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ADDITIVE USE OF SPECIAL MATERIALS IN THE MILITARY

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ABSTRACT

The use of additive solutions can be found in the civil sector, in factories and in homes. The ever-evolving technology and materials system also requires continuous scrutiny by professionals to ensure they have up-to-date information to perform their tasks. In the case of specific materials that can be used in 3D printing, continuous filament reinforcement is perhaps one of the most interesting, especially for military applications. In our paper, we explore this in detail, but with reference to a specific product line and analysing the details of a possible general military application.

KEYWORDS:
Additive, 3D printing, military, fiber reinforcement, polymer

1. Introduction

Specialized technologies and materials used in the military domain have a long history. When it comes to military applications, the high quality and reliability of components and products are always crucial. However, for technical equipment, other requirements may also come to the forefront. One such requirement could be the installation and operation in special locations, which are not limited to specific operational areas. The challenges posed by climate change (Padányi, 2023) and the resulting disaster relief operations (Padányi & Nyers, 2006), which also qualify as extreme environments, are increasingly demanding for military personnel.

These and numerous other special tasks and locations necessitate the use of equipment and components with extreme capabilities, which in turn imposes significant demands on the continuous supply chain. These military technical challenges, impacting logistics and many other areas, underscore the need for the integration of modern solutions into the

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armed forces to ensure we are prepared to meet our tasks effectively.

Our objective is to examine fiber-reinforced polymer composites from the perspective of their military usability when components and objects are fabricated using additive manufacturing methods. The investigation will consider both continuous fiber reinforcement and polymers mixed with microfibers to provide a comprehensive overview of the field. Naturally, it is not feasible to analyse all the materials available on the market, so we have selected one that also offers a printer intended for military use for our research.

2. Additive manufacturing

We consider it unnecessary to examine the significance of additive manufacturing, specifically 3D printing, as it proves itself daily in the industry. However, its importance is not limited to industrial use, as this technology is also increasingly spreading in households. Some view it merely as a hobby for creating decorative items, while others see 3D printers as technical tools that can be integrated into household tasks, maintenance, and repairs. This is an important detail, as the practical experiences of users are rapidly accumulating across various social media platforms, often providing researchers with valuable insights.

Primarily, Fused Deposition Modelling (FDM) and Stereolithography (SLA) processes are becoming widespread because these are relatively inexpensive technical tools, and the associated materials also do not entail significant costs, although this is clearly and closely related to the quality of manufacturing and the final product.

Industrial applications operate in a different dimension of requirements, which can only be met with high-quality technology. In this segment, certain powder bed fusion techniques have become widely adopted, with base materials that can be either metal or polymer. Metal components hold significant importance in the industry, prompting the continuous introduction of the latest technologies. Some methods involve the high-speed injection of metal powders to create objects, while others require multi-step, complex manufacturing processes (Hegedűs, 2023).

The creation of components requires the use of Computer-Aided Design (CAD) software, although there are cloud-based or online applications that are suitable for designing simple components and do not require extensive design knowledge. These design options pave the way for digitally creating complex parts (Gyarmati, Hegedűs & Gávay, 2022, p. 125) optimized for specific technologies. The process has recently been enhanced with generative design, as the development of complex geometries necessitates designing objects optimized for their intended stress loads (Markovits, Erőss & Fendrik, 2019, p. 50).

This manufacturing technology can even be considered for constructing buildings or preparing food, as these areas are also rapidly advancing. The scale of manufacturing speaks for itself; for instance, in contrast to the aforementioned buildings, some advanced printing devices are capable of producing layers as thin as 20 µm (Kajner et al., 2023, p. 4). This scale is significant, and as a result, the possible areas of application and research are virtually limitless.

3. Possible applications in the military

Why might this technology be necessary for a military force? Military applications invariably demand high-quality materials, ideally used under factory conditions. This principle does not change with the adoption of 3D printing. While high quality may not always be achievable, there are manufacturers who have recognized the importance of military applications and have developed technologies and materials aligned with these standards.

Maintaining a military force is costly even in peacetime, and during war, financial resources are consumed rapidly.

