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Influence of the printing process on the traces produced by the discharge of 3D-printed Liberators

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A B S T R A C T

Since its introduction in 1986, 3D printing technology is in constant development. 3D printers are becoming more and more performant and accessible. In 2013, the Liberator blueprints are released online. This single-shot pistol can be entirely manufactured using a 3D printer, except for the firing pin and the ammunition. First, this research aims at establishing an overview of all the elements and traces potentially present when a 3D-printed firearm is involved, whether it is fired or not. In the second part, we study these elements for exploitability to obtain information about the manufacture of the firearm (printing processes, 3D printers and polymers). For this purpose, a total of 36 Liberators were manufactured using different printing conditions (i.e., printing processes, printers, polymers and parameters). The tested printing processes were based on the principles of Material Extrusion (ME), Vat Photopolymerization (VP) and Powder Bed Fusion (PBF). All 3D-printed firearms manufactured via ME and PBF were able to fire whereas Liberators manufactured by VP printing could not be fired. This could be explained by the lack of precision of the prints making it impossible to assemble some of the Liberators, or by the fact that the polymer was not suitable to produce the springs. All the barrels were broken by the discharge, projecting polymer pieces or fragments into the environment. These polymer pieces or fragments were examined to determine which printing process was used as well as other elements related to printing parameters and conditions (e.g., layer height, filling pattern and infill density). This information is useful to determine whether a certain command file, slicer or 3D printer could be at the source of a questioned 3D-printed firearm. Melted polymer or polymer particles on elements of ammunition may also be present after the firing process. However, the examination of these particles does not allow inferring other information, except the possible use of a 3D-printed polymer firearm.

1. Introduction

Since its introduction in 1986, additive manufacturing, also known as 3D printing, is continuously developing in terms of performance and manufacturing quality [1]. In parallel, 3D printers became readily available to the general public [2], with three main printing processes. First, Material Extrusion (ME) relies on the deposition of a melted polymer filament, layer after layer [1,3]. This process is commonly referred to as Fused Deposition Modelling (FDM) by Stratasys, Ltd. or as Layer Plastic Deposition (LPD) by Zortrax S.A. The second one, Vat Photopolymerization (VP), is one of the oldest printing processes. After curing a layer of liquid resin, a new one is added between the previous one and a UV source. A post-treatment under UV light is required for VP-produced parts to be fully solidified [1,3]. The FormLabs Inc. company is commercialising a Form2 printer equipped with a UV laser set as a light source, the term Stereolithography (SLA) is used to describe this process. Finally, Powder Bed Fusion (PBF) consists of thin layers of powder fused together by using a laser. Powder grains are fused together to form a horizontal layer, combined with the previous layer at the same time. The cycle then repeats, with the addition of a new layer [1,3]. This process is also known as Selective Laser Sintering (SLS). Given the diversity of additive manufacturing processes, different forms (e.g., liquid (resin), powder, filaments) of feedstock polymeric materials can be found on the market [3].

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The superficial geometry of objects to be printed is included in electronic files, the most frequent format being STL. These files are commonly known as "plans" or "blueprints". A slicer software is also required to convert the plan file into a command file readable by a printing device. This file contains instructions to be executed by the printer to produce an object. Several printing parameters such as support material, infill and layers height can also be set up through the slicer software.

Plans of the Liberator – the first 3D-printed firearm widely covered by the media – were published on the Internet in 2013 before being massively downloaded until public authorities would request their removal. However, plans of the Liberator can still be found on the Internet and on the Dark Web [2,4]. Later, more plans were designed for firearms models to be manufactured – entirely or partially – through 3D printing [5]. The original version of the Liberator is composed of nineteen pieces. Eighteen are 3D-printed and the remaining one is a metallic nail which acts as firing pin. Furthermore, the Liberator is fuelled by conventional .380 Automatic calibre handgun ammunition. Projectiles fired with this firearm were found to have sufficient power to penetrate soft tissues and reportedly human skulls, suggesting that this 3D-printed firearm is functional and able to inflict serious and potentially lethal wounds [6–8]. The potential efficiency of 3D-printed firearms and the fact that their manufacturing is difficult to control led to several security concerns raised by law enforcement agencies [9]. Besides, since a 3D-printed Liberator might be considered as a homemade firearm, it could be harmful for users as well [7,10].

From a forensic perspective, literature is limited to a broad overview of the traces produced by the manufacture or use of a 3D-printed polymer firearm. To date, little is known about the traces that could be used to inform on the manufacturing process of such firearms, meaning the printing process, the type of printer, the polymer, as well as printing parameters. In a case involving a 3D-printed firearm, its pieces (e.g., if there was no discharge) or residues produced by the discharge could inform on the process used to manufacture the firearm and thus support the investigation.

Since they attracted media's attention, 3D-printed firearms have been studied by several law enforcement agencies and forensic laboratories. Crowe's study showed that, along with almost standard gunshot residues (GSR), plastic residues were found after a Liberator discharge (.380 Automatic). In addition, polymer smears on cartridge cases and bullets were also observed [11]. Black et al. studied the polymer depositions on elements of ammunition and GSR using direct analysis in real time coupled with mass spectrometry (DART-MS) after the discharge of polymer barrels (.38 Special) and Washbear handguns (.22 Long Rifle) [12]. Honsberger et al. researched the exterior ballistic, wounding potential and discharge traces a Liberator (.380 Automatic and .25 Automatic) may release in the environment and leave on the ammunition [7,8]. AlShamsi's studied firing pin marks (a nail for the Liberator) to establish a link between a fired cartridge case and a firearm [13]. In their article, Scott and Jones described the characteristics that can be found on parts produced with SLS type printers [14]. Finally, Falardeau et al. compared the polymer degradation of the 3D-printed barrel of a Ruger 10/22 rifle (.22 Long Rifle) at three points in time, specifically before the printing, after the printing and after the discharge [15].

The aim of the present research is to explore to what extent the traces produced by the discharge of a 3D-printed firearm can support the inference on the type of 3D printer used to produce the firearm. To this purpose, 36 Liberators have been printed using 4 different printers relying on various processes and polymers. Once assembled, they were discharged in controlled conditions and different types of traces were recovered. Traces left on the 3D-printed firearm itself, in the environment and on the discharged elements of ammunition were studied in order to highlight characteristics related to the printing procedure (i.e., process, printer, polymer and parameters).

2. Material and method

2.1. Printing

The blueprints (STL files) of the Liberator in .380 Automatic calibre used for the present research have been used previously to produce and assemble Liberators [7]. Four printers were used, covering three different printing processes: a Stratasys Fortus 250 mc (Stratasys, Ltd., USA) and a Zortrax M200 (Zortrax S.A., Poland) both ME printers, a Formlabs Form2 (Formlabs Inc., USA) based on VP and a PBF printer EOSINT P 395 (EOS GmbH, Germany).

Three Liberators were printed with the Stratasys Fortus, using ABS P430 polymer sold by Stratasys, Ltd., the layer height was set at 0.178 mm and the infill density at 90%. With the Zortrax printer, three frequently used polymers were selected: Z-ABS, Z-PLA Pro and Z-PETG.[1] Components of the Liberators were printed with a layer height set at 0.14 mm and an infill density at 70%. Three Liberators were printed with each polymer. In addition, three Z-ABS Liberators with a layer height of 0.14 mm and an infill density of 100% were also printed with the same 3D printer.

With the third 3D printer, the Formlabs Form2, three Liberators were produced with each of the seven selected resins: Tough, High Temp, Grey Pro, Rigid, Flexible and Durable, which are all distributed by Formlabs Inc. The layer height was set at 0.1 mm and the default infill density of 100% was selected. It must be noted that the process failed with the Flexible and Durable resins, leading to incomplete sets of pieces.

The fourth 3D printer used was the EOSINT P 395, relying on SLS. Three Liberators were printed with the PA 2200 polymer sold by EOS GmbH. The layer height was set at 0.12 mm and all parts produced with this technique had a 100% infill by default. The details of the printed Liberator specimens – including the number of firearms printed, assembled and discharged – are summarised in Table 1. For each process, proprietary slicers and command file formats were used: GrabCAD, Z-Suite, PreForm and EOSPRINT respectively.

Prior to assembling the firearms, observations were conducted on the Liberator's pieces to highlight characteristics related to the process used. Observations on unused parts have been considered relevant since a case involving a 3D-printed firearm does not necessarily mean that the firearm was discharged (e.g., a 3D-printed firearm may have been found or seized in another context such as illicit drugs and firearms trafficking).

Since the layer height is a parameter that can be adjusted manually within a range depending on the printer, it seemed relevant to measure it on the produced pieces. A stereomicroscope Leica M125 (Leica Microsystems, Germany) combined with a camera Canon EOS 600D (Canon Inc., Japan) was used to measure the layers. The surface layers were observed and documented. The barrel being one of the pieces most likely to break during the discharge, each printed barrel was observed under various types of illumination, at different wavelengths, and under selected observation conditions (filters), using a Polilight PL500 (Rofin Australia Pty Ltd, Australia). Manufacturing defaults were searched on each part. The relevant observations were photographically documented using either a camera or a stereomicroscope.

2.2. Assembling

Four distinct steps must be followed to assemble a 3D-printed Liberator [7]. First the trigger spring and the trigger itself are assembled and inserted into the frame. Second, the group of pieces

[1] "Z" means that the polymers are those produced by Zortrax S.A. for their printers. It is worth noting that the Zortrax M200 can also be used with other polymers than those from Zortrax S.A.

Table 1
Printed, assembled and discharged Liberators.

