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Defence Industry Applications for Multi-Material Additive Manufacturing[2]

In the world of 3D printing, additive technology that uses multiple raw materials in parallel is a special field. It offers amazing advantages but also poses challenges in both factories and design interfaces. Segmented design, which fills every segment of space with data, offers the possibility of using special raw materials and combinations, which in many respects yields astonishing results. There is also a place for this technological innovation in the defence sector, but there are still limitations at present. These are particularly evident in the areas of material compatibility and quality assurance. Regardless, research into military applications is necessary, even if there are still obstacles in this area.

Keywords: *3D printing, additive manufacturing, voxel-based planning, defence industry, military logistics*

Introduction

Additive manufacturing is a rapidly developing technology today. Classic plastic manufacturing technologies, such as injection moulding, offer significant advantages, but we must accept that 3D printing also has an important industrial role to play. These solutions have a place in industry, including the defence industry, where they can coexist and complement each other.

This technology also plays a significant role in military research, as it can help the defence sector overcome many challenges. Additive manufacturing can support the defence sector in addressing several challenges, including environmental constraints,[3] the increased number of different drones used for military applications (Figure 1),[4] the application of special, resistant metals such as titanium,[5] or even simply auxiliary materials related to military education and

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[3] Padányi 2022; Padányi 2024; Dénes et al. 2024.

[4] Daruka 2014.

[5] Hlinka et al. 2023.

training[6] and aftermarket or spare parts[7] when it comes to military equipment, 3D printing can provide a solution for everything.

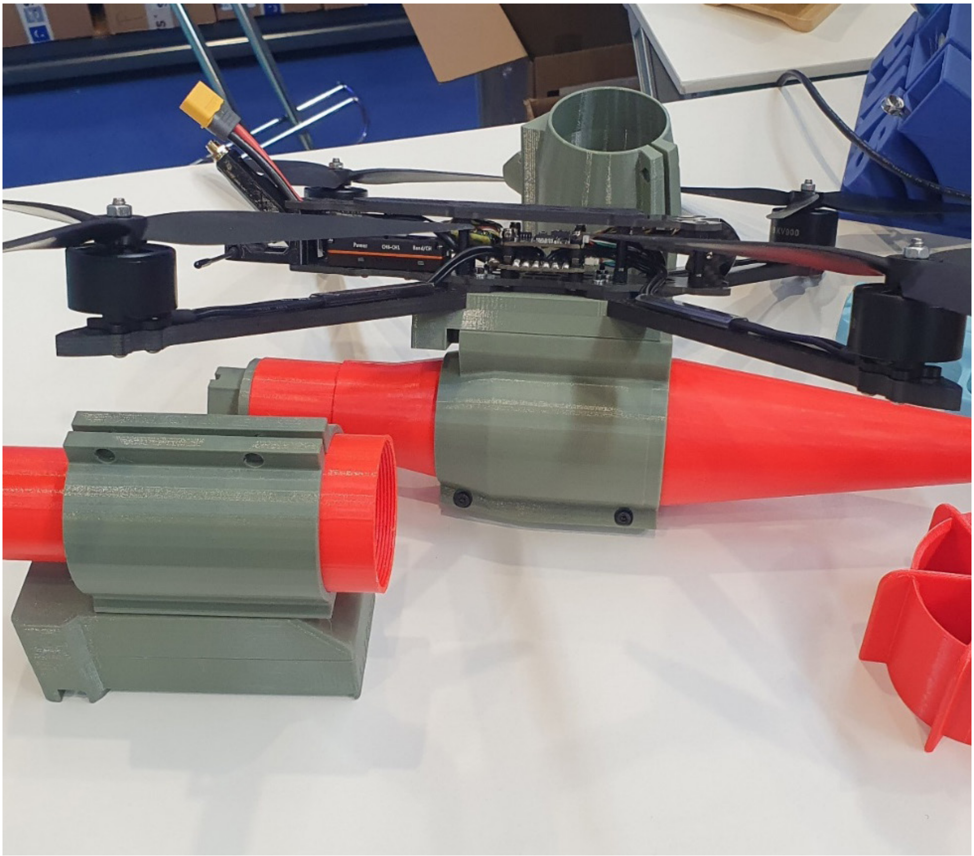

Figure 1: 3D printed drone parts
Source: compiled by the author

Of course, there are challenges that must be faced in this segment as well. This manufacturing technology requires a high level of component design, which today already involves topological optimisation and generative design.[8] In addition, however, it is now possible to edit the raw materials from which the components and final products are made in much greater detail, including their material and other properties. Our goal is to summarise the possibilities and limitations of the military application of additive technology using multiple types of raw materials.

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[6] Daruka et al. 2024; Vég 2023.
[7] Gávay 2024; Gyarmati–Gávay–Hegedűs 2026.
[8] Hegedűs et al. 2024.

