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Additive manufacturing in military using

Produkcja przyrostowa w zastosowaniach wojskowych

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Abstract. MThe paper presents the current potential of Additive Manufacturing (AM) in the production of devices, replaceable parts, construction infrastructure, medical materials, etc. As part of the presentation of the potential of AM, the currently available technologies and materials used in the implementation of 3D printing were discussed, with particular emphasis on printing technology in metal. The authors reviewed and analyzed the development trends in the use of additive manufacturing in technologically leading armies. The analysis of the available information shows that AM in military applications is mainly used in the production of spare parts for „aged" military equipment and for military equipment operated in conditions far away from the sources of supply with „original" technical material means. Available information indicates a dynamic development of the use of 3D printing both in industrial and military applications. The aim of the article is to identify the level of development and application of AM technology in the military domain. The research problem was defined as follows: does the current level and scale of the use of AM technology both in industry and in the military domain justify the implementation of this technology to the logistic support of the Polish armed forces. The paper presents a review of selected literature from the last 10 years. Based on this analysis, AM technology is presented in two areas: industrial and military. The article is an attempt to review the current state of knowledge about additive technologies. It also presents research perspectives that should be undertaken within the disciplines: construction and operation of machines and production engineering, especially due to the perspective of implementing this technology

in the Polish Armed Forces. The paper concludes with the thesis that the introduction of AM technology to the logistic support of the Polish Armed Forces will increase its effectiveness, efficiency and resilience of the logistics supply chain, especially in the field of technical combat service support.
Keywords: additive manufacturing, AM technology, 3D printing, AM military applications, military logistics

Abstrakt. W referacie przedstawiono aktualny potencjał wytwarzania przyrostowego (Additive Manufacturing - AM) w produkcji urządzeń, części wymiennych, infrastruktury budowlanej, materiałów medycznych, itp. W ramach prezentacji potencjału AM omówiono aktualnie dostępne technologie i materiały wykorzystywane w realizacji druku 3D, ze szczególnym uwzględnieniem technologii druku w metalu. Autorzy dokonali przeglądu i analizy tendencji rozwojowych wykorzystania wytwarzania przyrostowego w wiodących technologicznie armiach. Z analizy dostępnych informacji wynika, że AM w zastosowaniach wojskowych wykorzystywane jest głównie w produkcji części wymiennych dla „wiekowego" sprzętu wojskowego oraz dla sprzętu wojskowego eksploatowanego w warunkach dużego oddalenia od źródeł zaopatrywania w „oryginalne" techniczne środki materiałowe. Dostępne informacje wskazują na dynamiczny rozwój wykorzystania druku 3D w zastosowaniach przemysłowych i wojskowych. Celem artykułu jest identyfikacja poziomu rozwoju i zastosowań technologii AM
w środowisku wojskowym. Podjęty problem badawczy został sprecyzowany następująco: czy aktualny poziom i skala wykorzystania technologii AM zarówno w przemyśle jak i w wojsku, uzasadnia wprowadzenie tej technologii do zabezpieczenia logistycznego sił zbrojnych RP. W pracy przedstawiono przegląd wybranej literatury z ostatnich 10 lat. Na podstawie tej analizy technologię AM przedstawiono w dwóch obszarach: przemysłowym i wojskowym. Materiał stanowi próbę dokonania przeglądu aktualnego stanu wiedzy na temat technologii addytywnych. Przedstawia on ponadto perspektywy badawcze, które należałoby podjąć w ramach dyscyplin: budowa i eksploatacja maszyn oraz inżynieria produkcji, szczególnie ze względu na perspektywę implementowania tej technologii w SZ RP. W artykule zawarto tezę, iż wprowadzenie technologii AM do zabezpieczenia logistycznego Sił Zbrojnych RP spowoduje wzrost jej efektywności, wydajności i odporności łańcucha dostaw, zwłaszcza w zakresie zabezpieczenia technicznego.
Słowa kluczowe: wytwarzanie addytywne, technologia AM, druk 3D, zastosowania militarne AM, logistyka wojskowa.

Introduction

Additive manufacturing is a particularly dynamically developing technology in last period of time. The possibility of its use in the defense sector can significantly affect the production of components and parts which are in conventional way not possible or unprofitable for acquire.

In addition, this technology also opens up completely new possibilities in terms of securing materials for the repair of military equipment, especially in the conditions of struggle carried out on the area of country or during operations and expeditionary missions.

Currently, in many armed forces (for example: USA, Great Britain, Germany) there is a trend related to the development of additive manufacturing technology using in field conditions to improve operational readiness of military equipment. Due to eliminate shortages of other equipment by producing it directly in field conditions or near the area where operations are carried out, as part of the so-called production on demand (European Military Additive Manufacturing Symposium, 2021).

Considering the dynamic growth of AM applications in the military domain, the aim of the research was to identify the level of development and application of AM technology in the military domain. On the basis of the defined purpose of the work, the research problem was defined as follows: does the current level and scale of the use of AM technology both in industry and in the military domain justify the implementation of this technology to the logistic support of the Polish armed forces.

Methotology

The research was conducted as a review of selected literature from the last 10 years. To define the analysis database, the following keywords were used, which are defined in the DIN standard ISO EN/ASTM 52900 to describe research related to AM: Additive Manufacturing, Additive Manufacturing, 3D Printing (in various variations). In addition, terms not listed in the standard have been added: Rapid Manufacturing, Direct Tooling, Direct Manufacturing, Direct Prototyping, Additive Repair and Reengineering. The conclusions from the literature analysis were supported by personal experience of the authors obtained during participation in thematic conferences, seminars and meetings.