Process	Printer	Slicer	Material	Layer height [mm]	Infill density [%]	Number of firearms		
						Printed	*Assembled*	*Discharged*
ME	Stratasys Fortus 250 mc	GrabCAD (.print)	ABS P430	0.178	90	3	3	3
	Zortrax M200	Z-Suite (.zcode)	Z-ABS	0.14	70	3	3	3
					100	3	3	3
			Z-PETG		70	3	3	3
			Z-PLA Pro		70	3	3	3
VP	Formlabs Form 2	PreForm (.form)	Tough	0.1	100	3	3	0
			High Temp			3	0	0
			Grey Pro			3	3	0
			Rigid			3	3	0
			Flexible			3	0	0
			Durable			3	0	0
PBF	EOSINT P 395	EOSPRINT (.sli)	PA 2200	0.12	100	3	3	3

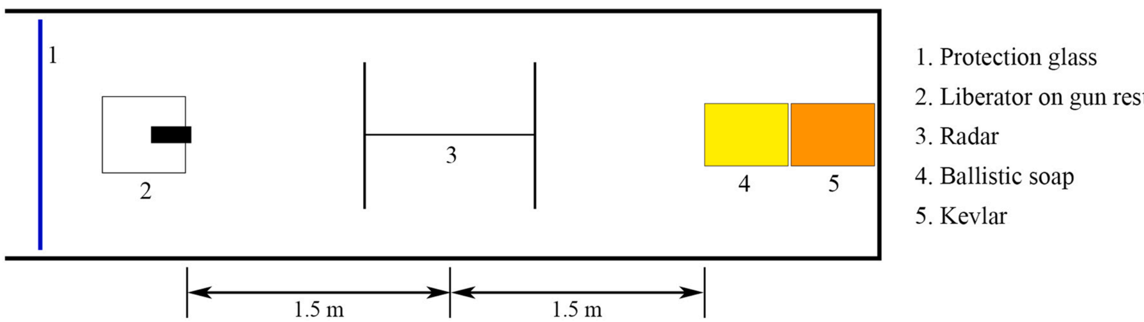

Fig. 1. Test firing setup (plan view).

composed by the hammer body, the hammer and two hammer springs is assembled and set on the frame within which it is attached using three pins. The grip can be attached at any time and locked with a pin. Third, the cartridge must be placed in the barrel, before it is inserted onto the frame. The barrel is locked with a slight rotation, engaging its lug in the frame's notch. Finally, a nail – cut at the right length – is inserted in a hole on the hammer body to serve as the firing pin. The pointy side of the nail is shaped by milling to obtain a rounded pin able to strike the cartridge head.

2.3. Test-firing

All the experiments were conducted with .380 Automatic ammunition (Magtech model 380 A, FMJ, 95 grains) in an indoor shooting range, as illustrated in Fig. 1. In order to limit contamination between successive discharges, the floor and the walls, up to 1.8 m, were covered with paper. Between each discharge, the paper on the floor was replaced, and the floor vacuumed. The shooting target was a block ballistic soap, behind which a box of Kevlar was positioned to recover the bullet if it went through the ballistic soap. A Drello Bal 4050 Counter (Drello GmbH, Germany) radar was used to measure the projectile's velocity. The Liberator was set on a firearm Ransom rest (Ransom International Corporation, USA), 3.0 m away from the target. For safety reasons, a protective glass was placed behind the firearm, which was remotely fired by using a string attached to the trigger.

After each discharge, polymer pieces and fragments torn from the firearm were collected. Smaller fragments were collected from the floor by taping (transparent adhesive sheets). Firearm and elements of ammunition were collected and bagged. If it was reached by the bullet, the ballistic soap was documented, including a measure of the penetration depth before the bullet was extracted. If required, the bullets were cleaned from ballistic soap residues before being observed under various wavelengths and filters, using a Polilight PL500, in order to highlight polymer traces. The expanded cartridge cases were also observed. The potential physical match between broken pieces and fragments was studied. The small fragments collected on the adhesive sheets were categorised according to their shape and size by using a Leica M125 stereomicroscope. Then, the different fragments were characterised in regard to the printing process used (i.e., printer, polymer and parameters) to determine how they could contribute to the inference on the process used to produce the firearm.

3. Results and discussion

3.1. Traces and characteristics variability induced by the printing process

3.1.1. Polymer support structure

During the printing process, pieces produced through ME and VP must be held by support structures, so they do not collapse under their own weight. These structures are designed by the slicer. Walls and rods serve as support structures and were printed under the piece with both methods (see Fig. 2).

Zortrax support structures and pieces are created using the same material. These supports must be removed manually and traces of them might subsist on the frame, as illustrated in Fig. 3. These traces could be removed with sandpaper, which could potentially leave sanding marks.

The Fortus 250 mc, however, relies on a specific support material made of a different polymer than the one used for the Liberator pieces. This polymer can be dissolved in a water-based solution.[2] No traces of this type of support have been observed on the pieces

[2] Stratasys, Fortus 250 mc User guide, available at: https://support.stratasys.com/products/fdm-platforms/fortus-250mc.

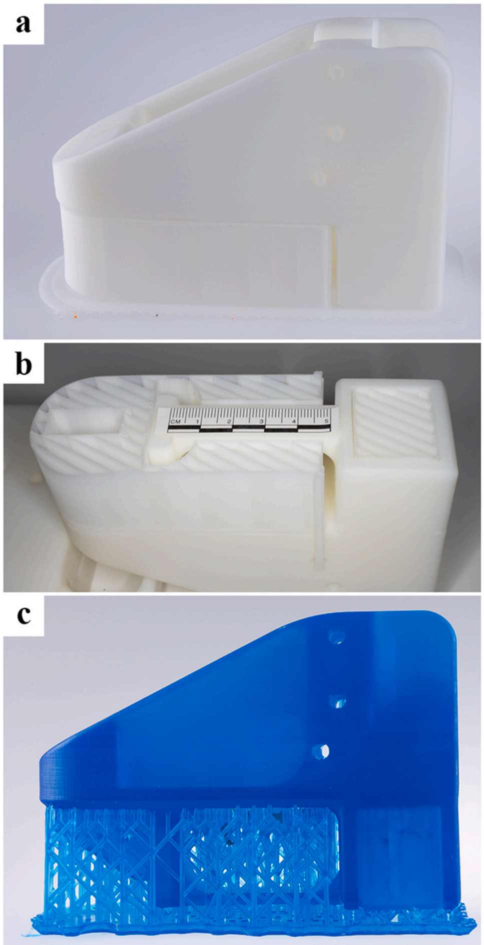

Fig. 2. Support structures with the Zortrax M200 (ME) using Z-ABS (a and b); and with the Formlabs Form 2 (VP) using Tough resin (c).

produced by the Fortus printer which has specific features such as a dual extruder with two nozzles, one for support material and one for the object. Thus, an ME-printed piece with no traces of support, nor marks indicating that the piece was sanded, could indicate that a 3D printer with a dual extruder has been used.

Support structures associated with VP-printing techniques must also be removed manually. This step systematically leaves traces in the shape of small dots, as illustrated in Fig. 4. These dots can also be removed by sandpapering the piece. As opposed to ME and VP, PBF process does not require any specific support structure, as the unfused powder fulfils this role.

3.1.2. Physical printed characteristics

All three printing processes (ME, VP, PBF) rely on layer-by-layer production, resulting in parallel and horizontal lines. However, pieces produced with these printing processes appear to have

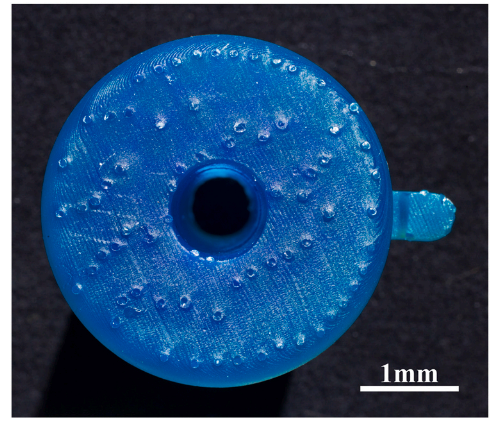

Fig. 4. Dots left on the base of the Tough barrel (VP) after removing the supports.

different surface texture, when observed with the proper magnification.

On the ME manufactured parts, the observed layers could clearly be distinguished from each other, making measurements easier. For example, the measured layer thickness on the pieces printed with the Fortus 250 mc match the chosen parameters (0.178 mm). However, pieces printed with the Zortrax M200 showed a layer thickness close to 0.15 mm while the chosen parameter was 0.14 mm. As illustrated in Fig. 5, both the top and bottom layers show a deposition of the polymer filament, which is typical of ME-printed parts. The aspect of the polymer thread was different between the lower and upper surfaces (see Fig. 5a–b), the second one being flattened. Examples of this characteristic for barrel are illustrated in Fig. 5, even though this may also be observed on any other parts of the 3D-printed firearm. External aspect did not allow to differentiate Z-ABS parts printed with 70% infill density from those printed with 100% infill density. On pieces manufactured by ME, the Z-seam was visible. This parameter corresponds to the starting and finishing point of a path in a layer, which is also visible on the surface (see Fig. 6a). The position of the Z-Seam can be modified with specific slicers. The quality of Z-seams varies according to the printer and polymer. However, the physical printed characteristic and the position of the Z-seams appeared as reproducible for a given combination of printer and polymer. It could be compared with the position in the command file. Layer delamination (i.e., separation of layers during the printing process) has been observed in the same position on the three frames printed with the Zortrax M200 in Z-ABS. Several pieces printed with the same printer in Z-PETG showed this printing defect as well as polymer threads (see Fig. 6b).

Layers of VP-printed pieces were also clearly distinguishable from each other, even though they showed a smoother surface (see Fig. 5c). Another particularity of this printing process is that, to ensure an efficient printing, some pieces are printed with a specific angle compared to the printing platform, producing layers that are not parallel to the axes of the piece. The printed layers matched the intended parameters (0.1 mm).

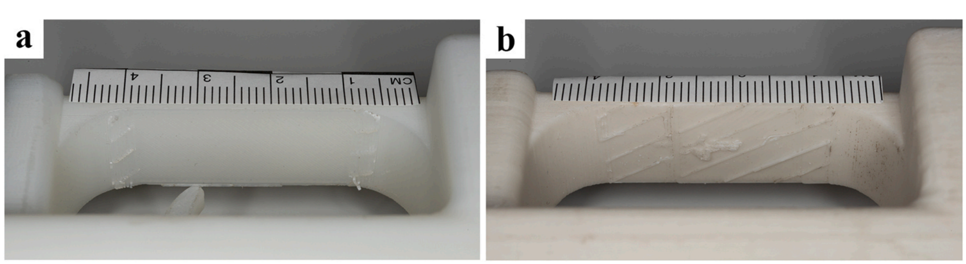

Fig. 3. Traces of supports inside the trigger guard of Z-ABS (a) and Z-PLA Pro (b) Liberators printed with the Zortrax M200 (ME).

