technology is layer-by-layer construction, making it essential for movement to occur in three dimensions within the build chamber. One common solution is where the print head can move horizontally (two dimensions) while the build platform adjusts vertically (3rd dimension). In other variants, the print head can move in one horizontal dimension and vertically, with the build platform providing movement in the other horizontal direction. There are also solutions with a fixed build platform and others where a robotised arm enables the construction of parts from multiple directions, although the latter is not yet widely adopted by the general public.

Figure 1: FDM/FFF printers
Source: photographed by the author

The second technology I intend to introduce is Selective Laser Sintering (SLS). This method is often known as powder bed printing, a term that more clearly describes the whole process. In contrast to the widespread Fused Deposition Modelling/Fused Filament Fabrication (FDM/FFF) technology, the selection of materials is significantly more limited. Basically, a form of polyamide (PA) is used as the base material, but polypropylene (PP) can also be employed for creating lighter components, and thermoplastic polyurethane (TPU) may be used when flexibility is important.

Initially, the powder material is transferred from a container to the build chamber and spread in thin[13] layers. The evenly distributed, smoothed powder surface is then targeted by a laser at the necessary points, causing it to solidify a layer. After the plate in the build area moves downward, a new thin layer of material is applied, which is also solidified by the laser. Both the process and the material require a consistently high and uniform temperature, which is necessary for the high quality of the parts.[14]

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[13] Between 50 and 200 micrometres.

[14] Gál–Németh 2019: 234.

The raw materials used in the research

The Faculty of Military Science and Officer Training (MSOT) at the Ludovika University of Public Service (LUPS) also possesses an SLS technology 3D printer. This is a Fuse 1 device manufactured by Formlabs, for which five materials are available.

The Nylon 12 (PA–12) powder used in the printer mentioned above is considered to be general purpose. It is a very versatile material that is biocompatible. It can be used to produce highly detailed and highly dimensionally accurate objects. It is also ideal for prototyping but can also be used to make complex structures that are durable and resistant to environmental influences. Of course, it is also ideal for end-use objects, i.e. for factory production.[15]

The second material used is Markforged Onyx, a special polyamide. The filament is filled with micro-carbon fibre and the end surface of the parts made from it is of high quality and can be used to make objects and parts with high dimensional accuracy. It is the matrix material of the technology and the manufacturer's proprietary continuous filament reinforcement. Even without a reinforcing insert, it provides high strength, toughness and chemical resistance. With some continuous fibres, its material properties can even rival those of aluminium, but I did not plan to use such inserts for this test.[16]

The third material used was Polimaker PolyLite ASA, which I found to be very easy to print. ASA is on the market as an alternative to ABS. It is the preferred choice when the environmental resistance of ABS is not sufficient for the object in question. It is also recommended by the manufacturer for the production of objects for everyday use. It has a density of 1.13 g/cm^3 at 23 °C and good resistance to acids and oils.[17]

I used this material in an Ultimaker S5 printer (FDM/FFF technology), which has a glass build tray and a print head optimised for water soluble supports.

Manufacturing process

The designs for all components were created using FreeCAD 0.20, a free, open-source software that is available for download. I am already familiar with this software, having used it for similar purposes before.[18] The dimensions of the shaped charges were determined through various methods,[19] incorporating my own parameters[20] that have consistently proven effective in multiple tests.[21] I kept the 20 mm diameter (internal) for the cone from the previous or base geometries, but I changed the apex angle to 90 degrees (Figure 2). While designing, I took manufacturing characteristics

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[15] Formlabs Nylon 12 Powder: https://formlabs.com/store/materials/nylon-12-powder/

[16] Markforged Onyx: https://markforged.com/materials/plastics/onyx

[17] Polymaker: PolyLite ASA – Technical Data Sheet: https://cdn.shopify.com/s/files/1/0548/7299/7945/files/PolyLite_ASA_TDS_V5.1.pdf?v=1640828798

[18] Ádám–Ember 2022a; Ádám–Ember 2022b.

[19] Ember 2022a.

[20] Lukács 1992.

[21] Ember 2022b; Ember 2022c; Ember 2022d; Ember 2022e.

into account, although supports were not significant in our case since SLS technology does not require them, which allows for greater design freedom.

