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# 3D Printing in Military Applications: FDM Technology, Materials, and Implications

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## Abstract:

*The article describes the 3D printing technology using the Fused Deposition Modelling (FDM) method and the materials used in this technology in the context of military applications. The author presents the potential that this technology carries and discusses the use of 3D prints in the contemporary conflict in Ukraine. The article lists currently used materials and filaments, including a fiber technology that allows for printing of composites. Then the author presents a SWOT analysis of this technology in the context of national defense and its citizens who have 3D printers and can use them to produce so-called "war gadgets". The article contains many examples of the application of this technology in the defense sector and also discusses potential threats associated with it.*

## Keywords:

*military applications, war gadgets, AM, 3D printing, FDM*

## 1 Introduction

The first 3D printing was developed in the 80s and was initially used for prototyping and modelling. In recent years, with advancements in technology, 3D printing has become more accessible and available to a wide range of users, including individual users and small businesses [1]. Since its development by S. Scott Crump, FDM (Fused Deposition Modelling) has become the mostly used AM technology (Fig. 1). FDM is a type of 3D printing technology. According to the ASTM F42 (Additive Manufacturing Technologies), this process can also be called as Fused Filament Fabrication (FFF) or material extrusion additive manufacturing (AM). It works by heating and extruding thermoplastic filaments (plastic materials) which are then deposited layer by layer to build up a 3D object. The melted material is extruded through a small nozzle onto a build platform where it cools and solidifies. The process is repeated layer by layer

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until the entire object is built (Fig. 2). Finally, the model can be taken out from the print bed manually or chemically removing the support structure [2]. FDM technology is widely used due to its affordability and ease of use.

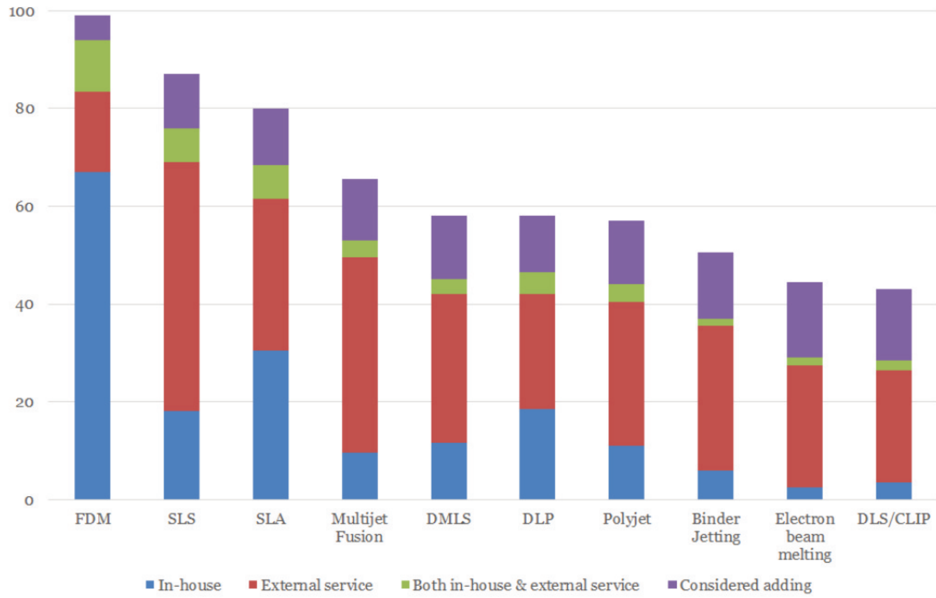

*Fig. 1 3D printing technologies used in 2020 divided by their usage* [3]

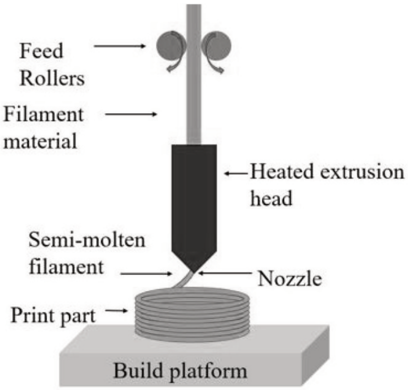

*Fig. 2 Common FDM printer scheme for polymers and short fiber reinforced composites (SFRC)*

The COVID-19 pandemic has likely led to disruptions in supply chains, changes in consumer behavior and demand, and shifts in priorities for many companies and governments. During the pandemic, the 3D printing community played a significant role in addressing the shortage of critical medical equipment, supplies and personal protective equipment (PPE). Below there are some examples of how 3D printers helped in modern conflict in the field of defense. 3D printing community rapidly responded to the shortage of face shields by producing them in large numbers. In some regions, there was a shortage of ventilators needed to treat critically ill patients, and 3D printing stepped in to help produce essential parts for the devices. Some 3D printing communities started producing nasal swabs, which are used to test for COVID-19, to help alleviate the shortage of these critical items. To reduce the spread of the virus, hands-free door openers to encourage people to avoid touching commonly used surfaces were produced.