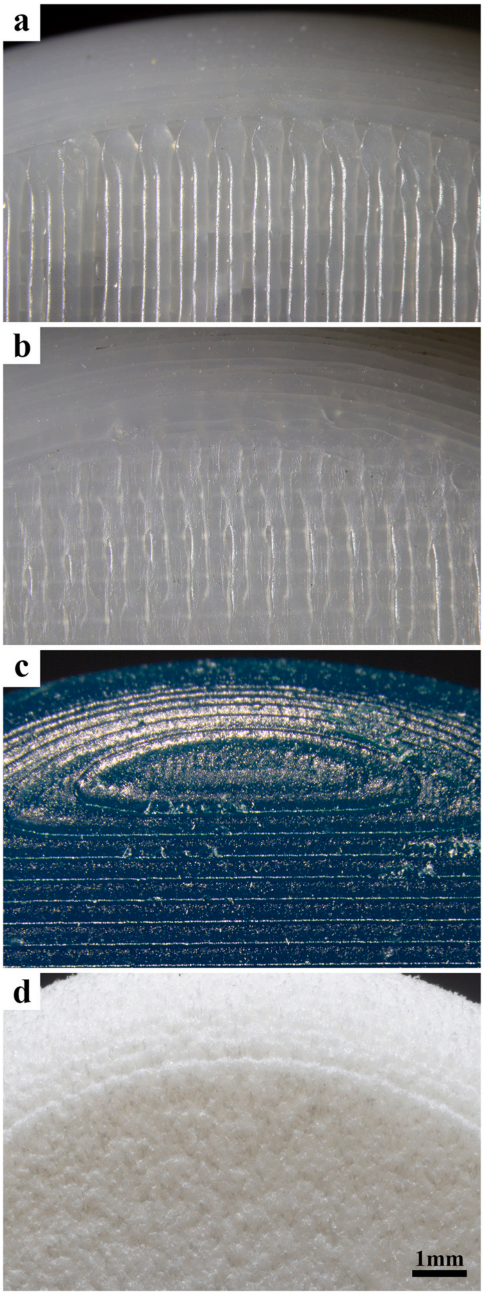

Fig. 5. Section of the back (a) and front (b) of a Z-ABS 70% infill density barrel (ME), the front of a VP-printed (c) and PBF-printed barrel (d).

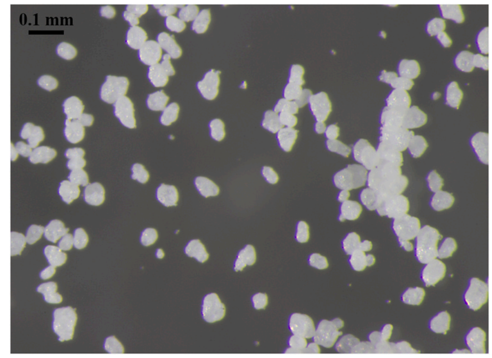

Fig. 7. Uncured powder from PBF-printed grip observed with a stereomicroscope.

Parts printed with the PBF printer showed coarse surfaces, as shown in Fig. 5d. The pieces appeared to have been manufactured layer by layer, even though it was not possible to distinguish the layers easily. A precise thickness measurement was not possible for these pieces. After printing, parts produced with PBF were sanded to remove the uncured powder. However, uncured powder could still be present in hard-to-reach areas of the pieces. Hence the uncured powder that has been found inside the grip (see Fig. 7). These powder residues could not fall by themselves, even though a simple scratch was enough to remove them. In our case, a small quantity of powder has been collected with the aim of observing it under magnification. For comparison purposes, infused powder and glass beads, used for sanding, have been recovered at the printing workshop as this type of material might be found if a PBF-printed firearm is involved in a case.

A peculiar default has been observed on the frames printed with PBF process as the last layer was not completely printed, as shows in Fig. 8. The same defect appears on all three frames printed simultaneously. This defect could be due to an issue within the slicer which is responsible for the interpretation of the STL files and creating the command file for the printer.

Preliminary observations show that pieces created with different printing processes have very different characteristics. These characteristics can thus be used to reliably differentiate pieces printed with different processes, as well as infer in the process used. The difference in the aspect of the polymer threads on upper and lower surfaces of ME-produced pieces could be used to determine the printing direction of the piece. However, it must be emphasised that a given piece is not necessarily printed in direct contact with the printing platform since a support structure might be used (see Fig. 2a). This would influence the shape of the polymer thread of the lower surface. Characteristics such as the supports' position and

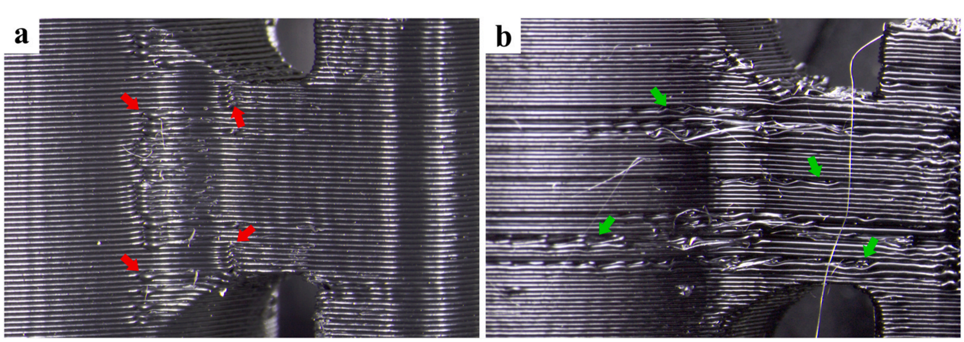

Fig. 6. Red arrows show some Z-seams visible on an ABS P430 barrel body (a) and green arrows indicate some layer delamination on a Z-PETG barrel body (b). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article)

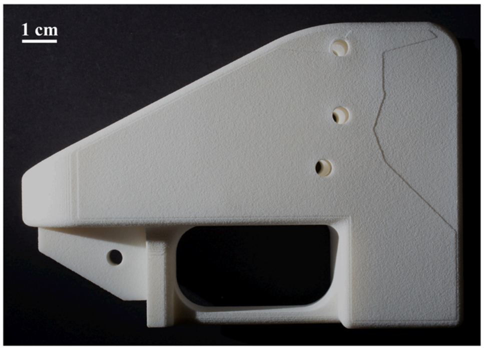

Fig. 8. One of the frames printed with the PBF printer, the incompletion of the last layer can be seen on the right.

shape, the Z-seam position, the layer height, the angle of layers relative to the piece, the direction of printing and potential defects could be used for comparison purposes. For example, if a 3D-printed firearm and questioned command files are recovered, it may be possible (if the questioned printer and the command files are compatible) to print new pieces from the command files. The aim would be to assess if both the questioned printer and command files could be at the source of the questioned firearm. Since the layer thickness is influenced by the printer's setup, it can also be used to determine if a given printer has been used to produce a questioned part. However, the results of the present study show that the measured layer thickness of a printed piece does not necessarily match the specified printing parameters. To address this, test pieces can be printed with the questioned equipment.

Using digital forensic methods, it may be possible to extract digital traces (i.e., log files, G-Codes, STL files, images, etc.) from devices such as computers or printers that contain information about the print job [16,17]. Whether and which types of digital traces are present depends on several factors such as the operating system, 3D printer and software. However, if such traces are present, relevant information about the printed objects can be extracted and then used for comparison with the questioned parts.

3.1.3. Luminescence of polymers

Different materials used in the present research were observed to be luminescent under several lighting conditions (an example is given in Fig. 9), especially the resins used for the VP process. Different luminescent reactions were observed, depending on the polymer. This does not seem to be sufficient to identify a specific polymer, even though it could be used to help recognising and collecting polymer fragments of interest when investigating a scene.

3.2. Impact of the printing process on the functionality of Liberators

3.2.1. Assembling

As opposed to the pieces printed with the Fortus 250 mc, most of the pieces manufactured with Zortrax M200 (ME) had to be manually reworked by sandpapering before assembling the Liberator. While this study focused on traces produced by the printing process and the discharge of Liberators, it must be noted that reworking the pieces before assembling created additional toolmarks which could be assessed in a forensic case.

Only the VP-printed Liberators specimens made of Tough, Grey Pro and Rigid resins could be assembled (see Table 1). Each piece produced with these resins was reworked. The Liberators printed with the other resins could not be assembled, essentially for two reasons:

(1) The lack of precision in the printings which made it impossible for the pieces to fit together,
(2) The lack of flexibility causing some pieces to break when applying tension to assemble them.

Pieces produced with the PBF printer were reworked as well, essentially because the diameters of holes were generally smaller than what was indicated on the blueprints. Namely, the barrel diameter as indicated in the blueprints was larger than the projectile diameter, while it was significantly smaller than the bullet on the PBF-printed parts. The diameter of the barrels was adjusted to 9 mm by milling. The chamber length was adjusted as well.

Along with toolmarks, reworking a piece will also produce residues such as powder resulting from the sanding operations, or shavings from the milling. During the investigation of a potential production site, it is therefore important to search for such residues and collect them. With further examination, such as chemical analysis, their nature and composition may be determined and later used for comparison with a questioned 3D-printed firearm. Toolmarks and the general quality of the reworking on the pieces could also inform on the type of tool used. Comparison of toolmarks may also be considered in such cases.

3.2.2. Discharge

None of the Liberators manufactured and assembled with the VP process have been discharged (see Table 1). In some cases, pieces broke under the cocking tension while in others the springs became too soft after being subjected to tension.

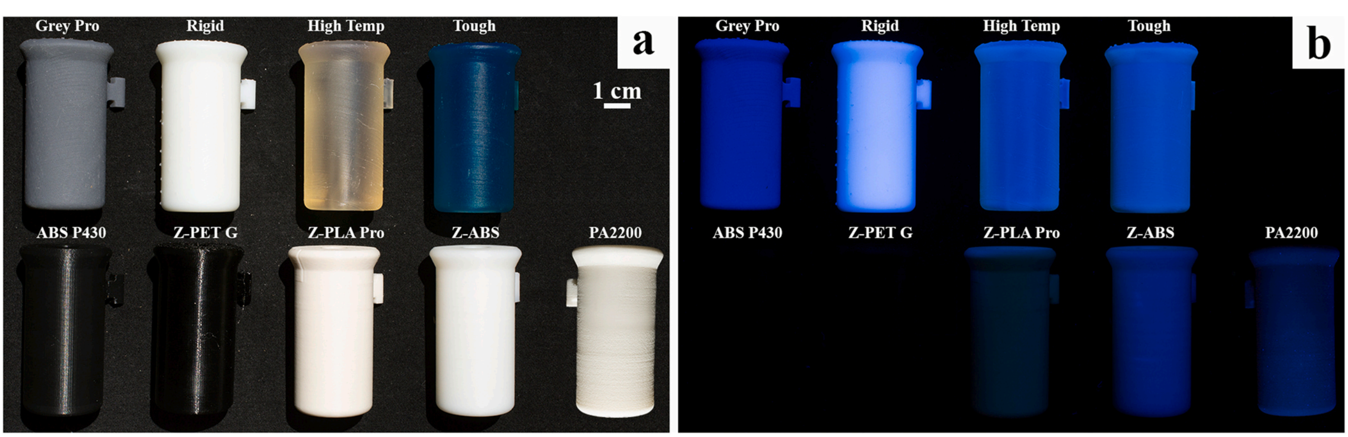

Fig. 9. Observation in white light (a) and under 350 nm illumination (b).