Literature review

Since additive manufacturing processes, were invented in the mid-1980s, there has being an upsurge in its use as an improving the speed of production, its flexibility and increasing the resilience of logistics supply chains to disruptions. Since then, hundreds of scientific studies have been published on general 3D printing as well (market and application domain) as on specific technical issues (material, machine and process, digital process chain, methodology). Publications devoted to the possibility of using AM technology in the military domain remain in the vast minority.

AM has the potential to "reduce lead time, cost, material waste and energy usage" (Wu et al., 2017). Industries that may benefit from these advancements include aerospace, automotive, energy, biomedical (Kluczyński et al., 2016) and military (Bird, Ravindra, 2021; Ficzere, 2022; Forecasting Change in Military Technology, [18 May 2023]). Moreover, AM offers a variety of potentials and advantages, such as the freedom of design, ease and unfettered form of creation (Francois et al., 2019; Ngo et al., 2018), which is seen as an enabler for light weighting (Gibson et al., 2015), part consolidation (Yang et al., 2015) or function integration (Gorn et al., 2019).

Significant advantages of 3D printing are small-scale production and facilitating the production of personalized and custom products, as well as low cost of production and less dependence on expensive and dedicated tools (Durakovic, 2018; Wu et al., 2017). Reverse engineering and 3D printing techniques may be used as a way of supporting the servicing of production machines (Loska et al., 2022). Due to its relatively high resistance of the production chain, AM technology can be used in crisis situations (Wysoczański et al., 2021).

In order to determine the main advantages and disadvantages of AM, measures (benchmarking) should be used that will enable comparison, in key correlating measures with classical production (economic, social and environmental). Thanks to them, manufacturing companies using additive manufacturing have the possibility of reliable comparison and usefulness of individual additive manufacturing technologies in relation to the assumed final results (Cf.: Kai et al., 2016). AM technology is an extremely complex process of the design process and the importance of pre-processing and post-processing activities cannot be underestimated in this complex process of 3D printing (Vayrea et al., 2012).

Before AM technology becomes dominant in mainstream manufacturing, a number of process and material challenges need to be overcome. As these are overcome, there will be other challenges such as standardization, inspections, business models, and of course unexpected consequences (Lyons, Devine, 2019).

One of the most important aspects of introducing 3D printing technology into production is the expected reduction in production costs. In the available studies, there is no unequivocal answer to the question whether AM is cheaper than classical methods of production (turning, milling, forging, welding) (Laureijs et al., 2017). The financial advantages of AM are achieved in the case of prototyping and unit production. Classic methods of large-scale production still turn out to be cheaper.

As COVID-19 pandemic has disrupted the supply chain around the globe, AM technology has come to the fore as one of the most reliable technology to improvise many medical devices (Arora et al., 2020).

AM is seen as a high tech in all areas of military technology (Forecasting Change in Military Technology, [18 May 2023]). AM technologies can hold great potential for enhancing defense capabilities, such as logistical support to forces deployed in remote or enemy environments. The time between failures and recovery of platform availability, the transport and storage of significant quantities of spare parts can be reduced, with associated cost reductions, reducing the logistical footprint of the operation (Ficzere, 2022).

3D printed sensor technology offers high-performance features as a way to track individual warfighters on the battlefield, offering protection from threats such as weaponized toxins, bacteria or virus, with real-time monitoring of physiological events, advanced diagnostics, and connected feedback (Bird, Ravindra, 2021).

Chosen information about Additive Manufacturing – Hardware, Technologies, Materials, and Applications

Despite the fact that three-dimensional (3D) printing technology was invented quite a long time ago, its significant development and commercialization took place at the beginning of the 21st century. The beginnings of 3D printing date back to the 70s of the last century, and Charles Hull is considered the inventor of 3D printing, who patented this invention in 1984. Over the last few years, there has been a significant development of 3D printing technology and it has recently begun to be perceived as a flexible and powerful technique that can be used both in the advanced manufacturing industry and for home use (Grochala, Boratyński, 2019).

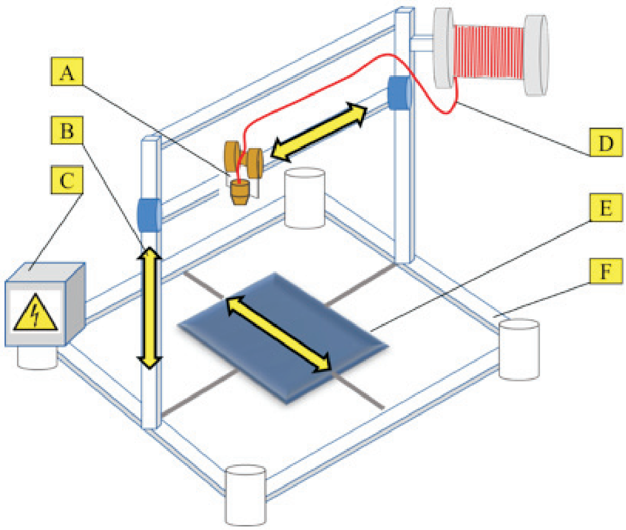


Fig. 1. Schematic diagram of the 3D printer with its essential components.
Source: Own study G. Stankiewicz

Process 3D is defined as printing consisting in the creation of elements (objects) by overlapping material or materials using a print head, nozzle or other technical solution. In turn, the additive manufacturing (AM) process itself is therefore the activity of combining materials to make an object based on digital data as to its three-dimensional shape – a 3D model of the object being made. In the literature on the subject, we can also meet such terms as (Cf.: Standard Terminology for Additive Manufacturing Technologies, [24 March 2023]):

- additive fabrication,
- additive processes,
- additive techniques,

– additive layer manufacturing,
– layer manufacturing,
– freeform fabrication.