Overall, the 3D printing community demonstrated its versatility and responsiveness during the pandemic by providing solutions to the pressing problems faced by society in these challenging times. Many organizations and projects appeared, such as project DIAMOnD (Distributed Injection Molded Additive Manufacturing for Directed Operations and Deployment), which is a U.S. based network of over 300 desktop 3D printers. The project aims to utilize the capabilities of desktop 3D printing to create a distributed manufacturing network that can support directed operations and deployments. The network leverages the advantages of 3D printing, such as speed, versatility, and cost-effectiveness, to provide on demand production of parts and components for military and other critical applications. The project is still ongoing and its specific applications in the context of the conflict between Russia and Ukraine are not publicly available.

In a war situation, the choice of production technology would depend on the specific needs and requirements of the products being manufactured. Factors such as time constraints, cost, material availability, and product durability would all need to be taken into consideration.

Both standard production technologies and additive manufacturing have their own advantages and disadvantages, and the choice between the two would depend on the specific needs of the situation [4].

For example, traditional manufacturing methods may be faster and more cost-effective for producing large quantities of a single item, while additive manufacturing might be better suited for producing complex or custom parts quickly and with a lower lead time. On the other hand, traditional manufacturing might be better for producing products with higher durability and long-term reliability, while additive manufacturing might be better for producing products with unique or specialized features. In the end, the choice of technology would depend on a thorough evaluation of the specific needs and requirements of the situation and the products being manufactured.

## 2 Raw Materials

Common materials used in FDM 3D printing include ABS (Acrylonitrile Butadiene Styrene), PLA (Polylactic Acid), PET (Polyethylene Terephthalate), Nylon. Tab. 1 illustrates main physical, and thermo-mechanical properties of the used materials.

### *2.1 ABS*

ABS is a popular choice for toy and household item manufacturing due to its relatively low harmful effects on humans compared to other polymer materials. However, ABS should not be used for medical implants because its chemical structure contains styrene, which lasts longer in the human body [7]. ABS is commonly used for testing samples due to its superior resistance to heat, chemicals, and moisture. FDM printing can result in more void regions within the final parts due to the absence of pressure during the printing process. This issue can be minimized by using a smaller layer thickness, which improves the bond between layers and reduces interlayer distortion that causes micro voids. To improve the strength of printed ABS parts, process parameters such as infill density, orientation, layer thickness, airgaps, raster angle, and width should be considered. Additionally, nozzle diameter has a significant impact on part strength, as increasing the nozzle diameter enhances the strength between layers by reducing voids, resulting in higher tensile strength [8].

*Tab. 1 Physical and thermo-mechanical properties of materials used in FDM method* [5, 6]

| **Material** | **Density [g/cm$^3$]** | **Glass-transition temp. [°C]** | **Melting temp. [°C]** | **Tensile strength [MPa]** | **Modulus of elasticity [GPa]** | **Flexural strength [MPa]** |
|---|---|---|---|---|---|---|
| **ABS** | 0.850-0.950 | 105 | 200 | 45.00 | 2.300 | 75.00 |
| **Nylon** | 1.110 | 46 | 215 | 4.22-16.88 | 2-4 | 274.27-773.59 |
| **PET** | 1.370-1.450 | 75 | 255 | 17.70 | 0.971 | 80.00 |
| **PLA** | 1.252 | 45-60 | 150-162 | 59.00 | 1.280 | 106 |
| **PEEK** | 1.300-1.320 | 142-198 | 322-346 | 70.3-103 | 3.760-3.950 | 105-116 |

### *2.2 Nylon*

In comparison to ABS and PLA, Nylon demonstrates superior chemical resistance, as well as higher tensile strength and Young's modulus. FDM printed Nylon parts possess high tensile and impact strength, good resilience, and low creep, making them advantageous [5]. Moreover, Nylon achieves better mechanical properties at elevated temperatures, as the bonds between layers become much stronger when exposed to higher temperatures. However, Nylon is a hydrophilic material, and its mechanical properties are negatively affected by moisture absorbency. Unfortunately, studies exploring the mechanical properties and effects of various parameters on Nylon are limited compared to ABS and PLA [9]. As with ABS and PLA, reducing the layer thickness of printed parts enhances the tensile strength, as the bond between layers is stronger. The mostly used Nylon material in the 3D printing industry is Polyamide 12 (PA 12). Nylon's crystallinity is the primary reason for achieving better functional properties such as printed part shrinkage, chemical, wear, and thermal resistance. As a result of these benefits, nylon is widely employed in the manufacturing of home appliances and white goods, as well as in aerospace and automotive engineering applications [10].

### *2.3 PLA*

When comparing ABS with PLA, it is apparent that ABS has better impact strength while PLA has higher tensile strength. PLA is capable of degrading under proper conditions, while other polymers are typically disposed of or recycled [5]. Furthermore, parts made from PLA retain their plasticity and toughness for extended periods. Similar to ABS FDM, many studies have been conducted to identify the optimal conditions to achieve better mechanical properties for PLA. It has been found that tensile strength is primarily influenced by the raster angle, followed by the raster width and layer height. Increasing the layer height of the print typically produces many voids in the microstructure, which decreases the tensile strength of the printed part. When the raster angle is set to 0°, the tensile load is mostly supported by the PLA filament aligned in the longitudinal direction, whereas at 90°, the load is carried by the bond between layers. As a result, failure occurs due to delamination and fracture of the layers in 90° rasters, while in the 0° orientation, failure is caused by filament fracture [11].