The finalised electronic forms were virtually arranged within the build area using the cloud-based PreForm software. This preparation tool is notably user-friendly, as it does not necessitate extensive knowledge of material science or manufacturing technology to operate. Various parameters are pre-set, so the user mainly needs to focus on maximising the use of space, which is crucial for material economy. Although the software can optimise the layout for us, I chose not to use this feature because it alters the orientation of the objects in space. This adjustment likely wouldn't cause significant differences in the blast results, but I preferred maintaining identical arrangements to ensure comparability across all aspects.

The Markforged 3D printer can also be worked using a cloud-based service which is the Eiger software. This printer is able to use Onyx material. Since it employs FDM/FFF technology, there are significantly more parameters that can be adjusted, although in this application, it is much more limited compared to a free slicing software. This limitation, however, promotes the production of very high-quality objects. Among the default or base printing settings, I only adjusted the infill to 100%, leaving the rest unchanged. The end product cones were of excellent quality; the internal supports detached almost automatically from the surface, without visible marks.

Figure 2: Onyx cumulative cone
Source: photographed by the author

For ASA material, I chose the Ultimaker S5 among several possible technical options. The "slicer" software Ultimaker Cura, offers numerous settings, but in this case, I retained the base settings recommended for the geometry, again only increasing the infill to 100%. These software programs typically recommend some infill pattern and a 15–30% infill for FDM/FFF technologies to promote low cost, efficiency and durability. However, for this research, this was not acceptable, as achieving the highest possible density required filling the entire volume to the maximum extent.

I also manufactured the other parts of the charges (Figure 3) using this device, but for those, I fully applied the recommended default settings. This approach resulted in significant material savings without compromising the quality.

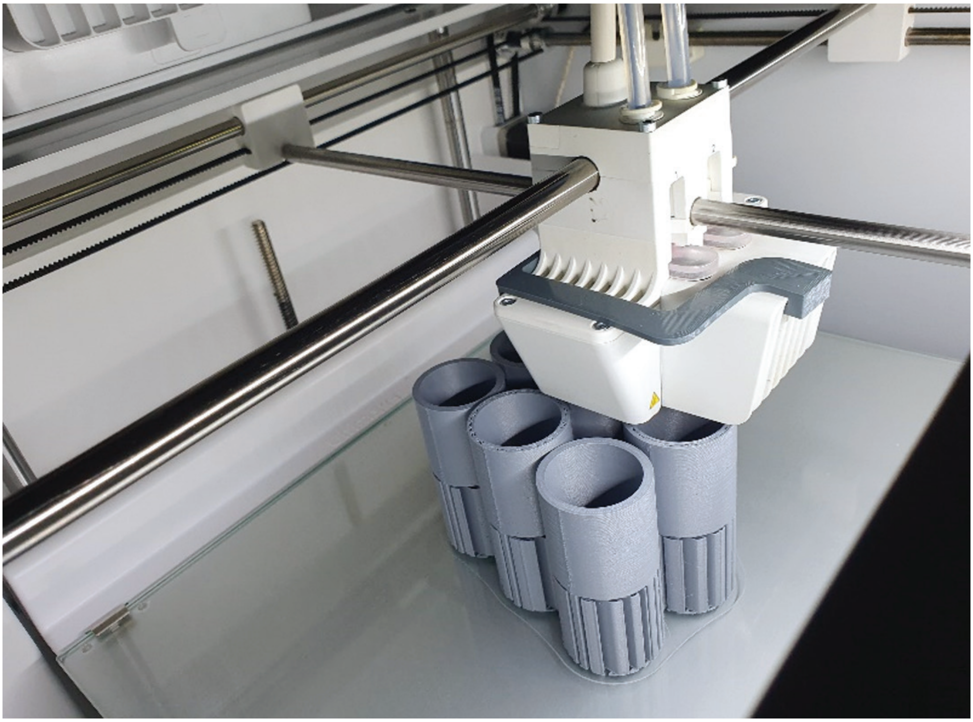

Figure 3: Charge bodies in the Ultimaker S5's buildchamber
Source: photographed by the author

Preparation for blasting

The tests were carried out with the assistance of the bomb technicians of the Hungarian Defence Forces (HDF) 1st Explosive Ordnance Disposal and River Guard Regiment (HDF 1st EOD&RG Reg.) in Táborfalva, at the designated blasting area of the HDF.

During the blasting task, more charges were detonated than those described in this article. Multiple series of blasting were conducted; however, the electrical network was configured in a series connection using the standardised electric detonators and wires of the HDF. Due to the required performance of the explosive placed in the charge body, a brisant military type[22] was chosen. This was the Semtex-H plastic explosive. A significant number of fragments were not expected due to the special implementation of the blasting and the materials. Interesting question: what changes would occur if the experiments were carried out with insensitive explosives?[23] I will be looking for the right answers to this in the future.