The idea of additive layer manufacturing (3D printing) was and is based on the creation of three-dimensional objects using special printers. A prerequisite for this type of additive manufacturing (AM) is having a three-dimensional computer design. The 3D (Fig. 1.) printer is a kind of device which allows you to create (by printing) objects with precisely defined shapes in the appropriate technology with using different, relevant for its filaments.

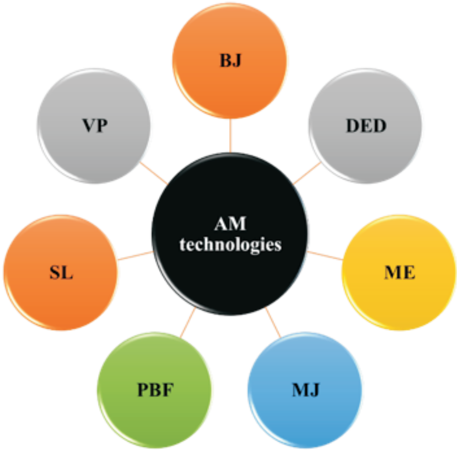
A 3D printer is built from many different elements. Each of them is responsible for the implementation of specific functions (tasks), which was presented by the authors in Table 1.

Table 1. Essential components of a 3D printer and their purpose

Lit.	Name of the element	The specific functions (tasks)	Additional information
A	PRINT HEAD	The print head is the element through which the filament enters, melts, and then forms in layers into the shape of the object to be printed. As a rule, it consists of two main parts, the cold end and the hot end. The head also has a filament movement mechanism.	There are two types of heads - single and double (with one or two nozzles). Single ones are used to print based on one type of consumable material, while double ones have the ability to print based on two different materials.
B	DRIVE (MOTION) MECHANISM	Provide the ability to move selected elements (parts) in x, y, and z directions to create a 3D printed object.	It is a crucial (next to the print head) element having a fundamental impact on the process of freeform fabrication
C	POWER SUPPLY UNIT	The power supply unit is responsible for supplying the individual components of the device at the appropriate power level.	It can be mounted both on the printer frame and separately, depending on the device producer.
D	FILAMENT	Filament is the raw material (material) needed to print objects in 3D technology. „Figuratively speaking" is like a cartridge (toner) in a traditional inkjet or laser printer.	Filaments are available in many colours and materials, so it is possible to choose them according to your needs.
E	PRINT BED	It is a working surface (tabletop) on which an object is created through its depositing in additive techniques. Printing beds come in two types – heated and unheated.	The heated „print bed" reduces the temperature difference between the hot filament material and the print table. This is an advantage because it allows the printed object to be easily separated from the surface on which it was manufactured.
F	FRAME	The frame is a kind of skeleton (base, foundation) of the 3D printer structure. It is an element that holds the other components together, at the same time responsible for the stability and durability of the machine.	Today, frames for 3D printers are made of various materials.

Source: Own work by G. Stankiewicz by on the basis of: (Cf.: 3D Printers components - how 3D printers work, [Accessed: 17 April 2023]; cf: Parts of a 3D Printer, [Accessed: 23 April 2023]

For many years, the additive manufacturing industry suffered from lack of categories of grouping AM (3D) technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings (Cf.: Standard Terminology for Additive Manufacturing Technologies, [24 March 2023]). Nowadays we have diffrent possibility for division of technologies which are used in additive layer manufacturing. They are for example connected with materials which are using in this kind of production. Below (Fig. 2.) Authors presented one such divisions.



BJ	binder jetting	an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials
DED	directed energy deposition	an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited
ME	material extrusion	an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
MJ	material jetting	an additive manufacturing process in which droplets of build material are selectively deposited
PBF	powder bed fusion	an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
SL	sheet lamination	an additive manufacturing process in which sheets of material are bonded to form an object
VP	vat photopolymerization	an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization

Fig. 2. AM technologies

Source: Own work by G. Stankiewicz by on the basis of: (An Introduction to Additive Manufacturing (Also known as 3D printing), [Accessed: 23 April 2023]; Standard Terminology for Additive Manufacturing Technologies, [Accessed: 24 March 2023])

Nowadays the AM technology has different areas of using (Fig. 3.). Key applications for 3D printing include:

- production process in industry - 3D printers deliver inter alia rapid tooling and replacement parts to maintain the production lines. Sometimes AM applications are used to creation of small batch the end-use products to speed up time to market of a product. This offers greater flexibility, enabling businesses to run small batches of goods without the risks involved of manufacturing a larger batch. There is also scope for "printing on the spot" and creating products for the customer while they wait;
- prototyping - low-cost and a lot of types of materials and short lead times make AM technology ideal for the iterative design process. 3D printed prototypes can be both visual (parts that look like a finished product) or functional (parts that are capable of being tested in real conditions);

– science and education - AM equipment and materials enables a variety of education applications – from engaging younger students with basics to providing research labs to work on engineering projects and develop skills in the much modern conditions.