Some of the 90% and 70% infill density Liberators (ME) required several attempts to discharge the firearm. Some pieces broke due to the tension and had to be replaced. The discharge caused all barrels to explode. The frame and other parts were also sometimes damaged. Z-PETG Liberators were the most damaged. Among all these discharges, only three bullets, two fired from Z-ABS Liberators and one from a Z-PETG Liberator, reached the ballistic soap. The penetration depth has been measured to 10 mm, 17 mm and 7 mm respectively.[3] The velocity of the projectiles could only be recorded with two Z-PETG Liberators on all ME Liberators. The first projectile, which reached the soap, was measured at 53 m/s and the second at 50 m/s. The discharges of the 100% infill density Z-ABS Liberators did not show significant differences from the previous ones. Several attempts were needed as well. The barrel of all the three Liberators broke. Two projectiles reached the ballistic soap for which the penetration depth has been measured to 28 mm and 34 mm respectively. The Liberators' condition after discharging one round are available in Figs. A1–A6 of the appendix.

The PBF-printed Liberators have shown a greater efficiency in terms of ability to discharge. Indeed, one (for two Liberators) and two attempts were needed to discharge the Liberators. Two projectiles reached the ballistic soap and had their velocity recorded. The penetration depth has been measured at 27 mm and 72 mm, for a velocity of 102 m/s and 106 m/s respectively. All barrels and frames broke in more pieces than the ME Liberators. Polymer fragments and pieces were also projected at a higher velocity, damaging the protective paper taped to the walls.

Compared to the Liberators fired for Honsberger et al. experiments [7,8], the Liberators fired in the present study showed less efficiency, shooting precision and energy transferred to the bullet (less velocity and smaller penetration depth). Projectiles fired from the 100% infill density Z-ABS and PBF Liberators showed greater efficiency than the other Liberators tested in this project. However, none of the projectiles had a stable behaviour and none were pointing directly forward when recovered in the ballistic soap. Moreover, a major difference compared to the studies by Honsberger et al. [7,8] is that some of the barrels they used resisted the discharge, even though the same blueprints and ammunition were used. Several explanations can be proposed to explain this. The quality of the printing, thus the printer, could play a role. The Fortus 400mc, used by Honsberger et al., is a high-end industrial printer while the Zortrax M200 is rather a desktop and more accessible device. The differences of infill density as well as the polymer used are likely to influence the quality of the manufactured pieces. The inner diameter of the barrels might be a reason as well, since it was unintentionally smaller than for the studies of Honsberger et al. On the blueprints, the inner diameter of the barrel is 9.40 mm. This is significantly wider than the projectile diameter, which is at most 9.04 mm according to the International Commission for the Proof of Small Arms (CIP) [18]. The inner diameter of an intact barrel printed by the Fortus 400mc was measured at 9.40 ± 0.03 mm. The inner diameters of the discharged Z-ABS barrels printed with 100% infill density were estimated at 9.22 ± 0.03 mm on average, and 9.06 ± 0.06 mm on average for PBF-printed barrels. This difference does not only mean that, with the barrels of the Fortus 400mc, the projectile could more easily go through the barrel, but also implies that there is more space between the projectile and the barrel for the combustion gases to escape. In fact, on the slow-motion videos of Honsberger et al., it can be observed that part of the gases and residues exit the barrel before the projectile does. Gases escaping through the gap between the projectile and the barrel reduce the pressure applied to the projectile. Reducing this gap with a smaller bore diameter would increase the pressure inside the barrel. While it could be efficient in terms of interior ballistics, it would also reduce the chances of the barrel to remain intact after the discharge.

3.3. Impact of the printing process on the traces left on the investigation scene

3.3.1. Traces on the liberator

Aside from the barrel, the parts which sustained the most damage were the hammer body and the frame. Frames printed with Z-ABS in 100% infill density showed the best resistance. Liberators printed with Z-PETG, and Z-PLA Pro and PA 2200 (PBF) least resisted the discharge and broke into multiple fragments. As for Liberators printed with PBF process, the most damaged pieces were the barrel and the frame. However, the hammer body part (including the springs and the hammer) was retrieved intact after all three discharges, although it broke away from the firearm and hurled into the surroundings during two of the three discharges. This was not always the case with ME-printed hammer body parts.

The frame pins securing the hammer body onto the frame itself were almost systematically broken by the discharge. They did not support the shear movement applied to them by the hammer body pushing backward during the discharge. They were broken even when the hammer body stayed attached to the frame during the discharge. The same observation was made with pins printed with PBF process. The damage sustained by the frame pins can be explained by the calibre used (.380 Automatic). This is a calibre of cartridges for semi-automatic pistols which contains a large amount of propellant and therefore produce a high pressure during the discharge. Since the Liberator does not have a breech system to absorb the recoil of the cartridge case, all the pressure exerted by the cartridge case is directly opposed to the resistance of the weapon, i.e., the hammer bodies and the frame pins. This phenomenon also explains the impression of the cartridge case head on the hammer bodies (see below).

Fractures on ABS P430 and Z-ABS parts tend, in most cases, to follow the printing layers or to be perpendicular to them (see Fig. 10a–b). This is striking for Z-PETG and Z-PLA Pro pieces (see Fig. 10c). On the contrary, the fractures on PBF parts do not follow the printing layers (see Fig. 10d). Fig. 10 shows the influence of both the polymer and the printing process on how a piece can break.

The damages sustained by each tested Liberator underline the fact that such 3D-printed firearms can pose a threat for the shooter. From a forensic point of view, the explosion produces a significant number of pieces, fragments and traces which are all remnants of the shooting that can be collected on an investigation scene (see Sections 3.3.2 and 3.3.3). Generally, most of the small fragments were collected around and close to the position of the Liberator, while larger fragments were projected further (effect of the deflagration). In the context of a case, such observation could help estimate the shooter's position.

Some of the hammer bodies were destroyed, as described above. For those that were not, a round depression, as well as combustion residues, are observed around the area where the cartridge case head was pressured. On ABS P430 and Z-ABS Liberators the circular depression is slightly embossed. Contrary to some of the Z-PETG and Z-PLA Pro Liberators, the depression is deeper as a polymer cylinder was broken and compressed by the cartridge case. As opposed to the observation made by Honsberger and colleagues [7,8], no impression of the cartridge headstamp was noticed. Regarding PBF, a slight round depression due to the case head as well as combustion residues have been observed on the hammer bodies. Examples of these marks are illustrated in Fig. 11. An explanation for the absence of impressions of the case head inscriptions could be that the barrel broke too early, which does not allow the cartridge case head to be pressured long enough onto the hammer body.

[3] The measured penetration depths are likely to be under-estimated since the soap blocs used for the experiments were a little dry, thus impacting their hardness.

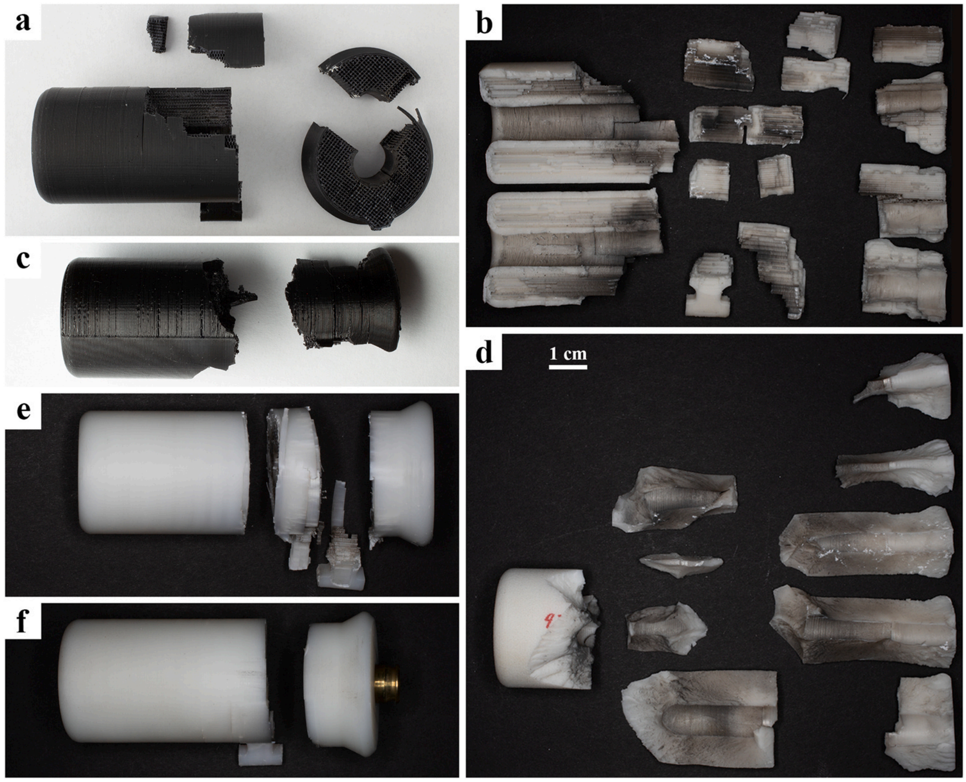

Fig. 10. Broken barrels in ABS P430 (a), Z-PLA Pro 70% infill density (b), and Z-PET 70% infill density (c), PA 2200 (PBF) (d), Z-ABS 70% (e) and 100% (f) infill density.

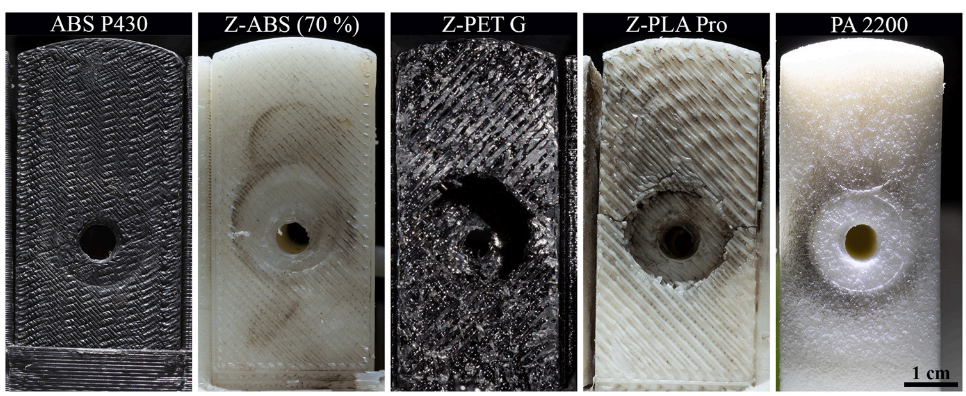

Fig. 11. Hammer bodies of different Liberators after discharging one round.