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[22] Lukács 2017: 26.
[23] Daruka 2024: 59–61.

Figure 4: A charge placed in the blasting hole
Source: photographed by the author

We dug pits in the ground, each with a base area of 30 × 30 cm and a depth of 50 cm (Figure 4), where the target objects with the attached charges were placed. The pits were spaced far enough apart so that the detonation shockwave and other effects of blasting would not influence the process. In practice, this meant a distance of approximately 3 meters. The parameters of the configured charges can be seen in detail in Table 1.

Table 1: Data of exploded charges

No.	**Type**	**Cone weight (g)**	**Explosive weight (g)**	**Target material**
1.	Cone: 20 mm, PA–12, 90˚ Charge body: 40 mm stand-off, back-flow preventer	2.4	32	30 mm wide, steel disc (sawed from a single steel pole)
2.				
3.				
4.	Cone: 20 mm, ONYX, 90˚ Charge body: 40 mm stand-off, back-flow preventer	2.8		
5.				
6.				
4.	Cone: 20 mm, ASA, 90˚ Charge body: 40 mm stand-off, back-flow preventer	2.5		
5.				
6.				

Source: compiled by the author

The process of preparing the charges:

1. Assembling the charge housings
2. Filling the charges with Semtex-H explosive
3. Creating the space for the detonator
4. Attaching the charges to the target objects with superglue
5. Placing the detonator support cap
6. Inserting the secured charges into the blasting pits prepared for detonation
7. Placing the electric detonators in the charges

Results

All of the PA–12 cumulative cone-equipped charges demonstrated the expected efficiency; however, the appearance of the created holes was not entirely uniform. The height of the rim ranged between 4.5 and 5.3 mm. The upper part of the penetration formed a cavity with a wider diameter, where the rim occasionally detached. The lower part of the penetration was relatively uniform, with diameters ranging between 15 and 16.8 mm. The bottom of the cavity, measured from the original surface of the disc, was between 10.8 and 12 mm in the target objects.

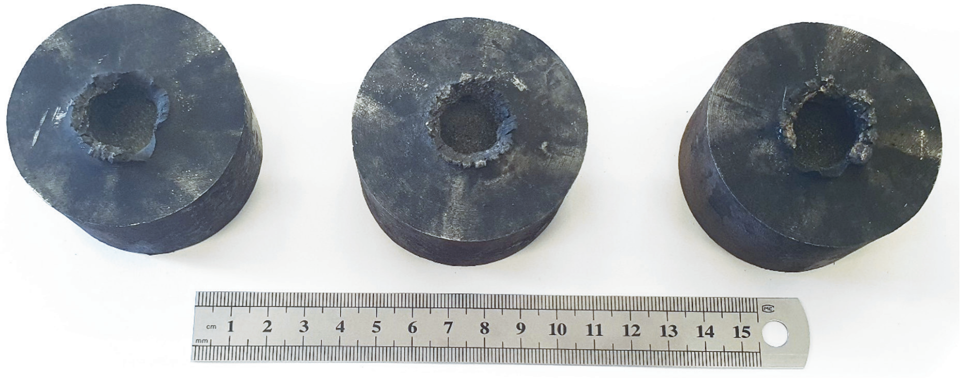

Figure 5: Target objects of charges with PA–12 cone
Source: photographed by the author

All of the Onyx cumulative cone-equipped charges also demonstrated the expected efficiency, and the appearance of the created holes was uniform. The height of the rim ranged between 3.7 and 4.3 mm. The upper part of the penetration formed a cavity with a wider diameter, where the rim occasionally detached. The lower part of the penetration was relatively uniform, with diameters ranging between 12.6 and 13 mm. The bottom of the cavity, measured from the original surface of the disc, was between 11.8 and 12.2 mm in the target objects.