### *2.4 PEEK*

Aside from the aforementioned polymers, the 3D printing industry also utilizes a group of high performance or engineering polymers. PEEK, which falls under the PAEK (polyaryletherketone) category, is a widely used colorless, semicrystalline, organic thermoplastic polymer in the engineering field for creating excellent quality aircraft, rocket, racing car, and drone parts. Despite its remarkable properties, only a few experiments have been conducted to determine the effects of print orientation, nozzle diameter, printing speed, extrusion speed, nozzle temperature, and infill density on the mechanical properties of PEEK [12]. Due to the inherent qualities of PEEK, it has found a prominent role in medical applications requiring better reliability such as bone tissue engineering, orthopedic implants, joint replacements, spinal implants, prosthesis systems, and dentistry [13].

## 3 Composite Materials

A composite material is formed by combining different materials to create a material with superior functional properties. The main objective of developing composite materials in the 3D printing industry is to obtain better mechanical properties and other functional characteristics such as optical, thermal, and electrical properties that cannot be achieved by pure polymers [14]. In a composite, one or more materials act as the reinforcing component, while another material serves as the binding or matrix material. FDM printed composites can use various reinforcing materials to achieve the required functional property, or a combination of properties from the same composite. Depending on the specific needs, particles, fibers, or nanomaterials can be added to the polymer to print a polymer matrix composite (PMC). The mostly used PMCs are micro or nanoparticle reinforced composites, metal particle reinforced composites, and short or continuous fiber reinforced composites. By incorporating metal particles such as iron, copper, stainless steel, or titanium, or nanoparticles like carbon nanotubes, graphene or graphite into the polymer, a high-performance composite material with embedded thermal, electrical, optical, and excellent mechanical properties can be produced. Glass fibers are the mostly used fibers in reinforcing polymers due to their cost effectiveness. They find wide applications in various industries such as defense, aerospace, and automotive sectors. Appropriate alignment of continuous glass fibers offers steel-like properties with a specific weight that is almost 75 % less than aluminum. Unlike carbon fibers, glass fibers are not inherently strong and can be easily damaged when used separately. However, when used with thermoplastics or thermoset materials, they complement each other and provide excellent mechanical properties [15].

Stephanie Kwolek invented a synthetic fiber called aramid fiber with exceptional tensile strength to weight ratio and heat resistance in 1965. This fiber is commonly known as DuPont Kevlar, and its tensile properties are primarily in the longitudinal direction, which requires careful fiber orientation management in products or composites. When executed correctly, its tensile strength to weight ratio is five times better than steel. While it was initially used in the military and aerospace fields, it is now applied in various products and is available on the consumer market. The price of aramid fibers varies depending on the diameter of a single thread. The price is relatively high for discontinuous fibers, and it increases for continuous variants, where fibers are twisted, and the turn per inch influences the physical characteristics and price. To make aramid fibers compatible with the matrix for usage in FDM, they are coated with a bonding agent.

The use of FDM printed composites has become widespread in various industries such as aerospace, automotive, marine, sports equipment, electrical, and medical industries. Prominent agencies in the aerospace industry such as NASA employ FDM for manufacturing tools, functional prototypes, concept models, and lightweight parts. In the automotive industry, FDM is mainly utilized for printing jigs, fixtures, and prototypes for testing purposes. While the biocompatibility of FDM printed composite parts is still under investigation in the medical industry, experiments have been carried out to incorporate these composites in the production of orthopedic and dental implants. The mostly used reinforcement material in PMC is short or continuous fiber reinforcements, which offer a high strength to weight ratio, rigidity, and corrosion resistance [16].

### *3.1 Short Fibers*

For many years, polymers have gained popularity due to their lightweight and ease of processing, but their material strength is lower compared to steel and aluminium, which are their competitors. A summary of fiber properties can be found in [17]. However, polymer fiber composites have shown outstanding behavior in enhancing mechanical properties and providing solutions to many of today's problems.

By introducing discontinuous (chopped) fibers and later continuous fibers to polymers, anisotropic material behavior can be achieved, and even stronger anisotropic behavior can be attained when combined with FDM technology. Several developments have been made to reinforce polymers in research institutes and industrial researches. The main types of fibers used to reinforce polymers are Carbon, Glass, and Aramid. Carbon fibers consist of filaments made of at least 92 % carbon, typically in a non-graphitic state, which are combined into tows of several thousands of strings with a diameter of 5-8 micrometers, measured in K number, such as 1K, 1.5K, and 2K. Carbon fibers have gained popularity in various industries due to their impressive mechanical properties, including high tensile strength and low thermal expansion. In fact, Carbon Fiber Reinforced Composites offer similar features to steel but are much lighter, making them an attractive choice for applications in aviation, automotive, and marine industries.