3.3.2. Pieces recovered in the environment

After the discharge of all Liberators, a significant number of pieces were collected from the surrounding scene. The layer height is measurable on most of the ME-printed fragments, provided that a piece of the external shell was present. The shell is the polymer wall separating the inside of the piece from the outside. With some slicers, it is possible to customise the number of threads composing the width of the shell. The layer height could theoretically be measured on fragments coming from the infill structure. However, this is not recommended as it would be necessary to consider the infill pattern, which is chosen in the slicer, to determine where the measurement must be performed. On fragments of sufficient size, the filling pattern can be observed, as illustrated in Fig. 12. In this example, the filling pattern consisted of a grid. The print head rose by a layer height between each perpendicular layer. With an infill density of 100%, no space was left between the polymer threads of the filling layer structure. PBF-printed fragments differ significantly from ME-printed ones. The breakage of these pieces does not seem to be influenced by their layer upon layer construction. No inner structure is visible like it is the case with ME-printed fragments. The interior of PBF-printed pieces is visually homogeneous.

ME fragments allow differentiating 100% infill density from non-100% infill density. Note that in the slicer used for this study (GrabCAD for the Fortus and Z-Suite for the Zortrax), infill percentages could only be chosen in increments of ten. The filling pattern can also be determined by observing the broken pieces. The slicer used for this study allowed to choose between three different ones. This could be used, to determine if a given slicer could have produced the command file to print a questioned part or to determine if a given command file could have been used to print a questioned part. Further experiments are needed to study variability between slicers and the influence of the filling pattern on how parts break.

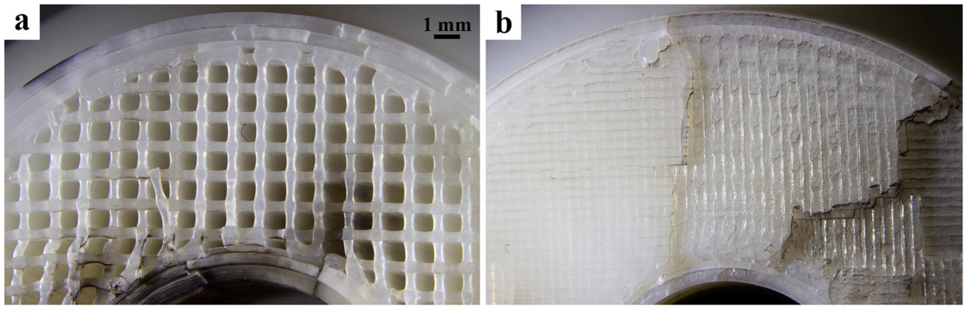

Fig. 12. 70% (a) and 100% (b) infill density Z-ABS barrels broken in the direction of the layers.

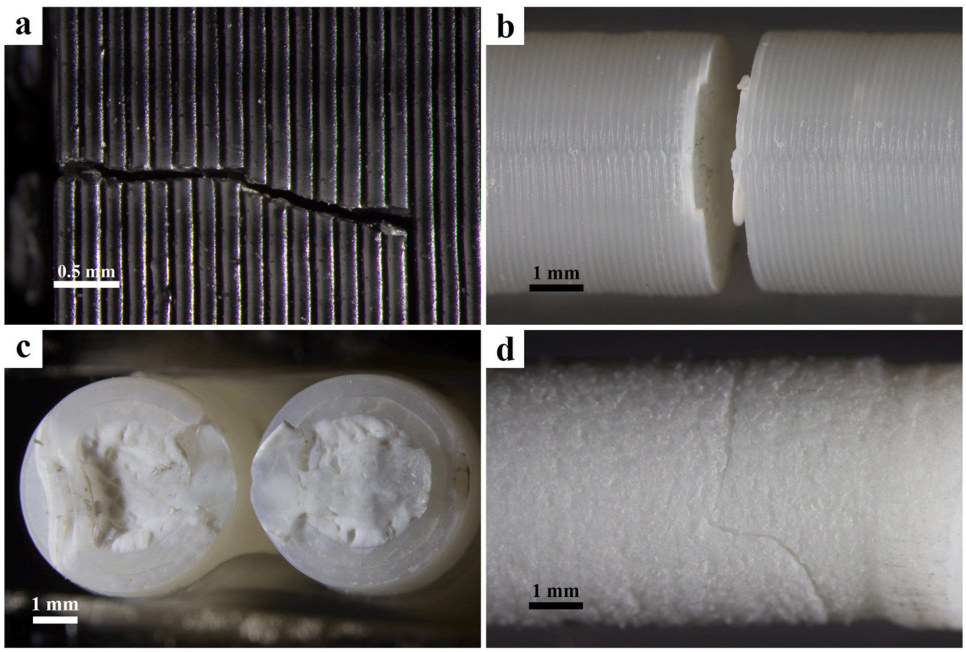

Fig. 13. Examples of physical matches between fragments of the outside of the ABS P430 barrel (a), ME frame pin of Z-PLA Pro (b and c) and PBF (PA 2200) frame pin (d).

Matching attempts have been conducted, mostly on barrels and frame pins. These parts are the most likely to break when the handgun is discharged. Moreover, while the end of the broken frame pins tends to fall on the ground, the central portion remains in the hammer body (and in the firearm if the hammer body is not ejected). It is possible to match the fragments of broken parts. However, the tension to which the piece is subjected during the discharge may slightly deform the fragments in addition to breaking them. Consequently, the fragments cannot always be precisely matched. Small fragments could also be missing and affect the physical matching. Examples of matching are shown in Fig. 13. Pins could be more difficult to physically match as the surfaces are smaller than those encountered while assembling bigger fragments. In addition, if an ME-printed pin is printed in its length, the fracture will follow the layers (see Fig. 13b–c). At first sight, a few features are visible to assemble two pieces of a pin. PBF-printed pins broke differently than ME-printed pins (see Fig. 13d). They showed more features supporting a physical match between two fragments.

Along with the morphology of the fracture, it is possible to use the surface texture and surface characteristics to support a physical match (see Fig. 13b and d), particularly with PBF-printed parts, as illustrated in Fig. 14a. In a case where firearms parts had to be reworked to assemble the gun, toolmarks can be used to support a physical match between two fragments. Fig. 14b illustrates the assembling between two pieces of a broken barrel, where toolmarks are observable.

It was thus possible to assemble broken parts of printed objects, reconstruct most of the pieces and infer the source of the model used (see Fig. 15). However, matching small ME pieces is challenging since the layer-by-layer construction influences the way pieces break. Two small fragments can, at first sight, appear as a coincidental match. In this example, a closer examination led to a non-physical match between some small fragments due to the physical characteristic and morphology of the surfaces. Further work would be necessary to study the variability in the way ME-printed pieces break.

3.3.3. *Polymer fragments and propellant powder residues recovered with adhesive sheets*

After the discharge of Liberators printed with 90% and 70% infill density, a great quantity of polymer fragments along with unburnt propellant powder flakes were recovered from the surrounding scene. Most of the polymer fragments originated from the internal filling structure. Fragments coming from the shell were present as well, allowing the measurement of the layer height. An overview of

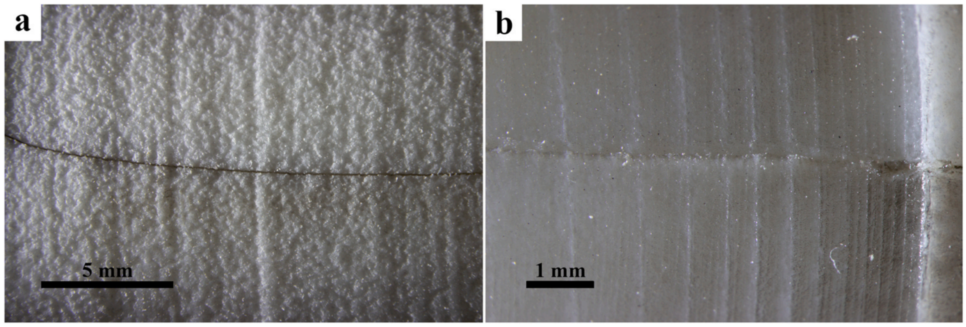

Fig. 14. Physical matching PBF-printed fragments on the outside of the barrel (a) and inside the chamber (b).

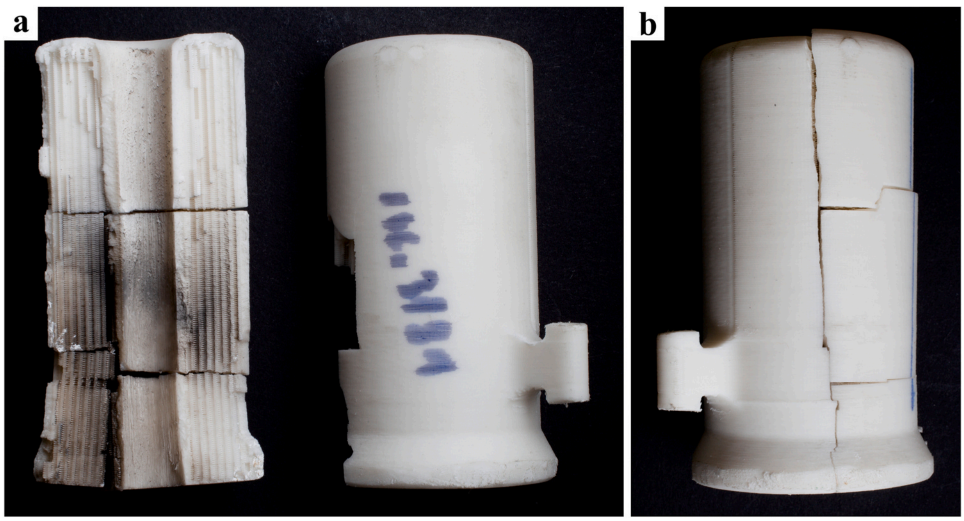

Fig. 15. Pieces of the Z-PLA Pro barrel (a) and their assembly (b).

the fragments recovered with the adhesive sheets is presented in Fig. 16.

Three main categories of fragments have been observed according to their shape and the structure they belonged to on the intact piece. Fig. 16 - Column A represents the smallest entity from the filling structure. Larger fragments have also been observed (Fig. 16 – Column B), they are made of small units from the filling structure described on Fig. 16 – Column A. It is expected that the shape and size of fragments originating from the filling structure will change if the infill density and/or the filling pattern are modified. Another type of fragment comes from the shell of the piece (see Fig. 16 - Column C). They can be used to measure the layer height. However, they are present in smaller quantities than the fragments originating from the filling structure. Fragments combining filling structure and shell structure were found as well. Fragments too small or too damaged to be linked to any known structure were also observed, in a lesser proportion. Less fragments were produced by the discharges of the Z-ABS 100% infill density Liberators. These fragments have a different morphology than those produced by 70% and 90% infill density Liberators. However, they can still be classified in the same way as illustrated in Fig. 16. The smallest elements coming from the filling are flat rather than curved as observed with the other Liberators.