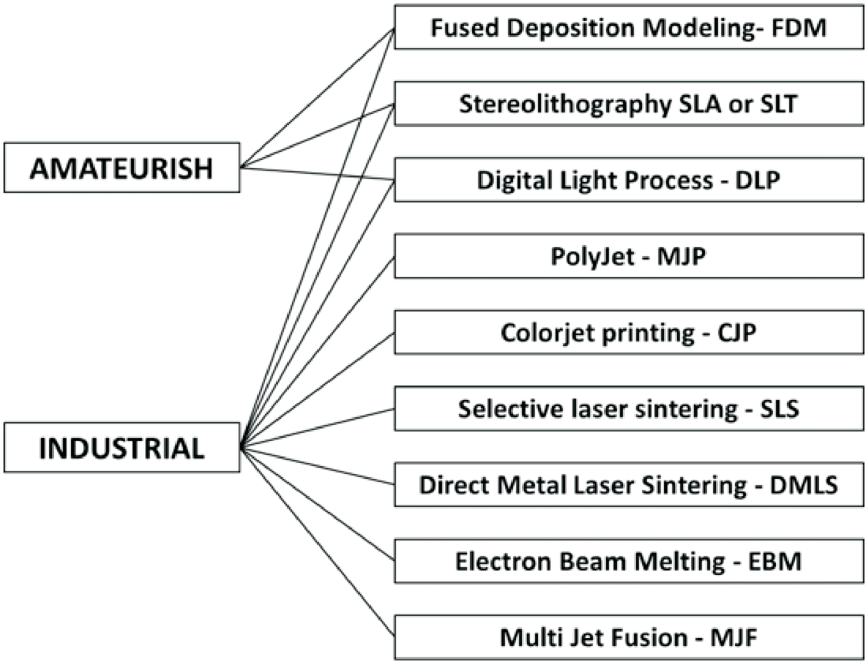


Fig. 3. Areas of application of individual 3D printing technologies
Source: own work by G. Stankiewicz by on the basis of: (Ślusarczyk, [Accessed: 27 October 2022])

We should be aware that in layer manufacturing particularly important are both the properties of the material (filament - its chemical composition, size, structure and particle distribution), as well as process parameters affecting, for example, the strength, ductility and surface finish of the final product. The use of appropriately selected materials for the construction of the object in layer manufacturing (the main classes of materials used and ways of use are introduced in Tab. 2.) is connected with the possibility of making different types of parts (including whole: elements and subassemblies) in accordance with the expected properties such as, for example: porosity, strength, stiffness or flexibility. (Cf.: About Additive Manufacturing, [23 April 2023]; cf.: Additive Manufacturing Materials, [04 April 2023]; cf.: An Introduction to Additive Manufacturing, [23 April 2023]; cf.: Gaweł, 2020):

– **Polymers** - in 3D printing can be used the popular plastics, including ABS and PC. The other structural polymers can also be used, as well as a number

of waxes and epoxy based resins. Mixing different polymer powders can create a wide range of structural and aesthetic materials. The following polymers can be used:
- ABS (Acrylonitrile butadiene styrene),
- PLA (polylactide), including soft PLA,
- PC (polycarbonate),
- Polyamide (Nylon),
- Nylon 12 (Tensile strength 45 Mpa),
- Glass filled nylon (12.48 Mpa),
- Epoxy resin,
- Wax,
- Photopolymer resins.

– **Metals** - a range of metals can be used, including a number of options suitable for structural and integral component parts. Common metals used: aluminum, titanium, stainless steel, Inconel and cobalt chrome, copper--nickel alloys. The main forms of delivery of metal filaments for additive layer manufacturing are usually wires or powders, or mixtures with other materials.

– **Composites** – are a group of materials dedicated to additive layer manufacturing, which has a heterogeneous structure, composed of two or more components. A composite can be created during the 3D printing process, or the process can start with a material that already contains the appropriate additive.

– **Ceramics** - a characteristic feature of ceramic materials is their particularly low level of absorption, which makes them difficult to print with laser systems. However, there are solutions based on extrusion, material spraying and photopolymerization. Ceramic powders can be used in the form of:
- Silica/Glass,
- Porcelain,
- Silicon-Carbide.

– **Sand** - even sand can be used as filament for 3D printing. By using n spraying of the binder, the grains are glued together. The technique is used for both prototype and production casting molds, as well as vacuum molds and other types of instrumentation, for example:
- Polymer-metal composites, polymer-ceramiccomposites and fiber--reinforced composites,
- Polymer composites, metal composites, metal-ceramiccomposites and fiber-reinforced composites,
- Polymer composites, ceramic composites, metal-ceramic composites, fiber reinforced composites,
- Composite with zirconia, alumina, calcium phosphate.

Table 2. Additive manufacturing process types and attributes, including example materials utilized in machines and typical ways of use

No.	Process	Group of Materials	Ways of use
1.	Vat Photopolymerization	Photopolymers	Prototyping
2.	Material Jetting	Polymers, Waxes	Prototyping, Casting Patterns
3.	Binder Jetting	Polymers, Metals, Foundry Sand	Prototyping, Casting Molds, Direct Part
4.	Material Extrusion	Polymers	Prototyping
5.	Powder Bed Fusion	Polymers, Metals	Prototyping, Direct Part
6.	Sheet Lamination	Paper, Metals	Prototyping, Direct Part
7.	Directed Energy Deposition	Metals	Repair, Direct Part

Source: Own work by G. Stankiewicz by on the basis of: (Scot et al., 2012)

Development and utilization of 3D in selected technologically leading armed forces

As mentioned above, 3D printing is increasingly used in almost all industries and beyond. The armed forces of many countries, based on the advantages of additive manufacturing technology, integrate 3D printing into their activities.