### *3.2 Continuous Fibers*

Continuous fiber reinforcement has become a recent possibility in FDM, expanding the range of applications for rapid prototyping. Polymers can be reinforced with fibers in various ways, including the discontinuous/dual (see Fig. 3A) and continuous (see Fig. 3B) placement of fibers. The mechanical properties of printed parts with discontinuous fiber reinforcement are significantly influenced by the fiber length. Conversely, parts reinforced with a bulk of continuous fibers typically exhibit more significant improvements than their discontinuous equivalents [18]. With co-extrusion, a thermoplastic resin filament and a fiber filament are supplied separately to the FDM printer head. The thermoplastic filament is melted inside a heated nozzle, and as the reinforcing fiber passes through the nozzle, it gets impregnated by the resin. The extruded filament is then deposited onto the printing platform, attaches to the previous layer, and solidifies. In the dual extrusion approach, the reinforcing fiber filament and the thermoplastic resin filament are extruded separately through two nozzles onto the printing plate.

The mechanical properties of printed parts with discontinuous fiber reinforcement are significantly influenced by the fiber length. Conversely, parts reinforced with a bulk of continuous fibers typically exhibit more significant improvements than their discontinuous counterparts [19].

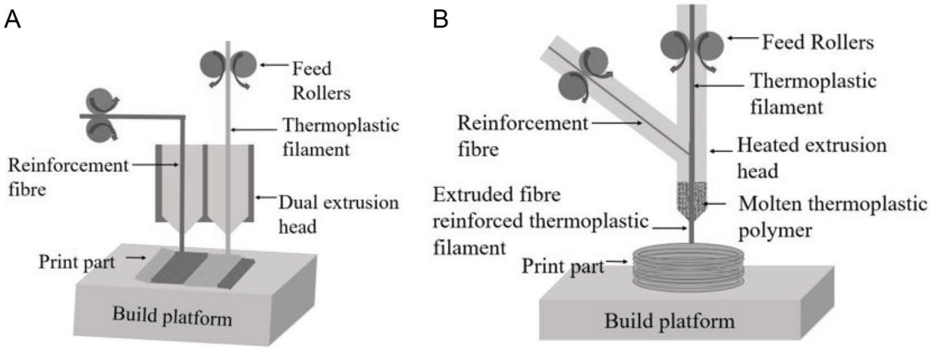

*Fig. 3 Schematic diagrams of: A - dual extrusion, B - continuous extrusion techniques*

## 4 3D Prints in the Modern Conflict

However, the use of 3D printing technology in military and defense applications has been growing in recent years. Starting from design and production of functional prototypes using FDM technology for use in military equipment and systems, 3D printing is able to create composite materials with improved mechanical properties for use in military applications, such as protective armor and structural components [20].

Additionally, 3D printing can allow for the producing complex, custom made parts and components that may be difficult to produce using traditional manufacturing methods. Some specific examples of the use of 3D printing in military and defense applications include the production of prosthetics for wounded soldiers, the manufacture of customized weapon components, and the development of prototypes for new military technologies.

### *4.1 Customized Weapon Components*

The company PJSC Mayak has developed a conversion kit that can be 3D-printed for the former Soviet Union RKG-3 grenade. This kit involves the removal of the handle and parachute of the grenade, and instead, fitting it with a tail cone and stabilizing fins that can be printed using a 3D printer (Fig. 4).

The 3D printed tail fins on the RKG 1600 have drastically improved its accuracy, allowing drones to drop them into a one-meter circle from 300 m up [21]. This makes hitting a tank much easier than before when using the inaccurate RKG-3, which required a dangerously close proximity to the target.

RKG 1600 serves as a prime example of how 3D printing technology can rejuvenate old materials. It also highlights the adaptability and responsiveness of this new form of manufacturing. Ukraine army simply distributed the print files to companies or volunteers with 3D printers. The conversion kit can even be printed on an affordable Ender 3 printer.

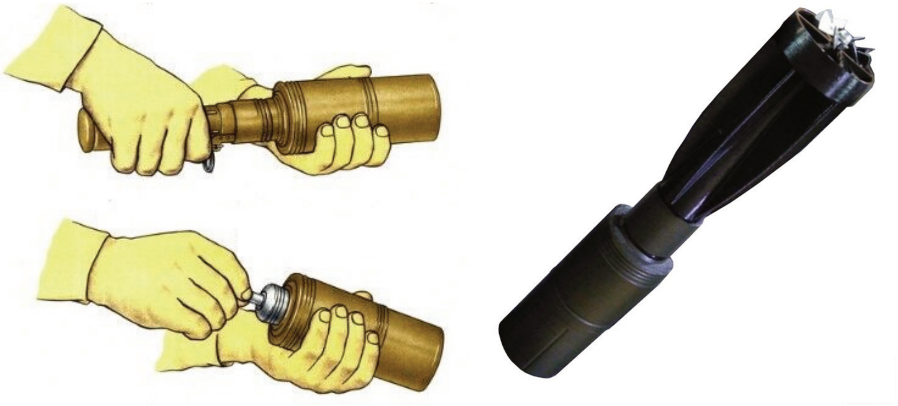

*Fig. 4 On the left view from ex-soviet RKG-3 grenade manual and on the right RKG-1600 with 3D-printed tail cone and stabilizing fins* [21]

Ukrainian forces have been utilizing various commercial drones for surveillance and reconnaissance, and have recently begun equipping them with converted grenades, now known as the RKG 1600.