In such times, the defence sector becomes a budgetary priority for any state, yet cost-effective solutions can be extremely valuable. A modern military's technical equipment is remarkably diverse, requiring a vast array of parts in both variety and quantity for continuous repairs and maintenance. We see this as a logistical challenge, for which the technology described offers an excellent solution. Although we are currently unable to produce everything needed via 3D printing, and the lifespan of some parts may be shorter, this should not lead to the rejection of this solution. Reducing dependence on disrupted global supply chains and ensuring continuous resupply is far more important than the decreased lifespan of individual parts. We believe that digital warehouses, where the designs of necessary components are stored, coupled with 3D printer farms, can greatly simplify and enhance the servicing of technical equipment.

Continuing this line of thought, the necessary tools should be capable, if not of producing components identical in quality to the originals, at least of ensuring continuous supply in terms of both quantity and manufacturing speed within national borders. Among the technical tools used in additive manufacturing, several can meet the aforementioned requirements. In our opinion, these technical tools can generally be integrated into military engineering tasks, explosive ordnance tasks, spare parts production, custom tool creation, the enhancement of existing components, military medical tasks (Mikolajevska et al., 2016, p. 132; Told et al., 2021, p. 2), technical construction and fortification tasks, educational and training tasks, as well as the production of optimized food supplies.

From the above list, we would like to highlight a few areas where results have already been achieved. In the case of explosives and explosive ordnance, additive manufacturing of actual explosives and their precise shaping is not yet possible, but it is feasible to create specially designed charges that can be filled with a brisant plastic (Lukács, 2017, p. 26), multi-component (Kugyela, 2020) or liquid explosives. In this form, 3D printing opens the door to the next generation of precision detonations, making the use of general-purpose charges nearly obsolete in the future, as it will no longer be a significant challenge to design and produce components precisely tailored to the task at hand.

High-performance polymer composites with excellent strength-to-weight and load-bearing-to-weight ratios could form the basis for producing replacement parts (Hliva & Szebényi, 2023, p. 2). The properties of composites reinforced with continuous fibers can rival those of some metals while weighing only a fraction as much. Although the accepted fact that 3D printed parts are of lower quality than industrial-grade parts is generally true, it does not necessarily hold in all cases. It is possible that by altering manufacturing parameters or using other advanced materials, better and more durable objects can be produced. These parts could play a significant role in one of the most important segments of military application: weapons technology. With 3D printing, it is easy to replace a broken or damaged weapon component or even customize a precision weapon to meet specific military requirements, making it more effective in use. The complex replacement of certain weapons is also feasible by combining metal and polymer technologies (Gál & Németh, 2019, p. 239).

In addition to custom-tailored weapons, a similar area is healthcare. In the case of various medical prosthetics, improving the quality of life for the injured largely depends on how accurately these devices can be tailored to individual needs. This demand exists for both dental implants and limb prostheses and must be taken into account by professionals. Naturally, custom tools can also be created and applied during other phases of treatment to aid in the healing process.

In certain technical construction tasks, 3D printing of concrete can be particularly practical. While this is not always the case, as the technology requires large equipment and significant installation efforts, its use should not be questioned. It can create custom vehicle and equipment shelters, which can also serve as important camouflage accessories. Additionally, during peace support operations, it is possible to construct defensive structures that more effectively absorb energy, thus enhancing the protection of personnel and becoming an essential part of force protection tasks. Modern defence solutions are in the toolbox of every serious army (Horváth & Padányi, 2006, p. 102).

Drones and autonomous systems are playing an increasingly significant role in conflict-affected regions today. As these are rapidly consumed and their replacement is not always assured, new types may frequently be deployed, requiring custom parts that can accommodate the same equipment or mounting. The technology allows for the design and relatively economical production of the necessary parts, even in quantities of several thousand. Moreover, upgrading existing units and making them safer is not a process that takes months; it can be accomplished in a matter of days with the help of a skilled professional.