Discharge of PBF-printed Liberators produces fragments different from the previous ones, as illustrated in Fig. 17. The fragments show fine edges, and variable shapes and sizes. On the smallest fragments, no evidence of any additive manufacturing process is visible. It is possible to observe evidence of the manufacturing process used only if a sufficient portion of the outer surface of the piece is present on the fragment.

These small fragments could be the only items recovered in an investigation scene where a 3D-printed firearm was discharged. They can be used to distinguish between ME- and PBF-printed parts. Nevertheless, given that none of the VP-printed firearms were discharged, it is not possible to determine to what extent it would be possible to differentiate VP from PBF and ME printing based on small fragments. Regarding ME printing, small fragments allow to differentiate between non-100% and 100% infill density. The layer height can be measured on the relevant fragments, while the filling pattern can be inferred from the biggest fragments. Uncured PBF powder was collected on the gun rest after the discharge with the three PBF-printed Liberators. From an investigative point of view, unmelted powder can be found on the scene of investigation and could help to estimate the shooter's position. Similarly, analysing the characteristics of these residues could provide information about the type of printing process (PBF), the polymer and even the type of printer (i.e., brand and model). Residues could also be recovered on the shooter (clothes, bag, etc.) and on the location where the 3D-printed firearms were produced. Subsequently, the analysis of the unmelted powder could allow to establish a link between a PBF-printed firearm, a shooter, and a scene.

Lastly, a larger amount of unburnt and partially burnt flakes of smokeless powder was released in the environment during the discharge of all Liberators, compared to the amount released by a

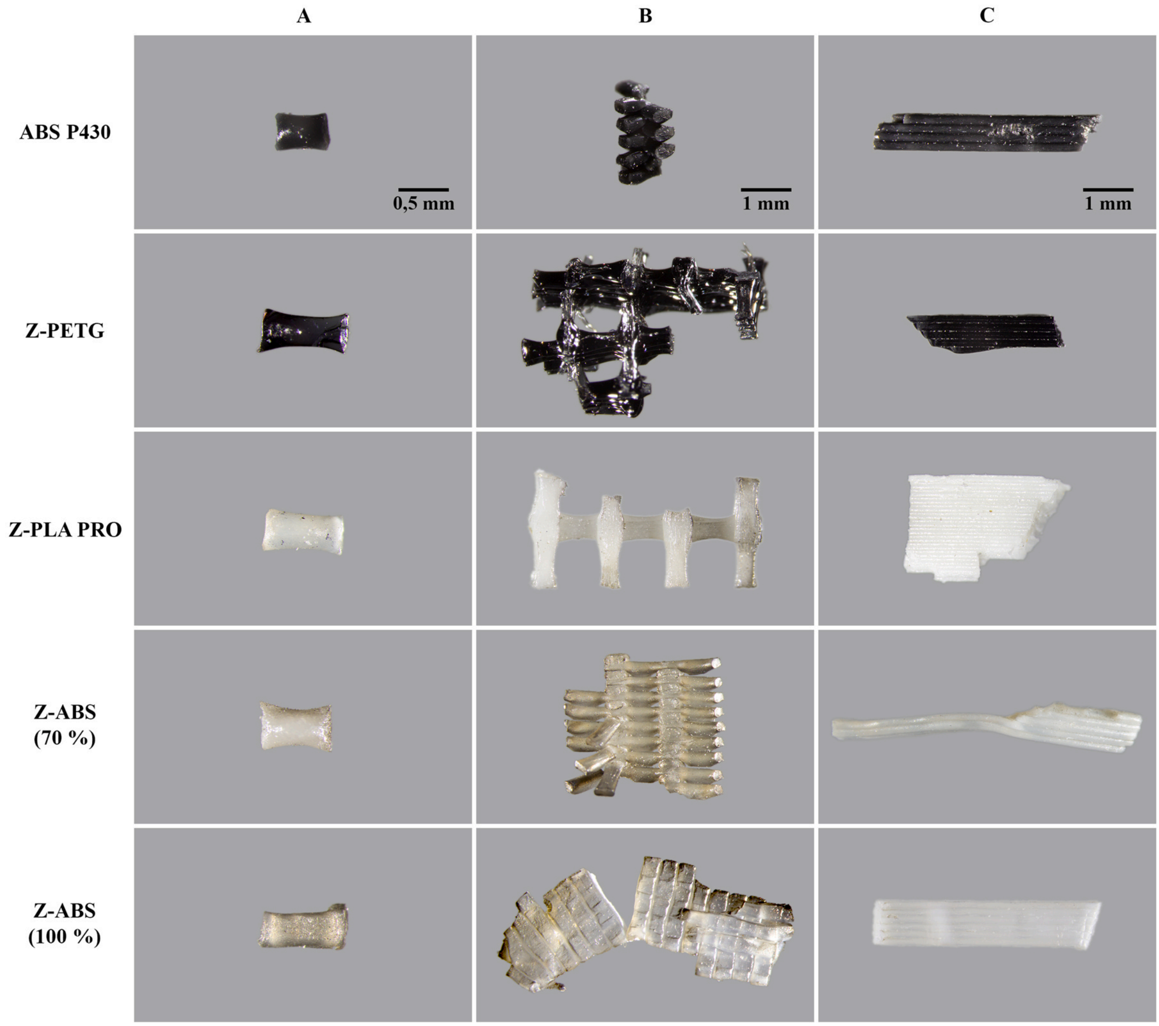

Fig. 16. Fragments recovered with adhesive sheets after the discharge of Liberators fabricated with an ME printer and different infill density. All images in each column share the same scale.

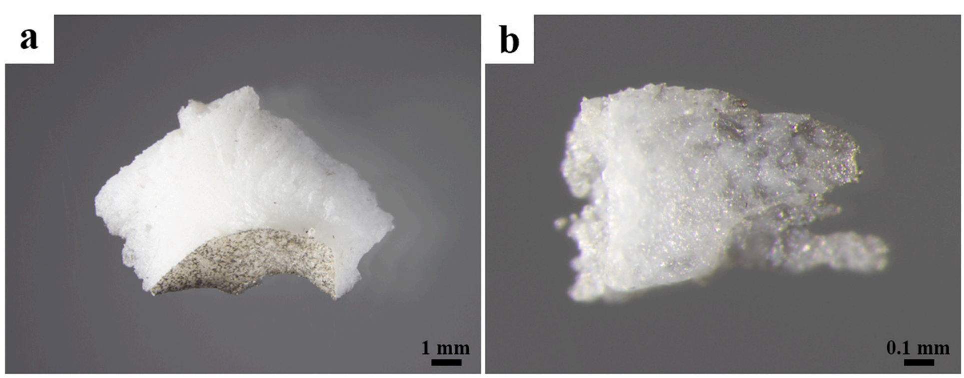

Fig. 17. Examples of fragments recovered with adhesive sheets after the discharge of Liberators fabricated with a PBF printer.

conventional firearm. It was subsequently very easy to characterise the initial morphology (shape, size, and colour) of the flake residues (black flattened balls). This can be explained by the incomplete and imperfect combustion reaction of the propellant powder following a very rapid explosion of the Liberators. Given the quality and quantity of powder flake residues on a scene where a 3D-printed firearm was discharged, these findings could support the determination of the brand and the model of the ammunition involved.

3.3.4. Elements of ammunition

As noted by Honsberger et al. [8], all the elements of ammunition fired with the Liberators of this study do not bear conventional

Table 2
Location and damages on the cartridge cases after the discharge.

Process	Polymer	Infill density [%]	Replicate	Location of the cartridge case	Damages on the cartridge case
ME	ABS P430	90	1–2	On the ground	Swollen
			3	Inside the barrel	Torn
	Z-ABS	70	1	On the ground	Torn
			2	On the ground	Swollen
			3	Inside the barrel	Swollen
		100	1–2	Inside the barrel	Swollen
			3	Inside the barrel	Torn
	Z-PETG	70	1–3	On the ground	Torn
	Z-PLA Pro	70	1–3	On the ground	Swollen
PBF	PA 2200	100	1–3	On the ground	Swollen

firearm marks (such as rifling traces, extractor or ejector marks) except the marks produced by the firing pin. Moreover, each element of ammunition presents polymer debris (flakes, melted polymer or both), in variable quantities.

On the projectiles, these melted polymer traces are present as grey smears and, under magnification, they appear as a thin polymer film that sometimes tend to detach, as illustrated in Fig. A7 of the appendix. A greater quantity of polymer traces was found on projectiles fired with Z-ABS and ABS P430 firearms (ME). PA 2200 melted polymer films tend to detach from the bullet more than the films of other polymers.

Luminescent polymer traces were observed on all projectiles. However, on bullets fired by Z-PETG and Z-PLA Pro Liberators, there were very few polymer deposits, and a rather weak luminescence, not visible to the naked eye on some projectiles. Photographic adjustments, such as a long exposure time and post-treatments provide good results when observing the luminescence. A 350 nm illumination with no observation filter is the best combination. Examples of fired projectiles in white light and under 350 nm illumination are provided in Fig. A8 of the appendix. No significant difference was observed between bullets fired from Z-ABS 70% and 100% infill density Liberators, except for a slightly higher transfer of polymer from the Z-ABS 100%. Although polymer is transferred on all projectiles during the discharge, the observed quantity transferred varies considerably. The resistance of the barrel during the discharge might influence the transfer. A barrel breaking as soon as the cartridge detonates is likely to transfer less polymer than a better resisting barrel. As described above, all barrels broke during the discharge, but the breaking was not uniform across all the pieces. If the barrel did not break at its base, it was possible for the cartridge case to remain stuck in it. In other firing experiments, the cartridge case was expelled. All cartridge cases were retrieved either swollen or torn. Locations of recovery and damages on the cartridge cases are summarised in Table 2. Cartridge cases discharged with Z-PETG Liberators suffered the most damage. All torn cases except two were expelled from the barrel. Hence, two cartridge cases were torn while the base of the barrel (constituting the chamber) was still around it. Several cartridge cases have not been torn even when the base of the barrel has been destroyed. This observation implies that the barrel did not fulfil its role of the chamber. Therefore, it seems that the