Armed military drones are typically expensive, such as the MQ-9 Reaper which costs roughly $32 million and can carry a 1.7 ton of weapons [22] In contrast, an off-the-shelf octocopter capable of lifting 2.5 kg costs less than $2,500 and can carry a pair of RKG 1600 mini bombs. On popular 3D printing community sites, there are ready STL parts of different drone types (Fig. 5) that are used in Ukrainian conflict.

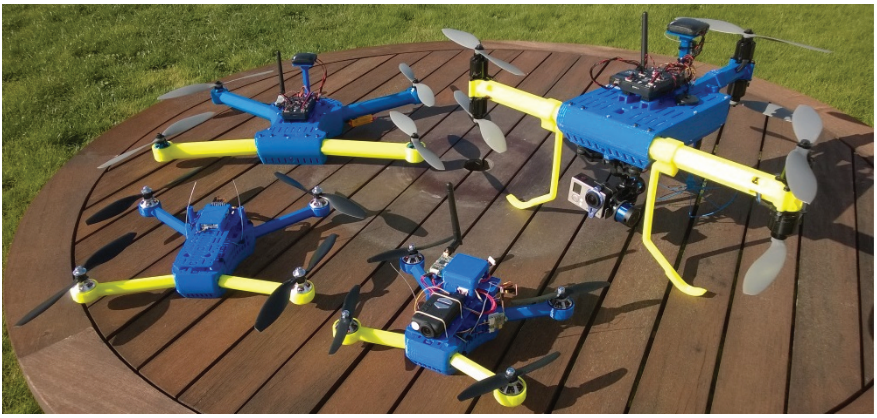

*Fig. 5 3D printed drones from STL files from 3D community site* [23]

3D Tech Additive is a company that designs and manufactures a variety of equipment enhancements for weapons, such as holsters for AK-47s to enable soldiers to secure their firearms, bullet magazines to repurpose spent cartridges, grenade bags for transport, and antiglare lenses for sniper scopes, the latest addition to their product line. The antireflective lenses reduce the likelihood of Ukrainian snipers being spotted by the enemy.

### *4.2 Medical Resources*

3D printing can also be used in the defense industry to produce prosthetics, orthopedic devices, and other medical equipment that are required for soldiers and other military personnel. In 2010, during the devastating earthquake in Haiti, medical devices were printed quickly, allowing doctors to provide health care without waiting for equipment to ship from abroad. In 2018, an organization called the Glia Project came to the aid of Palestinian civilians injured in the Gaza Strip while protesting against Israel, creating and shipping them a 3D printed "Gaza tourniquet".

The intensity of the conflict in Ukraine resulted in numerous casualties and a depletion of essential medical resources. Members of the 3D printing community engaged in discussions with Ukrainian military authorities, hospital managers, and charitable groups to determine the most beneficial items they could produce rapidly. The mostly requested items were bandages and tourniquets (Fig. 6).

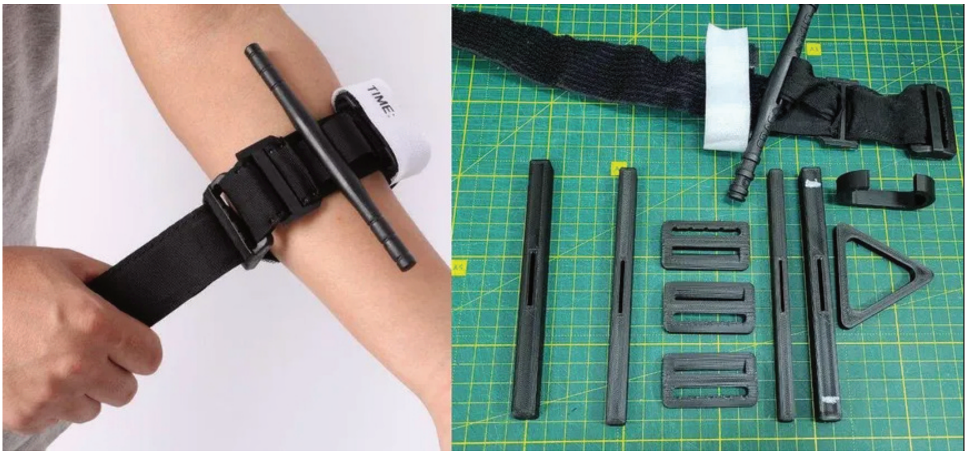

*Fig. 6 FDM printed tourniquet (material: nylon, PC Blend, PETG)* [24]

Although the majority of 3D printers produce items that help prevent fatalities or alleviate the harsh conditions of warfare, some are concentrating on the rehabilitation of soldiers. Brett Carey, a physical therapist based in Hawaii, creates 3D printed splints (Fig. 7B) that can be sent to combatants. Hand fractures are prevalent in combat, and when they are not treated correctly, they can result in long term problems. If the injuries are severe, Carey has people use EM3D, a 3D imaging application, to submit images of their injuries. This allows him to create a personalized splint that can be shipped to Ukraine.