The adopted solutions, which are still being developed, vary depending on the functioning of the armed forces of a given country and its technological potential. There are countries that have been using AM technology in the military sector for many years: the USA, Great Britain, Germany, Norway and Australia. There are countries that started their adventure with the use of 3D printing in the defence sector just a few years ago: Italy, Spain, the Czech Republic and Portugal. There are also countries that have not introduced AM technology to support the operations of the armed forces. These countries include, among others, Poland.

The current state of development and the use of 3D printing in the armed forces of selected, technologically leading armed forces are presented below.

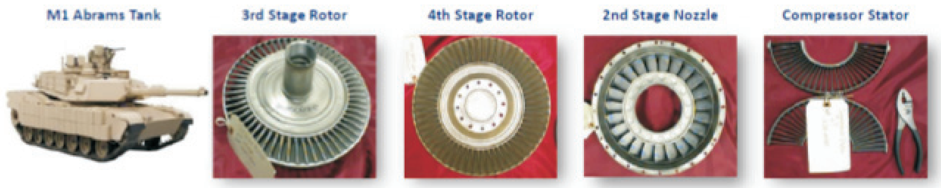
AM Technology in the US Military

In the U.S. Armed Forces, AM technology has been developed and used by the Army, Navy, Air Force and Marine Corps since at least 2012. However, the widespread use of 3D printing in the U.S. military began in 2016. What is more, the wide use of 3D printing in the US military began in 2016. Since then, the military's ongoing use of AM has grown significantly, evolving from basic prototyping to end-use parts in vehicles, planes, weapons, gear, shelters, and more.

All of the US military branches using 3D printing technology. Additive manufacturing projects across the US military can be categorized into three basic areas (Final Report. Department of Defense USA, [18 May 2023]):

1. Maintenance and Sustainment:
   - manufacture of parts typically produced using conventional manufacturing,
   - AM repair of conventionally manufactured parts (Fig. 4),
   - manufacturing aides for support to conventional manufacturing,
   - Prototyping for rapid innovation and reverse engineering.
2. Deployed and Expeditionary:
   - manufacturing of parts typically produced using conventional manufacturing,
   - AM repair of conventionally manufactured parts,
   - prototyping for rapid innovation and reverse engineering.
3. New Part/System Acquisition:
   - new parts/systems designed for AM and manufactured using AM,
   - manufacturing aides for support to conventional manufacturing,
   - prototyping for rapid part/system development.

Selected 3D printing applications across the US Military are presented below.



Material	Inconel 713	Inconel 713	Inconel 713	321 Stainless
New Cost	$ 8297	$ 5485	$ 6032	$ 910
Repair Cost	< $2,000	< $2,000	< 2,250	< $300
Savings/Part	> 75%	> 60%	> 60%	> 60%

Fig. 4. Example: US Army repair of components from Honeywell AGT 1500 gas turbine engine
Source: OPTOMEC presentation, AM Village 2nd preparation meeting, Prague 12-13.04.2023

In 2020, the U.S. Army needed a significant amount of night vision devices, with the ability to mount on combat vehicles, to increase visibility during low-light missions. The original supplier stopped producing parts, and replacing them would require a three-month lead time and cost $10,000. The Army used AM to solve the problem. In a matter of short days, they 3D printed two versions of the part using different materials, while maintaining significantly lower costs (Cf.: How are Different Branches of the US Military using Additive?, [25 April 2023).

In 2021, the US Army announced its intention to build the world's largest 3D printer using metal filaments. The U.S. Company DEVCOM Army Ground Vehicle Systems Center began work on building the printer with the help of ASTRO America, Ingersoll Machine Tool, Siemens and MELD Manufacturing at the Rock Island Arsenal – Joint Manufacturing and Technology Centre. In its assumption, the created printer is to be part of a wider Jointless Hull Project. Its ultimate goal is to be able to print monolithic (one-piece) hulls for combat vehicles. At the time of the announcement, it was assumed that the project would take about 14 months, and the final printer would be able to print metal parts 30 feet long, 20 feet wide and 12 feet high (Cf: Ficzere, 2022).

Another example is ITAMCO (Indiana Technology and Manufacturing Companies), which developed a runway for military expeditionary airports based on the use of additive layer manufacturing. The issue of runway surface is a key element of expeditionary airports (EAF). Their function using AM is to be carried out on weaker ground surfaces to enable landing and take-off of military aircraft (Cf.: Clemens, 2023). What is more, the Air Force Lifecycle Management Center regularly uses additive techniques to manufacture older parts for many obsolete fighter jets, including the B-52 fleet, the massive C-5M Super Galaxy and the B-2 Stealth bomber.

2017 is the year in which, for example, the additive fabrication was used by the US Navy to produce selected parts for submarines. This is the period in which the U.S. Navy and Naval Sea Systems Command (NAVSEA) undertake research into wider ways to use AM to design, print, approve and install critical or obsolete parts at sea. The crew members were taught how to set up, operate, and maintain 3D printers. They were also taught computer-aided design techniques and how to use precision scanning equipment. Once at sea, they will have the opportunity to practice their new skills on the ship by 3D printing various components (Cf.: Clemens, 2023).