In any military, there is a fundamental need for high-level training and preparation, which cannot be achieved without high-quality training materials. Various models and educational materials allow soldiers to gain practical experience with realistic tools for specific tasks without facing actual life-threatening situations. This is crucial because trained personnel need to be provided with conditions that match real-life situations, thereby increasing their survival chances on the battlefield.

4. Fiber reinforced polymers

In our discussion, we focus on the FDM (Fused Deposition Modelling) technology among the many possibilities. This technology widely uses carbon fibers as additives to polymers. Most commonly Polyethylene terephthalate (PET), Polyethylene terephthalate glycol (PETG), Acrylonitrile styrene acrylate (ASA), Acrylonitrile butadiene styrene (ABS) and Polyamide (PA) polymers are mixed with carbon fibers, typically in quantities around 15-20%. The added carbon fibers enhance the strength of objects and components. This can be advantageous during the critical cooling phase of the manufacturing process, as the temperature drop during the process can lead to volumetric changes, causing deformation and damage to the finished products. The expected operating temperature of the objects will not reach the over 200°C extrusion temperature, so a slightly shrunken size of the component can be expected during use. The carbon fibers mixed into the base material can improve the quality of the final product by reducing the extent of this shrinkage. The finished products are generally less sensitive to moisture.

Continuing with the technology, it is essential to highlight a manufacturer that places significant emphasis on fiber reinforcement and produces military-grade technical equipment. The Markforged printers and materials allow for a wide range of components to be produced not only with micro-sized carbon fibers mixed into the filaments but also with continuous fiber reinforcement. During manufacturing, the 3D printer embeds a thermoplastic matrix-coated fiber bundle into the melted layers, thereby reinforcing the desired component (Szederkényi et al., 2022, p. 83).

Markforged's printers, which enable continuous fiber reinforcement, use filament material and employ several distinct technological solutions compared to classic FDM technology. In the case of the Mark TWO 3D printer, the matrix material is not fed by pulling but by folding it into the hotend. The print head features two nozzles. In addition to the extruder handling the matrix material, there is also a component that feeds the continuous fiber reinforcement, meaning they do not operate independently. The build plate only provides “Z” dimension movement, while the print head can move in the other two directions. The build area is enclosed but not hermetically sealed. The production of PA (polyamide) requires a build chamber maintained at relatively high temperatures, so this design was a necessary consideration. The technology described here is the same as that used in the manufacturer's military-grade “X7 Field Edition” model.

The matrix material used by Markforged is called “ONYX” and a developed version is already available – Base, Fire Resistant (FR) and Electrostatic Discharge (ESD) types – but our study focuses on the widely adopted first-generation material. The ONYX matrix material is PA (polyamide) enhanced with micro carbon fibers. The Onyx materials have outstanding properties on their own (Figure no. 1), but their material properties significantly improve with continuous fiber reinforcement (Figure no. 2) (Markforged, 2023).

It is important to note, however, that continuous fiber reinforcement can only be incorporated in dimensions parallel to the build plate, so in the case of “Z” directional loads, it is worth reconsidering the build orientation. This is not a new observation; it has long been known in FDM technology, but we consider it essential to mention as a known limitation.