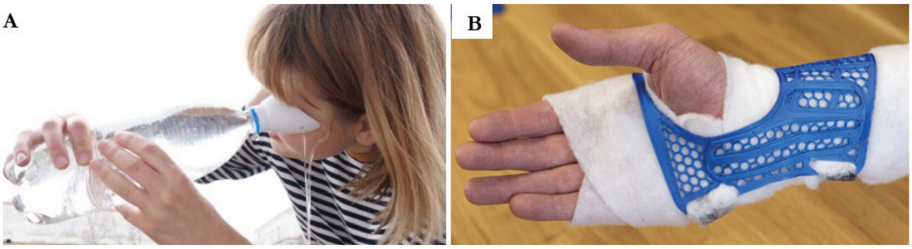

*Fig. 7 A -3d printed eyewash* [25], *B - 3D printed wrist splint* [26]

## 5 SWOT Analysis

In this part, the author uses SWOT analysis which is a strategic planning tool that is used to identify and analyze the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of an organization or project. The objective of a SWOT analysis is to help organizations or projects to understand their internal and external environment, to identify their strengths and weaknesses, and to identify potential opportunities and threats. This information can then be used to develop a strategic plan to achieve their goals and objectives. The SWOT analysis can be applied to a wide range of organizations and projects, including businesses, non-profit organizations, and government agencies [27].

To conduct this SWOT analysis, a group of 50 university technology students with a background or interest in FDM technology was chosen to contribute. Participants were provided with relevant materials and resources about FDM technology and its potential in military applications in advance.

Introduction and Context Setting: The brainstorming session was conducted in a structured manner. Firstly, an overview of FDM technology and its relevance in military applications was provided. The purpose of the SWOT analysis and the importance of their insights were explained. For idea generation participants were encouraged to share their thoughts on the strengths, weaknesses, opportunities, and threats associated with FDM technology in the military sector. Facilitators encouraged open and free discussion, ensuring that all participants had the chance to contribute. Ideas were categorized into the four SWOT components.

Facilitators and participants engaged in a discussion to evaluate and elaborate on the generated ideas. Similar ideas were consolidated, and unique insights were highlighted. Participants were given the opportunity to prioritize the most critical and relevant SWOT elements using a voting system. The elements with the highest votes were identified as the most significant.

The analysis was later compiled into a report whose components and their elements are presented in the Tab. 2.

### *5.1 Strengths*

3D printing technology offers quick and efficient production of complex parts and prototypes, reducing production times and costs. Moreover, flexibility to produce a wide range of parts and components in a short amount of time, enables rapid prototyping and production of essential components for defense operations.

3D printing also offers the potential for decentralized production, making it possible for defense forces to produce parts and components in the field without relying on supply chains. Printers can be put into the container with the electricity aggregator and go close to the front lines to create the most needed parts.

### *5.2 Weaknesses*

FDM is still in its early stages of development, and many challenges remain to be addressed, such as material quality, precision, and consistency. The technology also faces competition from traditional manufacturing methods, which may be more established and cost effective in many cases. 3D printing may also pose a security risk if the technology is used to produce counterfeit or malicious parts.

*Tab. 2 SWOT analysis of FDM technology potential in war conflict*

| **Strengths** |
|---|
| Wide availability and affordability of FDM printers, allowing many owners to participate in the project. |
| FDM printing technology can produce a variety of parts quickly and with a high degree of accuracy. |
| The involvement of FDM printing owners in defense operations can provide valuable support to the country. |
| **Weaknesses** |
| FDM printing technology may not produce parts with the same level of strength and durability as those produced using more advanced technologies. |
| The quality of the parts produced by individual FDM printing owners may vary, potentially leading to inconsistencies in the final product. |
| There may be a lack of standardized processes and quality control measures for the project, leading to further inconsistencies and potential for mistakes. |
| **Opportunities** |
| The project provides FDM printing owners with an opportunity to contribute to their country in a meaningful way. |
| The project can lead to the development of new, more advanced FDM printing technologies and processes. |
| The success of the project can increase the recognition and appreciation of FDM printing technology and its capabilities. |
| **Threats** |
| There may be resistance from traditional defense contractors and manufacturers to the involvement of FDM printing owners in the project. |
| Competition from other 3D printing technologies may lead to the loss of support and investment in the FDM printing aspect of the project. |
| The project may not receive adequate funding and support from the government, leading to limitations in its scope and impact. |

### *5.3 Opportunities*

On the other hand, 3D printing technology offers the potential to revolutionize the defense industry by enabling new ways of producing parts and components. It can be used to support a wide range of defense operations, including disaster relief, special operations, and peacekeeping missions. There are new opportunities for innovation and collaboration between the defense and commercial sectors.

### *5.4 Threats*

The technology may be vulnerable to cyberattacks, which could result in the production of faulty or malicious parts. The potential for large scale production of counterfeit parts may pose a threat to the defense industry, and it is important to ensure that the technology is used responsibly and ethically. 3D printing with plastic materials can be used to produce prototypes and small batches of items such as magazines, shields, and accessories, but it is not recommended for producing items that are exposed to high temperatures and loads.