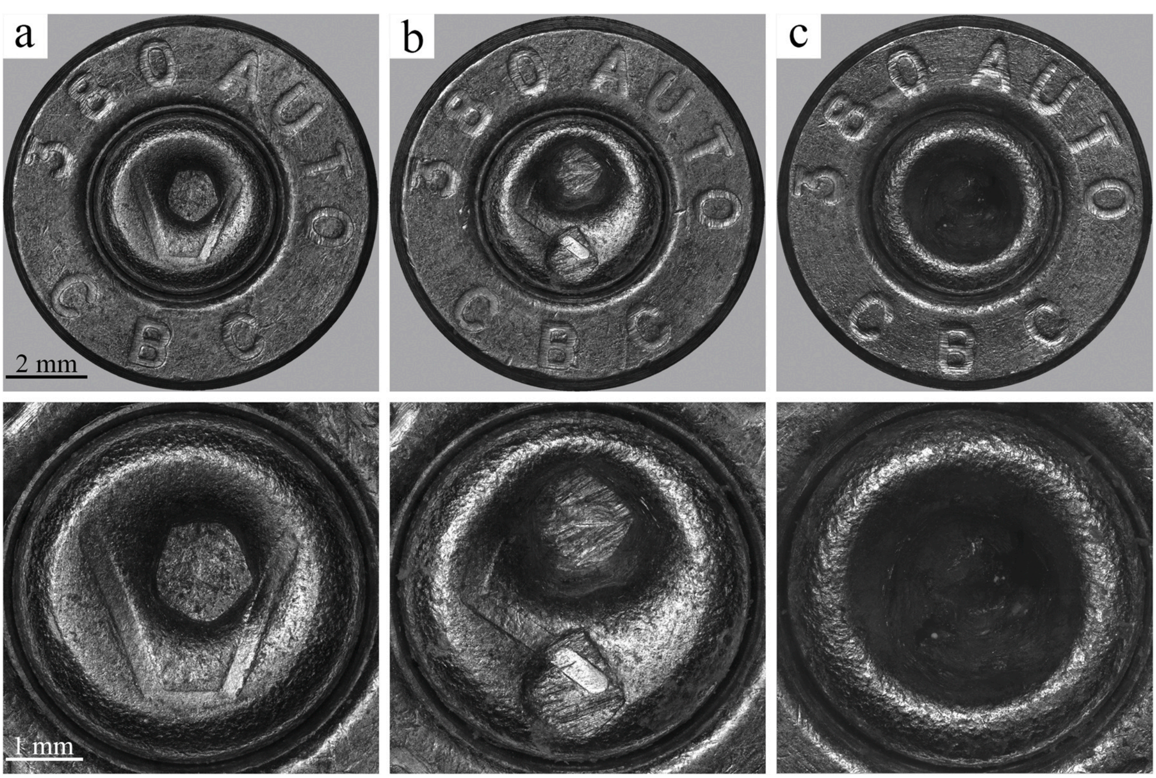

Fig. 18. Examples of firing pin marks made from a reworked nail and left on different primer caps scanned with the Evofinder® ballistics identification system (ScannBI Technology Ltd, version 6.5.1.54). Marks in the form of a pentagon (a and b) as well as pierced primers (c) were observed.

main parameter influencing whether a cartridge case is torn or just swollen is the ability of the barrel to resist enough so that the pressure in the case drops, but not enough to tear the cartridge case.

The amount of polymer deposition on the cartridge cases is less than that observed on the projectiles (see Fig. A9 of appendix). ABS P430, Z-ABS 70% and Z-ABS 100% Liberators transferred the most polymer on the cartridge cases. This larger quantity of polymer may be explained by the fact that the barrel of these Liberators has a better resistance during the discharge. The cartridge cases fired with the Z-ABS 100% Liberators even had to be removed from the barrel, increasing therefore the contact between the cartridge case and the polymer. Melted polymer and particles were observed with a stereomicroscope on most of the cartridge cases fired by ME-printed Liberators. In cartridge cases fired by PBF-printed Liberators, only a small number of white particles were observed. The cases fired by Z-ABS 100% infill density Liberators had to be hammered out of the barrel, rendering the observation of transferred polymer on these elements less relevant. Melted polymer on the cartridge cases shows some luminescence. However, the luminescence of melted Z-PLA Pro and Z-PETG is so weak that it can only be seen on photographs with long exposure time. No luminescence is observed on cartridge cases fired by PBF-printed Liberators. Polymer transfer on cartridge cases varies considerably, even between two replicates of the same firearm. Factors influencing the transfer onto cartridge cases could be the same as those influencing polymer transfer on the projectiles. The main parameter influencing the damages to the case seems to be the resistance of the barrel. Thus, a heavily torn cartridge case (like those fired with PETG Liberators) could indicate a rather non-resistant barrel.

Since the firing pins are made from a reworked nail, unusual marks may occur as shown in Fig. 18. In our case and after modification, the nails had a flat end in the shape of a pentagon. This same shape was also observed on the firing pin marks (Fig. 18a-b). In some cases, even partially pierced primer caps were observed (Fig. 18c). On closer inspection, it may be possible to use these marks in the context of a forensic identification case [13]. It must be added that this kind of mark is not specific to the use of a 3D-printed firearm, but rather a mark that can be observed in cases involving homemade firearms.

The absence of conventional firearm marks, an unusual firing pin mark and the presence of melted polymer or polymer particles on the elements of ammunition allow to infer that a homemade 3D-printed polymer firearm has been used. Polymer traces could then be collected for further chemical characterisation [12,15,19]. However, the sole observation of the elements of ammunition does not seem sufficient to obtain information on the polymer or on the printing process used.

4. Conclusion and perspectives

In this study, a total of 36 Liberators were 3D-printed using four different printers relying on three different printing processes and eleven different materials. The 3D printers used were a Stratasys Fortus 250 mc and a Zortrax M200, both ME-type desktop printers, a Formlabs Form 2, a VP desktop printer, and a EOSINT P 395, a PBF high-end industrial printer. Among all the printed Liberators, only those manufactured with ME and PBF processes could be fired, but no barrels were intact after the discharge. None of the 3D-printed firearms could be used more than once.

In general, there were more traces produced during the present firing experiments than previously reported in other projects [8]. This can be partially due to the inferior quality of the used printers (compared to the Stratasys Fortus 400 mc). Polymer pieces and fragments were projected in all directions, leading to an extension of the field of investigation, as suggested by [8], and thus to the possibility to find items in unusual places in the surroundings. Observation of intact polymer pieces or fragments allow to easily differentiate between elements printed with different processes and can also provide information about some of the printing parameters, such as layer height, filling pattern and infill density for ME-based printers. Such information can be used to determine if a given command file, slicer or 3D printer can be at the source of a questioned 3D-printed part.

Examining elements of ammunition provides information on the possible use of a homemade 3D-printed polymer firearm. Elements of ammunition, especially projectiles, often bear melted polymer or polymer particles transferred from the barrel in the same way as in the work of [8]. Since the observation of polymer traces found on elements of ammunition do not inform on the printing process, such traces could be submitted to more advanced techniques, including chemical analysis, to characterise the polymer and printing process used to print the firearm.

All the barrels have been destroyed during the discharge. Thus, it was not possible to observe traces produced by a Liberator which did not explode. Further study is necessary in order to address the variability between different printers of the same process. All the tested 3D printers work with a proprietary slicer and command file format, preventing the testing of different slicers, or open command files. Other 3D printers rely on G-CODE format text files that can be edited by using open-source slicers.

Since the publication of the blueprints of the Liberator in 2013, 3D printing processes have evolved, as have 3D-printed firearms designs. Today, there is an active online community in the field of craft-produced firearms. Some of these firearms are more advanced than the Liberator, especially hybrid firearms [5]. It is likely that such firearms will pose significant forensic challenges in the future, requiring further research on this topic.

CRediT authorship contribution statement

Théo Trincat: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Michel Saner:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Stefan Schaufelbühl:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Marie Gorka:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Damien Rhumorbarbe:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Alain Gallusser:** Conceptualization, Methodology, Validation, Investigation, Writing – Original Draft, Writing – review & editing, Supervision, Project administration. **Olivier Delémont:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Denis Werner:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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Appendix

Liberators after discharge

See Figs. A1–A6

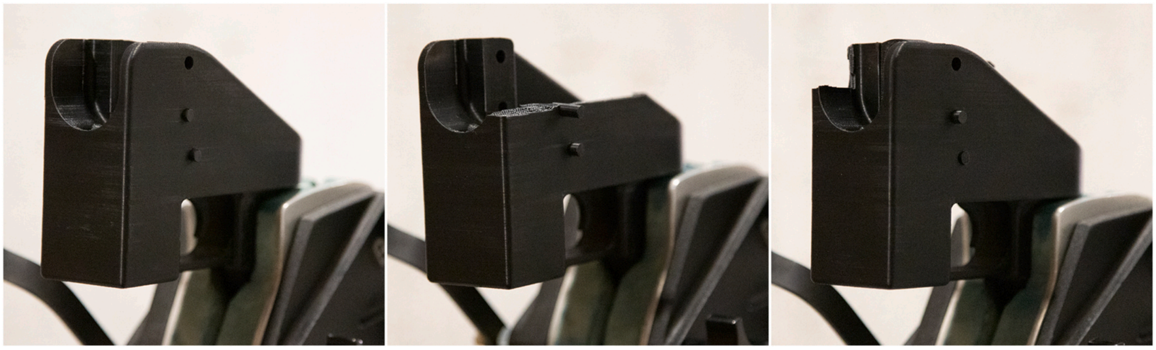

Fig. A1. ABS P430 Liberators printed with an infill density of 90% on the Fortus 250 mc (ME).

Fig. A2. Z-ABS Liberators printed with an infill density of 70% on the Zortrax M200 (ME).

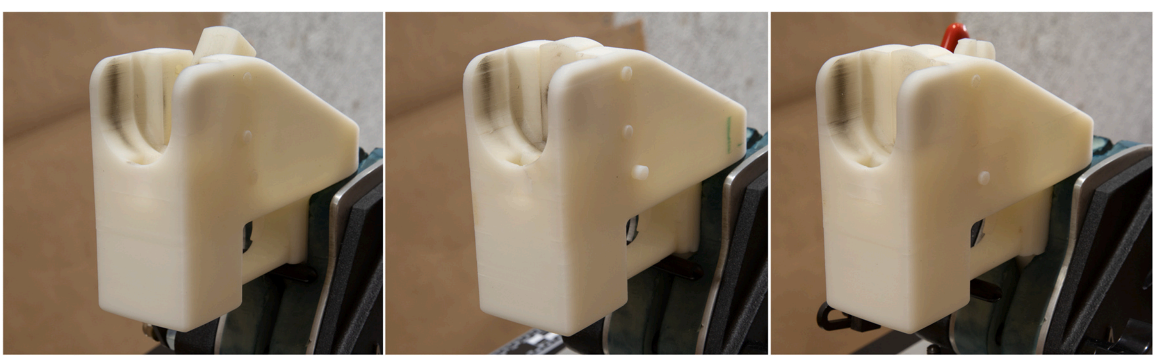

Fig. A3. Z-ABS Liberators printed with an infill density of 100% on the Zortrax M200 (ME).

Fig. A4. Z-PETG Liberators printed with an infill density of 70% on the Zortrax M200 (ME).