Volumetric pixels

A volumetric pixel (hereinafter: voxel) is the smallest discrete unit of three-dimensional space with volume to which geometric and material properties can be assigned. Properties can be assigned to each voxel – such as density, colour, other material properties, and other values – similar to how a picture element (hereinafter: pixel) stores values on a two-dimensional surface. Voxels therefore define the entire volume rather than the surface, allowing for more detailed modelling of the internal structure and any inhomogeneous properties, which is difficult, if not impossible, to achieve with traditional surface-based representations.[9]

3D printing technologies – primarily methods and technologies used in industry – often follow a logic whereby objects are formed from layered spatial elements or voxels. Each voxel is a tiny unit of space that the printer places on top of each other to form the final body. This voxel-based layering helps the printer to produce parts layer by layer, accurately and in great detail.[10]

Certain technological solutions – such as Hewlett-Packard (hereinafter: HP) Multi Jet Fusion (hereinafter: MJF) technology – allow each voxel to be controlled individually. This means that not only can the geometric shape be defined on a voxel-by-voxel basis, but even the material properties of the part (e.g. colour, mechanical properties, elasticity, etc.) can be modified at the voxel level. As a result, functionally separated or internally optimised parts can be produced that would not be feasible with conventional manufacturing processes.[11]

One significant advantage of using voxels is that during design, the focus is not only on the outer surface, but the entire volume can be modified in minute detail. This is particularly important when designing functional components. In such cases, the internal structure affects the mechanical properties (mass, strength, energy absorption capacity, etc.). Voxels help, for example, in the design of internal lattice structures or in the creation of stepwise variations in material density, which improve performance without significantly changing the basic geometry.[12]

Traditional Computer-Aided Design (hereinafter: CAD) models are often based on polygonal surfaces, whereas voxel-based design also allows for the representation of an object's internal structure, supplemented with data. This helps, for example, in optimising products or automating simulations, where the relationship between the model and the analysis can be maintained at the voxel level. This solution makes it easier to quickly update, refine, and fine-tune the part during design iterations.[13]

The size of the voxels directly affects the resolution and accuracy of the 3D printed body or part. This is especially true for laser and microprinting processes. The smaller the voxels, the finer the details that can be printed, which is crucial when manufacturing precision parts

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[9] PADT 3D printing & scanning [s. a.]; TechTerms.com [s. a.].

[10] HP 2018: 4–6.

[11] HP 2018: 4–7.

[12] polySpectra [s. a.].

[13] Li et al. 2023.

or other microstructures. The size of the voxel therefore affects not only the visualisation, but also the actual physical details.[14]

The voxel-based approach is key to the implementation of multi-material additive manufacturing (hereinafter: MMAM). It enables the volume of an object to be broken down into discrete, locally deformable volume units. While traditional surface-based modelling primarily carries geometric information, voxel-based modelling can also store information related to material properties and functions. This creates a solid foundation that allows multiple materials and different material properties to appear within a single printing process. In MMAM, the voxel becomes the basic unit to which specific material composition, mechanical properties, or other special functions can be assigned. As a result, material distribution can be optimised beyond the layer level according to three-dimensional volumetric logic. Voxel-based design thinking thus directly links digital design and multi-material manufacturing.

This design paradigm is particularly relevant in military applications, where locally optimised mechanical behaviour, energy absorption, or multifunctionality can directly influence operational effectiveness and survivability.

Multi-material additive manufacturing

MMAM, or multi-material additive manufacturing, is a 3D printing technology in which two or more materials with different physical or chemical properties are incorporated into an object, essentially with microscopic precision and precise spatial control. This technology enables the production of components and objects with locally distinct mechanical, optical, and electrical properties. In practice, this may include materials that have functionally stepped properties or internal structures with hidden, embedded functions. MMAM does not only mean the use of multiple materials, because optimising their spatial distribution is also one of the possibilities inherent in the technology. Ultimately, this can result in, for example, intelligent, special properties or multifunctional components.[15]

Scientific interest in MMAM has grown significantly in recent decades, particularly in the field of polymer-blending systems. Thousands of scientific publications deal with this topic, with research focusing on improving the accuracy of the technology, developing interfaces, optimising manufacturing efficiency, and micro- or nanoscale MMAM. However, it is clear that materials scientists and engineers are exploring the topic in greater depth, presenting newer polymers and composite solutions, while interface optimisation is a less analysed subfield.[16]

MMAM can be implemented through several 3D printing technologies. These processes enable different material combinations and functions, including polymers, composites, hydrogels,[17] and metal-polymer hybrid materials. These technologies include but are not limited to the following:[18]

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[14] Bougdid–Sekkat 2020.

[15] Emergent Mind 2025.

[16] Zheng et al. 2021: 1.

[17] Vég 2024: 86.

[18] Zheng et al. 2021: 12–20.