Unfortunately, this availability of 3D printing technology has also enabled some users to produce firearms without control and oversight. As a result, many countries have taken steps to limit the illegal production of firearms using 3D printing and increase citizen safety. In many countries, it is illegal to print firearms, and penalties for doing so can be severe.

The widespread use of 3D printing technology in the defense industry may also lead to job losses as traditional manufacturing methods become less necessary.

The SWOT analysis underscores the potential of FDM technology in war conflicts, emphasizing its accessibility, versatility, and citizen engagement as strengths. Nevertheless, the analysis also underscores the need for quality control and standardization to address weaknesses. FDM technology presents an opportunity for civilians to actively participate in defense projects, spurring technological advancements. However, resistance from traditional defines stakeholders, competition from alternative technologies, and limited government support are tangible threats. To maximize FDM technology's potential, mitigating weaknesses and addressing threats is imperative.

## 6 Pairwise Comparison

Pairwise comparison is a method used to compare and evaluate the relative importance or priority of multiple options, items, or criteria. In this method, each option is compared to every other option in a systematic manner and the results are used to rank the options based on their relative strengths and weaknesses. Pairwise comparison is commonly used in decision making processes, such as product selection, prioritization of tasks, and project management. The method helps to make objective, data driven decisions by taking into account multiple factors and reducing subjectivity [28].

The basic equation for pairwise comparison in a Multi-Criteria Decision Analysis (MCDA) can be represented using the following formula

$$A_{ij} = \frac{P_i}{P_j} \tag{1}$$

where $A_{ij}$ – represents the score or ratio of the preference of option $i$ over option $j$, $P_i$ – is the performance or value of option $i$, $P_j$ – is the performance or value of option $j$.

This equation is used to express the relative preference of one option over another based on their performance or value for a specific criterion. The value of $A_{ij}$ can be interpreted as how many times option $i$ is preferred over option $j$. If $A_{ij}$ is greater than 1, it implies that option $i$ is preferred over option $j$. If it is less than 1, it implies that option $j$ is preferred over option $i$.

$$\text{Weighted Score for an Option} = \sum_{i=1}^{n} \left( W_i \times C_i \right) \tag{2}$$

Weighted Score for an Option is the overall score for the option being evaluated, $W_i$ – represents the weight assigned to the $i$-th criterion, the weights represent the relative importance or priority of each criterion, $C_i$ – represents the performance, value, or rating of the option with respect to the $i$-th criterion, $n$ is the total number of criteria being considered in the decision-making process.

This formula allows you to compute a weighted score by multiplying each criterion's weight by the option's performance with respect to that criterion and then summing up the results. The resulting weighted score provides a quantitative measure of how well the option meets the specified criteria while taking into account the importance of each criterion in the decision-making process.

There are several options that can be used for making a pairwise comparison between additive manufacturing (3D printing) and traditional production technologies. Here are some of the common criteria that are used:

- speed of production – how quickly can the products be manufactured using each technology,
- cost-effectiveness – the cost of producing the products using each technology,
- design flexibility – how much freedom is there in terms of design options and customization,
- materials options – the variety of materials available for use in each technology,
- precision and accuracy – how precise and accurate the final product is,
- surface finish quality – the level of surface finish quality that can be achieved,
- scalability – how easy is it to scale up or down production as needed,
- energy efficiency – how energy-efficient is each technology,
- waste generation – how much waste is generated during the production process,
- environmental impact – the impact on the environment from each technology.

These are just some of the options that can be used to make a pairwise comparison between additive manufacturing and traditional production technologies. The specific criteria selected will depend on the context and the goals of the comparison.

To compare the injection molding process and FDM technology for defense applications during a war, we will use example criteria: Speed of Production (SP), Cost-Effectiveness (CE), Design Flexibility (DF), Materials Options (MO), and Precision and Accuracy (PA). The next step is to assign scores to each technology for each criterion on a scale from 1 to 5, with 1 being poor and 5 being excellent (Tab. 3).

Now, we assign weights to each criterion based on their relative importance, based on the priorities of defense applications during a war. For example, for low volume production: SP (W_SP) = 0.3, CE (W_CE) = 0.2, DF (W_DF) = 0.2, MO (W_MO) = 0.1, PA (W_PA) = 0.2

Weighted Score for molding process = (W_SP * SP_Mol) + (W_CE * CE_Mol) + (W_DF * DF_Mol) + (W_MO * MO_Mol) + (W_PA * PA_Mol) = 2.8

Weighted Score for FDM Technology = (W_SP * SP_FDM) + (W_CE * CE_FDM) + (W_DF * DF_FDM) + (W_MO * MO_FDM) + (W_PA * PA_FDM) = 3.5

*Tab. 3 Multi-Criteria Decision Analysis matrix for pairwise comparison*

| Criteria | SP | CE | DF | MO | PA |
|---|---|---|---|---|---|
| Injection molding | 2 (slower setup for low volumes) | 2 (expensive molds) | 3 (limited design flexibility) | 4 (various materials available) | 4 (high precision and accuracy) |
| FDM | 4 (quick setup for low to medium volume) | 3 (relatively cost-effective for low to medium volume) | 4 (good design flexibility) | 3 (limited materials compared to traditional manufacturing) | 3 (moderate precision and accuracy) |
| Weight | W_SP | W_CE | W_DF | W_MO | W_PA |
| | 0.3 | 0.2 | 0.2 | 0.1 | 0.2 |

Based on the weighted scores, the molding process has a score of 2.8, and FDM Technology has a score of 3.5. For low volume production weight score 3.5 to 2.8

points FDM to be preferable technology. Injection molding is suitable for large scale production of consistent and uniform parts, because it has an ability to produce high volumes of parts at a lower cost per unit compared to FDM printing. Parts are produced with high precision and accuracy.