This is to allow crews to 3D print parts and tools on demand to reduce repair time and further reduce part production costs. In 2022 the US Navy opened an Additive Manufacturing Center of Excellence in Virginia, where they hope to train young engineers on 3D printing technologies and to develop the use of the processes in order to scale them for big picture use.

AM Technology in the British Military

The British military, like the US military, uses 3D printing technology in all its military branches and in similar circumstances (the military forces of both countries are expeditionary in nature).

Particularly noteworthy in the use of AM technology in the British Army is the production, using 3D printing, of replacement parts for military vehicles in service. UK defence supplier Babcock International Group has introduced its first 3D printed metal parts for the British Army's Titan and Trojan fleets. This marks the first time that a UK defence supplier has produced metal-based 3D prints to extend the operability of the service's armoured vehicles. The metal printed components form part of the fleets' periscope system, which enables the Titan and Trojan operators to have complete visibility of the surrounding environment. 3D printed metal parts for the British Army's Titan and Trojan fleets is a significant step forward in the use of additive manufacturing in the UK defence industry. It demonstrates the potential of 3D printing to address technical and commercial obsolescence, as well as the ability to rapidly manufacture parts to support operations (British Army Gets AM Parts for Armoured Vehicles, [25 April 2023]).

The British Army will deploy SPEE3D's metal cold-spray printing for unplanned repairs via the purchase of an XSPEE3D printer and a two-year contract to provide training courses for Royal Electrical and Mechanical Engineers. One feature that makes the XSPEE3D well suited to this application is that it's built into a customized shipping container that measures 20 feet long, 8 feet deep and 8 feet high and contains both the printer and the necessary auxiliary equipment (Fig. 5.). It can produce parts as large as 1,000 mm x 700 mm and up to 40 kg in weight, with a deposition rate of up to 100 grams/minute via cold-spraying and it is compatible with a variety of alloys, including aluminium 6051, aluminium bronze and copper (Wright, 2023).

Fig. 5. Containerised metal 3D printer

Source: SPEE3D Will Work With British Army To Develop Their Additive Manufacturing Capabilities [online]. Available at: https://www.spee3d.com/resources/?resource=brochures [Accessed: 28 April 2023]

The UK and US army have also collaborated in the use of 3D printing to improve battlefield capabilities, as part of what is known as Project Convergence. Thanks to this project the British Army were able to contribute towards the manufacture of replacement parts for the US army using a 3D printer.

AM Technology in the German Military

The German Armed Forces started using 3D printing in their operations in 2016 initiating the research phase. This was followed by parallel activities in general 3D printing approach and the testing and trial phase. In 2020, the Customer Product Management Project was launched in the Bundeswehr and together with it the implementation phase was started. From 2023, the phase of using 3D printing technology in the German Armed Forces is being implemented. The multi-criteria approach to operational modelling of the use of AM in German Armed Forces and the time dependence of German Armed Forces activity in the AM field is presented in Fig. 6.

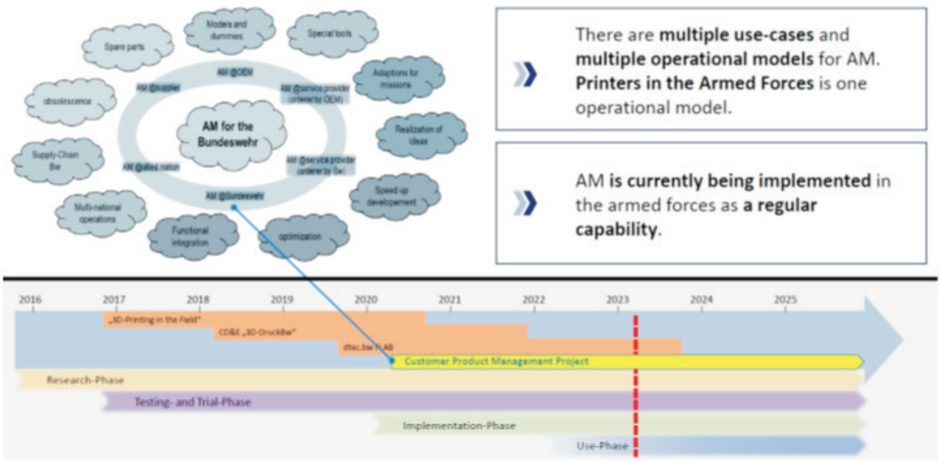


Fig. 6. DEU activities in the field of additive manufacturing

Source: Bundesministerium der Verteidigung presentation, AM Village 1st preparation meeting, Ede, Niderlands, 22-23 February 2023

Activities of German Armed Forces in the field of 3D printing are accompanied, coordinated and supported by the 3D Center of Excellence for materials and constructions methods (WIWeB). In a pilot project, WIWeB has rebuilt a steel spare part for the Weapon System WIESEL. It is a part from the undercarriage and it is used to attach the track wheels to the tank hull.

In the framework of the dtec.bw-project FLAB-3Dprint a high tech laboratory was set up at the University of the German Armed Forces in Munich for intensive research activities in the area of additive manufacturing.

3D printing was tested in action by German Armed Forces at a remote repair base in Mazar-e Sharif. During this test parts with low complexity can be constructed in the field by soldiers. The construction of complex parts was possible with reach back to experts from Germany.