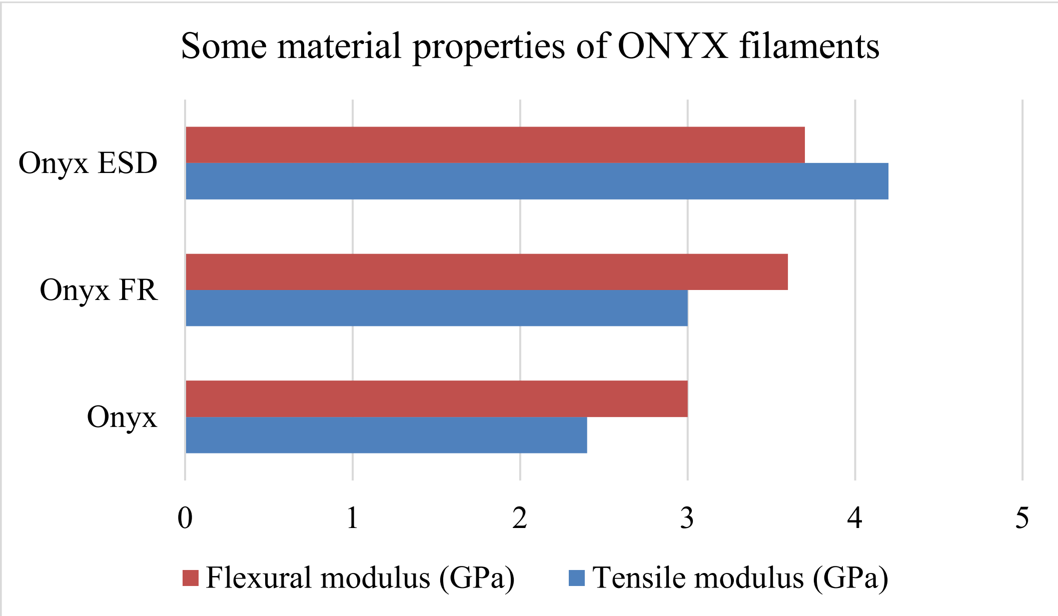


Figure no. 1: *Some material properties of ONYX filaments*
(Source: Authors, based on Markforged, 2023)

In the case of continuous fiber reinforcement, several inserts are available: carbon, fire-resistant carbon, Kevlar, fiberglass, and high-strength high-temperature fiberglass. The choice of which to use greatly depends on the intended application and the expected load demands, so it is crucial to carefully consider and select the appropriate insert. Carbon fiber components, for example, can potentially replace elements made of aluminum. Fiberglass allows to produce larger and stronger parts, while Kevlar is better suited to withstand forces arising from bending and tension (Markforged, 2023).

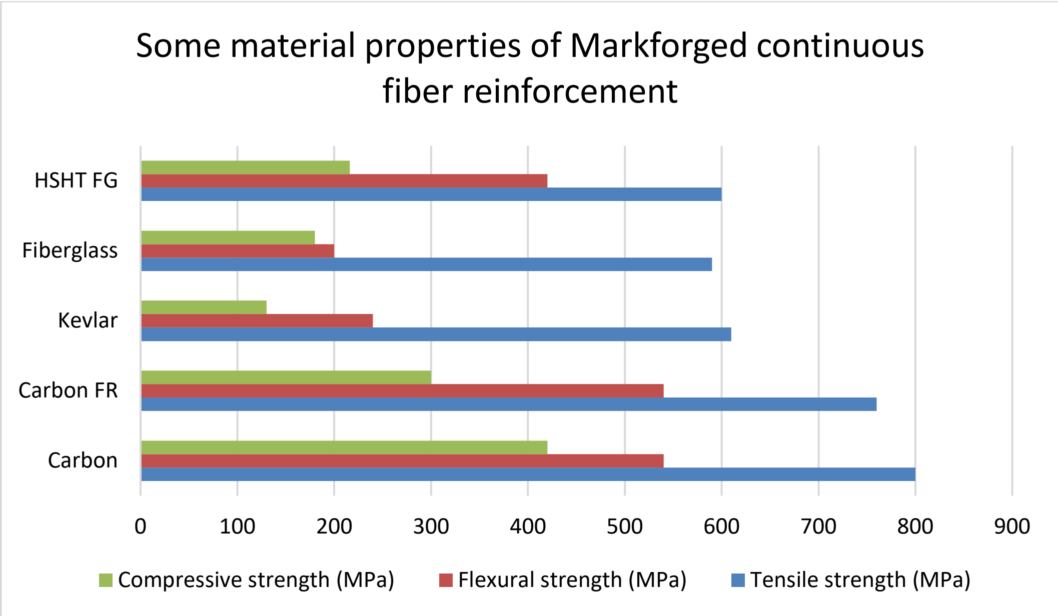


Figure no. 2: *Some material properties of Markforged continuous fiber reinforcement*
(Source: Authors, based on Markforged, 2023)

In the course of our ongoing research, we applied the presented results in practice and considered them when designing some components. The importance of these can be especially great in the case of the production of spare parts that can be attached to a drone.