FDM Printing main domain is quick production of spare parts or replacement parts for equipment on the battlefield. Another advantage is the ability to rapidly produce custom or complex parts that may not be available through traditional manufacturing methods. Lead time compared to traditional manufacturing methods is reduced especially when we use already prepared STL files. In both technologies, it is important to consider the availability of raw materials, the quality of the finished parts, and the speed of production when choosing a manufacturing method for defense applications during war.

## 7 Conclusion

In conclusion, FDM is a popular and accessible 3D printing technology that uses a variety of materials to produce objects with a wide range of properties. The mostly used material for FDM is PLA due to its ease of use, low cost, and environmental friendliness. However, other materials such as ABS, PETG, and nylon are also frequently used in FDM printing, each with their own unique characteristics.

While PLA is the most widely used material for FDM printing, its low melting point and brittleness can be limiting factors in certain applications. ABS, on the other hand, is known for its strength and durability, but it requires a higher printing temperature and can produce toxic fumes during printing. PETG offers a balance of strength, flexibility, and ease of use, while nylon is a highly versatile material that is often used in industrial applications.

Overall, the choice of material for FDM printing depends on the specific requirements of the project, such as strength, flexibility, or surface finish, as well as considerations such as cost, environmental impact, and ease of use. By understanding the properties of different materials and selecting the most appropriate one for the job, FDM printing can be a highly effective and versatile tool for producing high quality objects for a wide range of applications.

3D printing technology has revolutionized many industries, and the military and defense sector is no exception. The ability to create complex and customized parts and components using 3D printing has opened up new possibilities in the design and production of military equipment and systems. From prosthetics for wounded soldiers to customized weapon components, 3D printing has proven to be a versatile and cost-effective solution for many military applications.

Based on the pairwise weighted scores, for small production volumes during a military conflict, FDM Technology has a score of 3.5, and the injection molding process has a score of 2.8. Therefore, FDM Technology is the better choice when considering the specified low volume production criteria and weights for this scenario.

One of the key advantages of 3D printing in the military and defense sector is the ability to produce parts and components quickly and on demand. This can be especially useful in situations where traditional manufacturing techniques are not feasible or where there is a need for rapid prototyping. 3D printing can also help reduce costs by eliminating the need for expensive tooling and molds.

Another advantage of 3D printing in the military and defense sector is the ability to create complex geometries and shapes that would be difficult or impossible to produce using traditional manufacturing techniques.

Conducted SWOT analysis and pairwise comparison point out that FDM technology is poised to exert a substantial impact on modern conflicts. Its influence can be assessed in several key ways:

Rapid Prototyping and Manufacturing: FDM's capability for on-demand and localized production of critical components and spare parts can enhance logistical efficiency during conflicts, reducing supply chain vulnerabilities.

Customization and Adaptability: FDM allows for the swift adaptation of designs, enabling military forces to respond quickly to evolving threats and operational requirements.

Reduced Costs: FDM can potentially reduce costs associated with traditional manufacturing, making military operations more cost-effective and sustainable.

Enhanced Stealth and Camouflage: The technology's ability to produce intricate and customized components can contribute to improved camouflage and reduced radar signatures.

Deployment of “War Gadgets”: With 3D printers becoming more accessible, troops and civilians alike can produce improvised "war gadgets" and tools, introducing a new dimension of asymmetrical warfare.

Sustainability and Resource Efficiency: FDM's additive manufacturing process minimizes waste, aligning with modern military trends focused on sustainability and resource conservation.

Security Concerns: However, the proliferation of FDM technology 7also raises security concerns, as it may enable adversaries to produce potentially lethal items with relative ease.

Intellectual Property Implications: The widespread use of FDM technology in conflicts could challenge intellectual property rights and trade secrets, necessitating new legal and ethical considerations.

However, there are also some challenges and limitations associated with 3D printing in the military and defense sector. One of the key challenges is ensuring that the printed parts and components meet the necessary quality and reliability standards. This can be especially important in applications where the failure of a single part can have serious consequences.

Despite these challenges, the use of 3D printing in the military and defense sector is likely to continue to grow in the coming years. As the technology continues to advance and become more accessible, we can expect to see more innovative applications of 3D printing in this field.

In conclusion, 3D printing technology has the potential to revolutionize the military and defense sector by enabling faster and more cost-effective production of parts and components, as well as more innovative designs. While there are some challenges and limitations associated with this technology, its benefits are likely to outweigh these challenges in the long run. As such, we can expect to see more widespread adoption of 3D printing in the military and defense sector in the coming years.

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