- Fused Deposition Modelling (FDM/FFF): one of the most widely used technologies that extrudes different raw materials in sequence or in parallel using a multi-filament or multi-printhead configuration
- Material Jetting (MJ): simultaneous placement of multiple photopolymer raw materials in the form of droplets, which allows for the creation of very fine material compositions
- Direct Ink Writing (DIW): printing of various liquid or paste-like materials
- VAT Photopolymerisation (VP): integration of several types of photosensitive resins where the spatial composition can be modified by exposure to light
- Hybrid systems: simultaneous application of several technologies in a manufacturing process

Hybrid 3D printing platforms have therefore appeared in research. These integrate several different additive technologies into a single system. A good example of this is the m^4 3D printer, which combines InkJet, FDM/FFF, DIW, and Aerosol Jetting technologies and, supplemented with a robotic module, is capable of creating complex parts made from multiple raw materials. These systems enable the simultaneous processing of incompatible materials, thus significantly expanding the manufacturing spectrum.[19]

A key factor in FDM/FFF-based MMAM is the solution for feeding multiple materials and bonding them properly. The two main configurations in this technology segment are single nozzle/multi-feed (single nozzle, multiple feed channels) and multi-nozzle/multi-feed (multiple nozzles, separate for each material). The quality of the surfaces created during production has a decisive influence on mechanical performance, as the bond between different materials can be weak, especially if they are not compatible with each other.[20]

One important area of MMAM is functionally graded materials (FGM), where continuous changes in material composition allow for precise adjustment of the local mechanical, thermal, or electrical properties mentioned above. This process is useful in the manufacture of components where the combination of mass, strength, and energy absorption is critical.[21]

Systems capable of simultaneously processing polymer-based materials are widespread in industry. For example, MJ technologies – such as certain Stratasys PolyJet systems – are capable of depositing droplets of multiple photopolymers with micron-level precision. These solutions are often used in prototype manufacturing and visual functional modelling.[22]

Military applications of MMAM

In a general and broad sense, additive manufacturing is becoming increasingly important in the defence industry, as it is capable of producing complex, integrated, and functionally optimised components that would be difficult or costly to produce using traditional manufacturing

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[19] Roach et al. 2019.

[20] Wang et al. 2024.

[21] Hasanov et al. 2022: 1–4.

[22] Emergent Mind 2025.

methods. Military applications often require special mechanical and material properties that cannot be optimally achieved with a single material but by combining multiple materials. In addition, decentralised manufacturing and the ability to produce on or near site are critical to the logistics of military operations and the organisation of supplies.[23]

MMAM can therefore be particularly valuable in terms of battlefield logistics and operations, where mobile printers close to the front line can produce unique parts, tools, or accessories without relying on traditional procurement-based supply chains. This not only speeds up the repair of military equipment but also reduces the amount of inventory required and can increase the response time of technical personnel, which is a critical factor in any operational environment.[24]

This process also shows significant potential for the manufacture of components for military unmanned aerial vehicles (hereinafter: UAV) and other aircraft. The integration of multiple materials can enable, for example, the integration of structural elements and embedded functions (e.g. antennas, sensors, other electronics) into a single component, significantly reducing the number of parts and the complexity of assembly. This integrated approach can offer significant advantages in optimising the mass-to-performance ratio and enabling higher-level design of aircraft.[25] As mentioned above, this form of manufacturing is not only feasible at the macro level but also plays a role in the production of microsystems and integrated mechanical-electrical units. The Defense Advanced Research Projects Agency (hereinafter: DARPA) for example conducts dedicated research programmes aimed at the development of high-resolution, multi-material microsystems, focusing on rapid manufacturing, functional integration, and system-level reliability.[26]

However, MMAM for military purpose still faces serious technical and regulatory challenges. From a military perspective, quality assurance and certification represent critical bottlenecks, as the failure of a single component may directly affect mission success and personnel safety. These include material compatibility, surface bonding, quality assurance, and certification according to military standards. These issues are particularly important for devices used in military operations. As the process is a complex manufacturing method, testing processes are not easily adapted to the new technology. New procedures and methods may be required for testing to ensure high-quality products for soldiers serving in the field.[27]

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[23] Colorado et al. 2023: 3900–3906.

[24] Raise3D 2025.

[25] Machi 2017.

[26] DARPA 2024.

[27] Raise3D 2025.

Summary

The data on MMAM technology clearly points in one direction. The technology is developing rapidly and will be used more and more widely, including by players in the defence industry. This is no surprise, as special applications require components with special capabilities. In addition, defence procurement processes typically prioritise reliability, performance, and compliance with military standards over unit cost considerations, so high-quality products can also play a significant role.

The demand and opportunity to define the objects to be manufactured on a voxel basis is also growing. This technology offers amazing possibilities that are yet to be exploited, although it can already be applied based on serious and up-to-date results. However, compatibility issues with certain materials have not yet been resolved in all cases, which is a significant challenge in this area. Military compliance is another such area. It is simply essential that combatants use high-quality components and equipment in the field. As this requirement is fundamental and current quality assurance does not meet expectations in all areas, it may be necessary to expand it as soon as possible to ensure that MMAM products are also reliable.

The potential is significant. The demand for special raw materials is considerable, and technology is capable of meeting this demand despite minor shortcomings. With the updating of regulations and control methods, it is now possible for devices made from MMAM technology and multiple raw materials to become widespread in the defence sector.

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