The Luftwaffe has also been working with AM technology for some time and has already tested various use cases for practical application and made them suitable for small series production.

More over, the AM technology was successfully tested on a seagoing unit. Among others things, test were run to determin how maritime specyfic environmental influences (e.g. sea state, vibratioons of the drivetrain, salty air) affect 3D printing.

Conditions for the implementation of AM technology in the Polish Armed Forces

Positive experiences of the allied countries resulting from the implementation of 3D printing technology to the military logistic support system of the troops, initiate the idea and the concept of using this technology in the Polish Armed Forces (PAF). The premise for the implementation of AM is to improve both the effectiveness and efficiency of individual activities (processes) of military logistic support.

The use of AM technology (with a reengineering process) by the maintenance and repair elements of the PAF technical support subsystem will significantly shorten the logistics supply chain, increase its resistance to its disruptions, improve the process of repair and regeneration of military equipment, and enable relatively quick production on an ad hoc basis (also in field conditions) hard-to-find spare parts, including obsolete parts.

For this purpose the conditions of the functioning of logistic support in the PAF, in terms of the implementation of the AM technology, must be analysed. A number of doctrinal documents must be analysed in terms of the implementation of 3D printing.

Organizational structures, the best suitable hardware needs (3D printers, scanners, post-processing devices, IT hardware and software), workforce needs, and human resources should also be analysed.

On the example of the armed forces of other countries, the AM implementation process should be divided into individual phases and their time course throughout the life cycle should be determined (concept, R&D, pilot studies, O&M and retirement).

Work on issues related to intellectual property rights, including technical documentation, must be undertaken.

An extremely important issue that should be given special attention is the definition of information and communication technologies (ICT) security requirements. For the proper functioning of the 3D printing technology in field conditions, it is necessary to exchange data via an ICT network between additive production stations and the AM database (Fig. 7.).

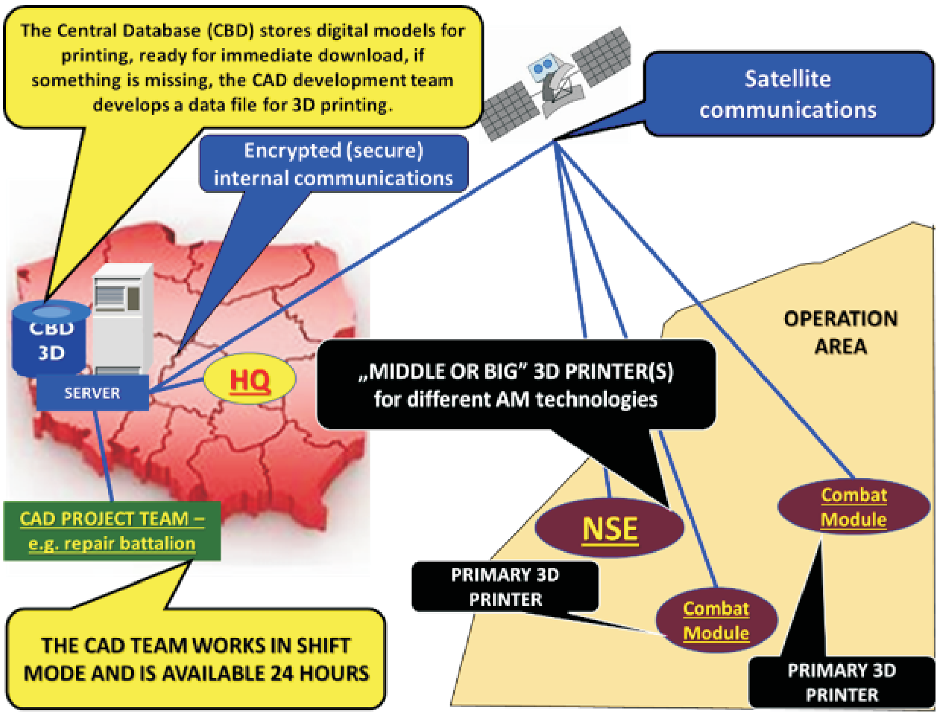


Fig. 7. Variant of placement means of AM to support expeditionary operations with chosen elements of ICT network

Source: Own work by G. Stankiewicz

More over the current national capabilities of the AM industry, possibility of cooperation with foreign partners, uniform printer model for the PAF, the life cycle and life cycle costs (total ownership costs - TOC) of AM technology should be taken into account.

Conclusions

The use of additive technology, acquiring knowledge and practical experience in the field of this technology is especially important from the point of view of the functioning of the Armed Forces in the future, because additive manufacturing will certainly be one of the factors increasing the repair and maintenance capabilities of military equipment.

It should be assumed that certainly, in the foreseeable future, that the Polish Armed Forces will implement a variety of additive manufacturing techniques, equipment and materials.

Of course, this will involve a number of procedural and organizational challenges concerning, for example, how to create databases with digital versions of components and parts, 3D scanning, creating mobile solutions, etc. In addition, attention should also be paid to the need to properly prepare personnel to operate 3D devices, as well as to perform activities as part of extensive programming using IT systems dedicated to additive manufacturing.

In the authors opinion, there is no doubt that the introduction of AM technology to the logistical support of the Polish Armed Forces will result in an increase in the effectiveness, efficiency and resilience of the supply chain, especially in combat service support.

BIBLIOGRAPHY

[1] 3D Printers components - how 3D printers work [online]. Available at: https://solectroshop.com/en/blog/3d-printers-components-how-3d-printers-work-n40 [Accessed: 17 April 2023].