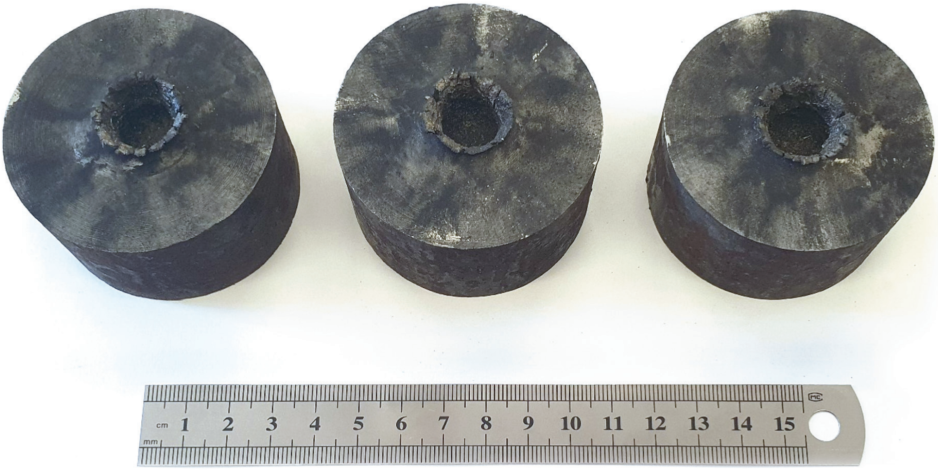

Figure 6: Target objects of charges Onyx cone
Source: photographed by the author

The ASA cumulative cone-equipped charges also demonstrated adequate efficiency, and the geometry of the cavities was uniform. The height of the rim ranged between 4 and 4.4 mm. The upper part of the penetration formed a cavity with a wider diameter, where the rim occasionally detached. The lower part of the penetration was relatively uniform, with diameters ranging between 14 and 14.7 mm. The bottom of the cavity, measured from the original surface of the disc, was between 11.8 and 11.9 mm in the target objects.

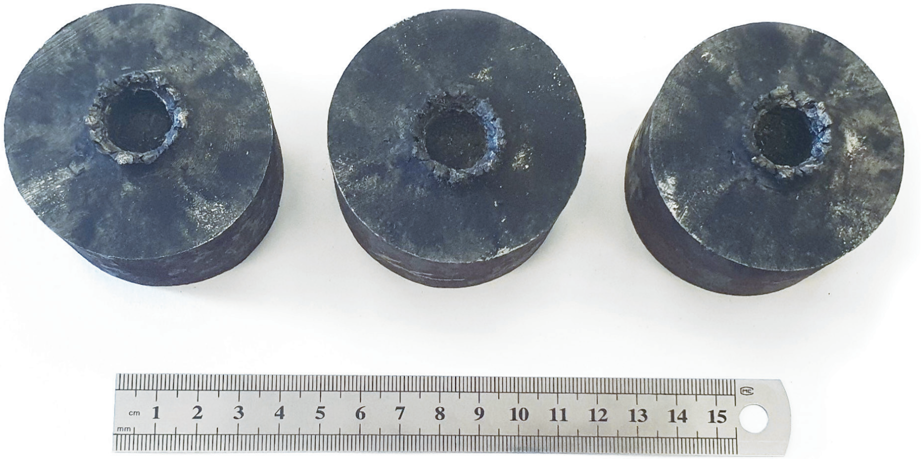

Figure 7: Target objects of charges ASA cone
Source: photographed by the author

All of the examined materials demonstrated the expected performance, although in the case of the PA–12 variants produced using SLS technology, it is visibly apparent that the geometry of the cavity is somewhat irregular. This is particularly evident when compared with the other materials, resulting in a contrasting outcome. The Onyx and ASA materials delivered nearly identical performance, with the cavities consistently forming in an orderly manner. The penetration and other parameters in these cases show relatively little variation, indicating that these charges are easily reproducible under field conditions. Additionally, this confirms that the conducted tests can be considered successful, as the charges formed were sufficiently uniform.

Summary

During the investigation, I detonated nine charges, whose design and assembly made them suitable for producing real results. The parameters established along the uniform geometry meet the requirements of scientific outcomes.

Although the nylon materials (PA–12 and Onyx) do not have completely identical properties, I considered this an acceptable variation due to the different manufacturing technologies. The disadvantage of SLS technology can be considered confirmed, likely due to the lower mass and density of the cones made from powder material.

The cones produced with FDM/FFF technology (Onyx and ASA) yielded similar results, with some differences in their efficiency and the geometry of the created holes, but overall, their performance can be described as uniform. This could also indicate that further investigations are needed, as there may be other polymers that could be more effective in piercing the target objects.

The above thus confirms my hypothesis and provides information for further studies. I find it important to test other potential materials under similar conditions in the next examination period of cumulative charges.

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