The spare part shown in Figures no. 3 and 4 was made with a Markforged Mark Two 3D printer, using ONYX printing material. This spare part unit is designed to carry an IT device, which can be easily attached to the drone and provides access to the connectors of additional electronic components.

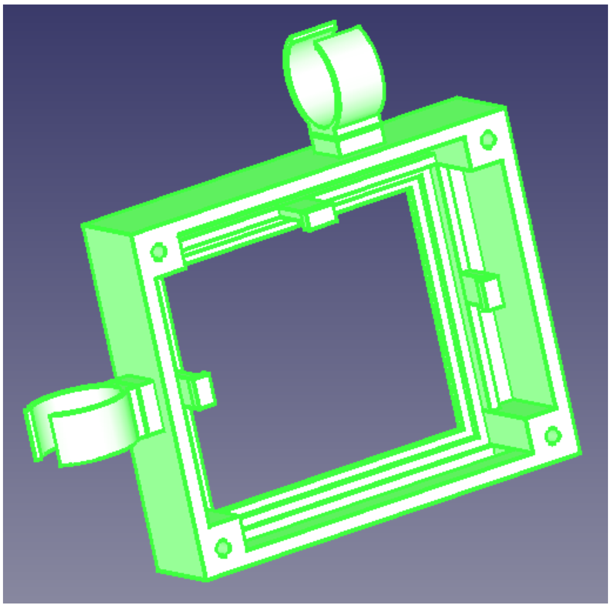


Figure no. 3: *The spare part unit in a CAD software*
(Source: Authors' drawing)

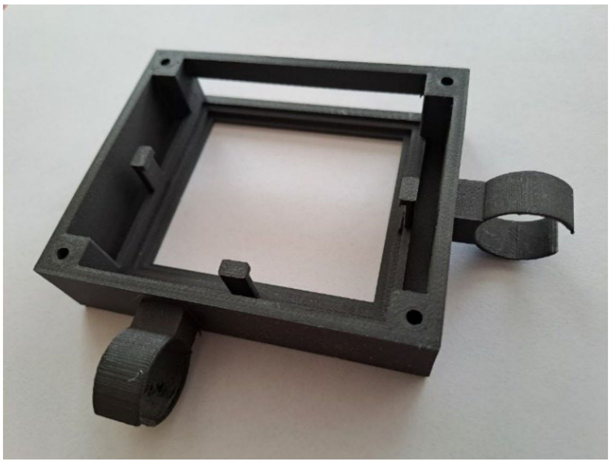
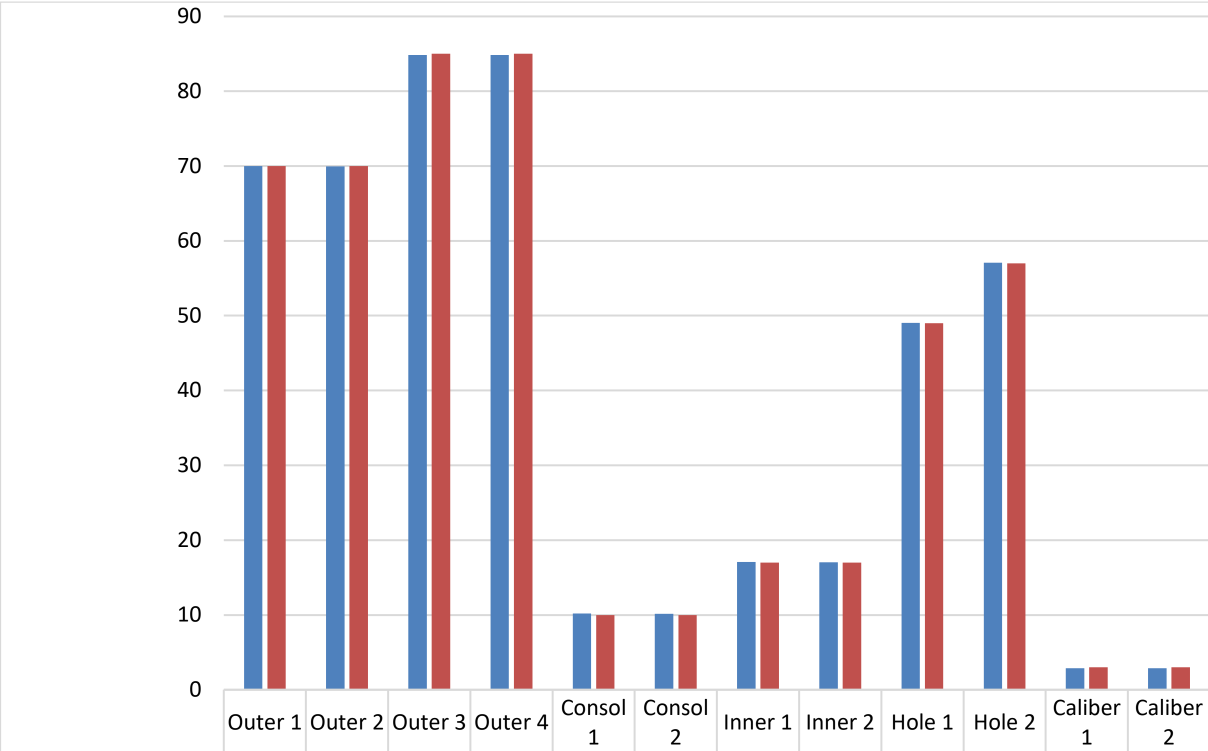