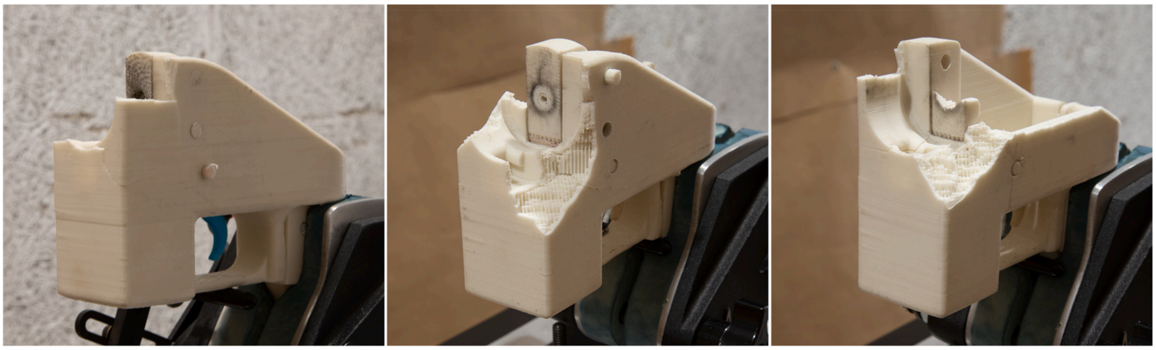

Fig. A5. Z-PLA Pro Liberators printed with an infill density of 70% on the Zortrax M200 (ME).

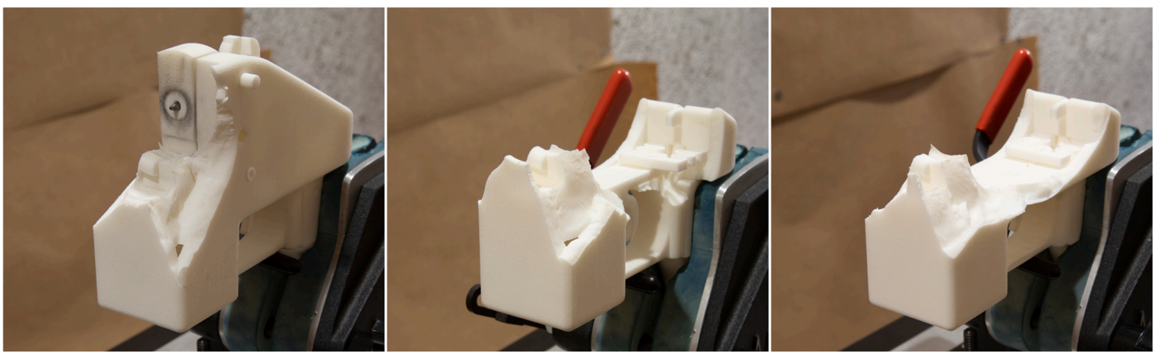

Fig. A6. PA 2200 Liberators printed with the EOSINT P 395 (PBF).

Polymer traces on elements of ammunition

See Figs. A7–A9

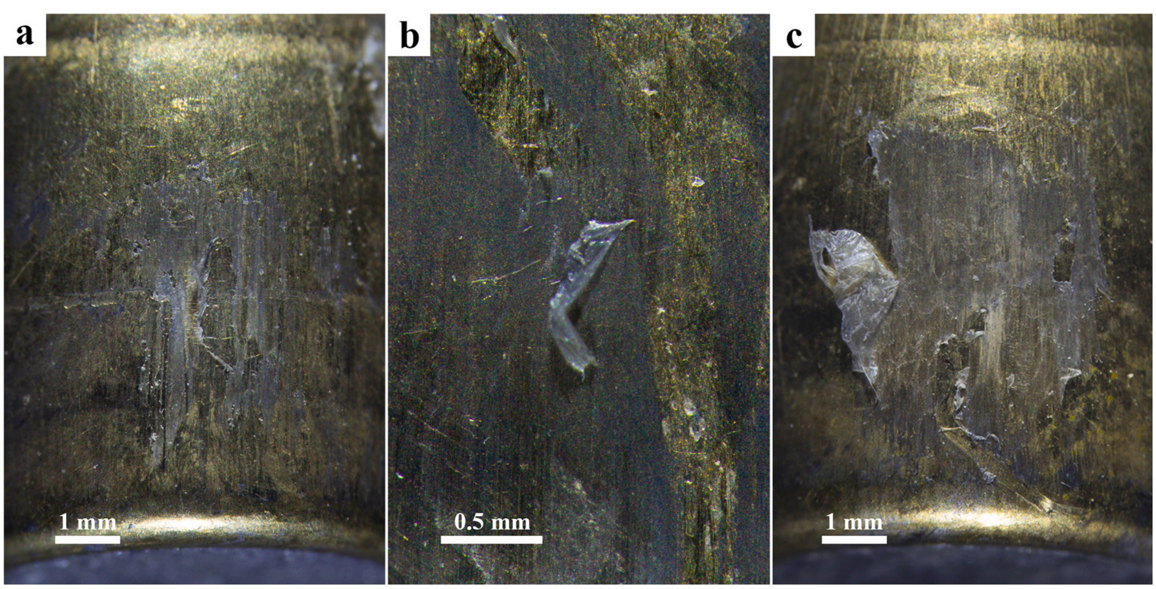

Fig. A7. Melted polymer deposits on the projectiles body from Z-PLA Pro (a), Z-ABS (b) and PA 2200 (c) barrels.

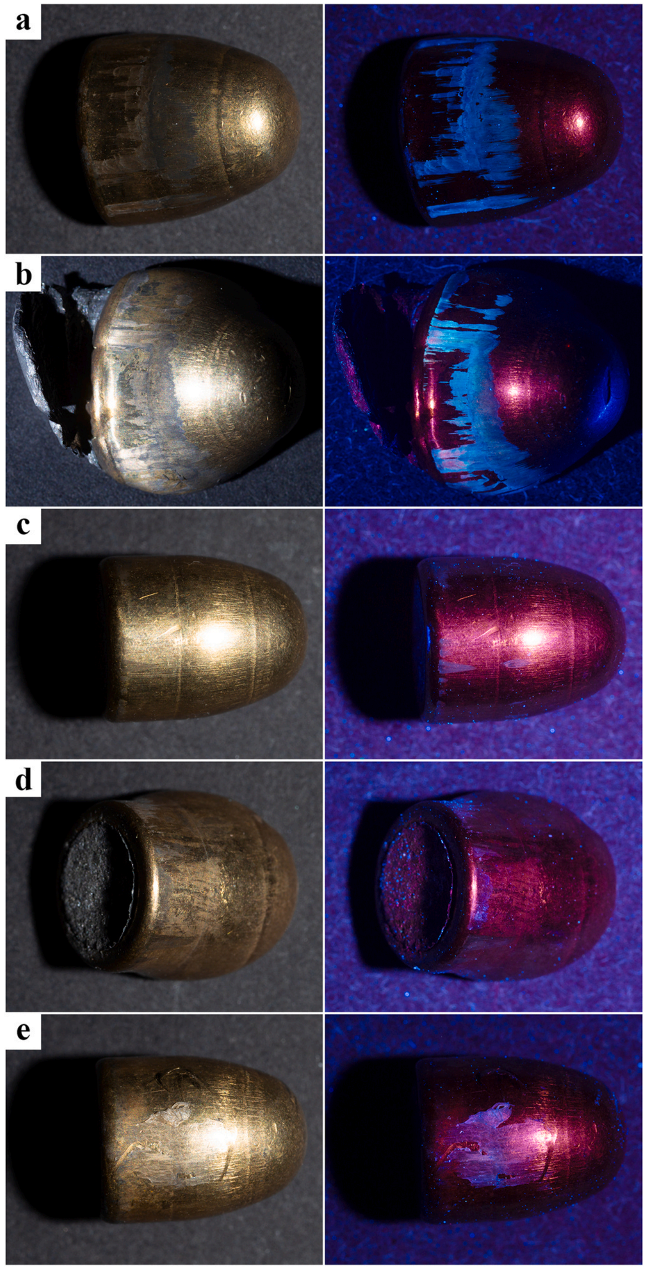

Fig. A8. Shot bullets under withe light (left) and under 350 nm light (right). These were fired from ABS P430 (a), Z-ABS with infill density 100% (b), Z-PETG (c), Z-PLA Pro (d) and PA 2200 (e) Liberators.

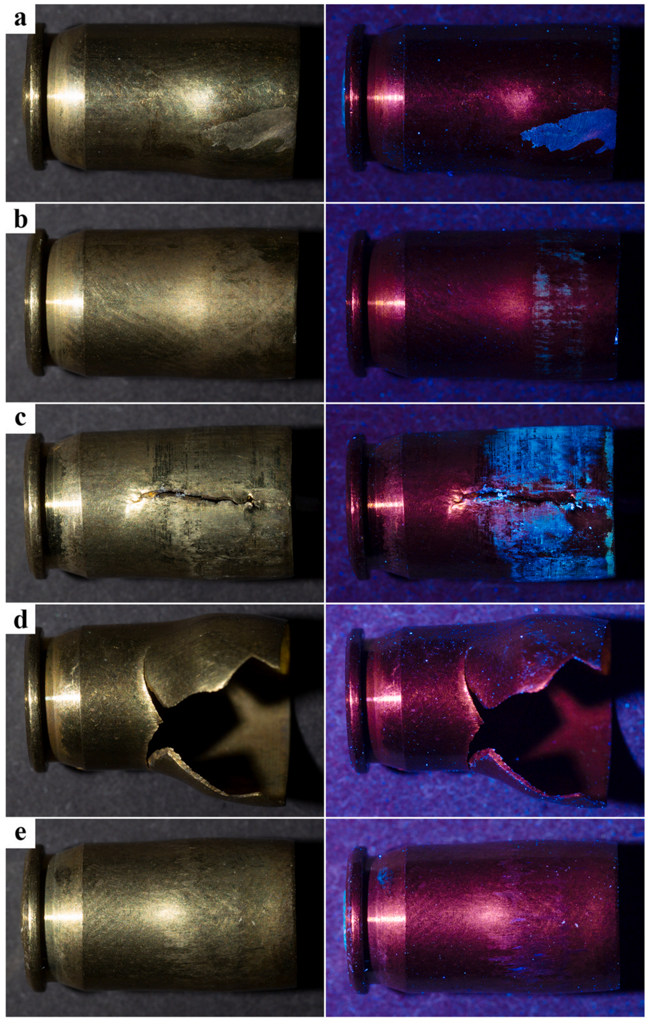

Fig. A9. Cartridge case bodies under withe light (left) and 350 nm light (right). These were fired from ABS P430 (a), Z-ABS with infill density 70% (b), Z-ABS with infill density 100% (c), Z- PETG (d) and Z-PLA Pro (e) Liberators.

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