Figure no. 4: *The printed spare part unit*
(Source: Authors' photo)

In the case of the presented parts, the advantageous properties of the ONYX printing material, such as the strong but relatively flexible structure, and the quality of the manufacturing process also played a major role. The technology met expectations and requirements. The dimensional accuracy is illustrated in Figure no. 5, according to our experience; the deviations did not cause installation problems.



	Outer 1	Outer 2	Outer 3	Outer 4	Consol 1	Consol 2	Inner 1	Inner 2	Hole 1	Hole 2	Caliber 1	Caliber 2
Measured (mm)	70.01	69.96	84.86	84.85	10.2	10.14	17.06	17.05	49.03	57.08	2.86	2.86
Planned (mm)	70	70	85	85	10	10	17	17	49	57	3	3

Figure no. 5: *Dimensional accuracy test results*
(Source: Authors' drawing)

5. Conclusions

The presented FDM technology and the specialized materials are deemed to meet military requirements and can be applied across a wide range of the tasks described above. Although they do not always perfectly align with all expectations, their application can prove particularly useful, even in operational environments.

While replacing metals with polymer components reinforced with continuous fibers is not always possible or necessary, significant and cost-effective results can be achieved by carefully exploiting their potential.

We consider it a crucial area for further research to conduct similar analytical studies of other technologies, which could either confirm or refute the feasibility of their integration into military applications, whether in operational theatres or in the rear.

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REFERENCES

Gál, B. & Németh, A. (2019). Additív gyártástechnológiák katonai alkalmazásának vizsgálata, különös tekintettel a katonai elektronika területére. [Analysis of Military Applications of Additive Manufacturing Technologies, With Special Regard to the Area of Military Electronics]. *Hadmérnök*, *Vol. 14, Issue 1,* 231-249. Available at: https://doi.org/10.32567/hm.2019.1.19.

Gyarmati, J., Hegedűs, E. & Gávay, Gy. (2022). Automata sebességváltóban alkalmazott kapcsolt bolygóművek – Wilson-váltó: Harckocsi-sebességváltó modell kialakítása 3D nyomtatással oktatási célból. [Application of Planetary Gears in Automatic Transmission – Wilson Gearbox Model of 3D Printed MBT Gearbox for Educational Purposes]. *Műszaki Katonai Közlöny, Vol. 32, Issue 3,* 113-126. Available at: https://doi.org/10.32562/mkk.2022.3.7.

Hegedűs, E. (2023). Az ADAM-fémnyomtatási technológia alkalmazási lehetősége a hadiiparban – 3D-s eljárás az UAV-k és könnyűjárművek gyártásában. [Application Possibility of ADAM Metal Printing Technology in the Military Industry - 3D Process in the Production of UAVs and Light Vehicles]. *Haditechnika, Vol. 57, Issue 6,* 61-66. Available at: https://doi.org/10.23713/HT.57.6.13.

Hliva, V. & Szebényi, G. (2023). Non-Destructive Evaluation and Damage Determination of Fiber-Reinforced Composites by Digital Image Correlation. *Journal of Nondestructive Evaluation, Vol. 42, Issue 43,* 1-15. Available at: https://doi.org/10.1007/s10921-023-00957-7.

Horváth, T. & Padányi, J. (2006). Műszaki eszközök a béketámogató műveletekben és a fejlesztés lehetőségei I. rész. [Military Engineer Equipment in Peace Support Operations and Opportunities for Development Part I.]. *Katonai Logisztika, Vol. 14, Issue 4,* 101-119. Available at: https://epa.oszk.hu/02700/02735/00060/pdf/EPA02735_katonai_logisztika_2006_4_096-130.pdf .

Kajner, Gy., Bélteki, Á., Cseh, M., Geretovszky, Zs., Ajtai, T., Barna, L., Deli, M.A., Pap, B., Maróti, G. & Galbács, G. (2023). Design, Optimization, and Application of a 3D-Printed Polymer Sample Introduction System for the ICP-MS Analysis of Nanoparticles and Cells. *Nanomaterials, Vol. 13, Issue 23,* 3018. Available at: https://doi.org/10.3390/nano13233018.

Kugyela, L. (2020). A többkomponensű robbanóanyagok múltja, jelene és jövője. [Past, Present and the Future of the Binary Explosives]. *Katonai Logisztika, Vol. 28, Issue 4,* 58-75. Available at: https://www.mkle.net/products/a2020-4-szam/.

Lukács, L. (2017). *Szemelvények a magyar robbantástechnika fejlődéstörténetéből, különös tekintettel a továbbfejlesztés várható irányaira és a kor új kihívásaira.* [Selections from the History of the Development of Hungarian Blasting Technology, with Particular Regard to the Expected Directions of Further Development and the New Challenges]. Budapest: Dialóg Campus Kiadó.

Markforged (2023). *Material Datasheet – Composites*. Available at: https://s3.amazonaws.com/mf.product.doc.images/Datasheets/Material+Datasheets/CompositesMaterialDatasheet.pdf.

Padányi, J. & Nyers, J. (2006). Műszaki-technikai eszközök az árvízi védekezésben. [Military Engineer Equipment in Flood Protection]. *Haditechnika, Vol. 40, Issue 6,* 65-68.

Padányi, J. (2023). Éghajlatváltozás, természeti katasztrófák, környezeti hatások, katonai képességek. [Climate Change, Natural Disasters, Environmental Impacts and Military Capabilities]. *Hadtudomány, Vol. 33 (E-szám),* 101-119. Available at: https://ojs.mtak.hu/index.php/hadtudomany/article/view/12268/9925.

Szederkényi, B.B., Turcsán, T., Kovács N.K. & Czigány T. (2022). Additív gyártástechnológiával készített, folytonos szállal erősített kompozitok szimulációs elemzése. [Simulation Analysis of Continuous Fiber-reinforced Composites Made with Additive Manufacturing Technology]. *GÉP, Vol. 73, Issue 3-4,* 82-87. Available at: http://www.gepujsag.hu/wp-content/uploads/2022/04/gep-2022-3-4.pdf.

Told, R., Marada, Gy., Rendeki, Sz., Pentek, A., Nagy, B., Molnar, F.J. & Maroti, P. (2021). Manufacturing a First Upper Molar Dental Forceps Using Continuous Fiber Reinforcement (CFR) Additive Manufacturing Technology with Carbon-Reinforced Polyamide. *Polymers, Vol. 13, Issue 16,* 2647. Available at: https://doi.org/10.3390/polym13162647.