[2] About Additive Manufacturing [online]. Available at: https://www.lboro.ac.uk/research/amrg/about/materials/ [Accessed: 23 April 2023].

[3] Additive Manufacturing Materials [online]. Available at: https://www.additivemanufacturing.media/kc/what-is-additive-manufacturing/am-materials [04 April 2023].

[4] An Introduction to Additive Manufacturing (Also known as 3D printing) [online]. Available at: https://additivemanufacturing.com/basics/ [Accessed: 23 April 2023].

[5] Arora, R., Arora, P. K., Kumar, H., Pant, M., 2020. Additive manufacturing enabled supply chain in combating covid-19 [online]. In: Journal of Industrial Integration and Management, 5 (4). Available at: https://doi.org/10.1142/S2424862220500244 [Accessed: 18 May 2023], 495-505.

[6] Bird, D. T. , Ravindra, N. M., 2021. Additive Manufacturing of Sensors for Military Monitoring Applications [online]. In: Polymers (Basel), 13 (9:1455). DOI: 10.3390/polym13091455.

[7] British Army Gets AM Parts for Armored Vehicles, 12 Jan 2023 [online]. Available at: https://3dprinting.com/news/british-army-gets-am-parts-for-armored-vehicles/ [Accessed: 25 April 2023].

[8] Bundesministerium der Verteidigung presentation, AM Village 1st preparation meeting, Ede, Niderlands, 22-23 February 2023.

[9] Clemens, M., 2023. The Use of Additive Manufacturing in The Defense Sector, 3dnatives.com [online]. Available at: https://www.3dnatives.com/en/the-use-additive-manufacturing-defense-sector300620224/#! [26 April 2023].

[10] Durakovic, B., 2018. Design for additive manufacturing: benefits, trends and challenges [online] [in:] Periodicals of Engineering and Natural Sciences, 6 (2). Available at: http://dx.doi.org/10.21533/pen.v6i2.224 [Accessed: 18 May 2023], 179-191.

[11] Ficzere, P., 2022. Additive Manufacturing in the Military and Defence Industry [online] [in:] Design of Machines and Structures, 12 (2). Available at: https://doi.org/10.32972/dms.2022.016 [18 May 2023], 80-85.

[12] Final Report. Department of Defense USA, Additive Manufacturing, Roadmap [online]. Available at: https://www.aimhigherconsortium.org/shared-files/1298/Final-Report-DoDRoadmapping-FINAL120216.pdf [Accessed: 18 May 2023].

[13] Forecasting Change in Military Technology, 2020–2040 [online]. Available at: https://www.brookings.edu/research/forecasting-change-in-military-technology-2020-2040/ [Accessed: 18 May 2023].

[14] François, M., Segonds, F., Rivette, M., Turpault, S., Peyre, P., 2019. Design for additive manufacturing (DfAM) methodologies: a proposal to foster the design of microwave waveguide components [online] [in] Virtual and Physical Prototyping, 14 (2). Available at: https://doi.org/10.1080/17452759.2018.1549901 [Accessed: 18 May 2023], 175-187.

[15] Gaweł, T. G., 2020. Review of Additive Manufacturing Methods [online] [in:] Solid State Phenomena, 308. Available at: https://doi.org/10.4028/www.scientific.net/SSP.308.1 [Accessed: 23 April 2023], 1-20.

[16] Gibson, I., Rosen, D., Stucker, B., 2015. Additive manufacturing technologies. 3D printing, Rapid Prototyping, and Direct Digital Manufacturing. 2nd ed. New York: Springer Science+Business Media [online]. Available at: https://doi.org/10.1007/978-1-4939-2113-3 [Accessed: 18 May 2023].

[17] Gorn, M., Cerwenka, G., Gralow, M., Emmelmann, C., 2019. Industrial 3D printing for modern machine and handling systems - Potential and solutions. In: Journal of Laser Applications. Laser Institute of America, 31 (2) [online]. Available at: https://doi.org/10.2351/1.5096098 [Accessed: 18 May 2023], 31, 022309-1- 31, 022309-6.

[18] Grochala, M., Boratyński, W., 2019. Potencjał druku 3D – wykorzystanie kostiumu „age suit", zaprojektowanego w technologii 3D jako narzędzia edukacyjnego dla studentów [online]. In: Medycyna Ogólna i Nauki o Zdrowiu, 25 (2). Available at: https://www.monz.pl [Accessed: 23 March 2023], 112-117.

[19] How are Different Branches of the US Military using Additive? [online]. Available at: https://markforged.com/resources/blog/how-are-different-branches-of-the-us-military-using-additive [Accessed: 25 April 2023].

[20] Kai ,D. A., Pinheiro de Lima, E., Wesley, M., Cunico, M. W. M., Gouvêa da Costa, S. E. 2016. Measure Additive Manufacturing for Sustainable Manufacturing [online]. Available at: https://ebooks.iospress.nl/publication/45397 [Accessed: 18 May 2023]. In: Advances in Transdisciplinary Engineering, 4: Transdisciplinary Engineering: Crossing Boundaries, 186 – 195. DOI: 10.3233/978-1-61499-703-0-186.

[21] Kluczyński J., Śnieżek L., Grzelak K., 2016. Development aspects of incremental technology in engineering industry applications [online]. Available at: https://www.researchgate.net/publication/330281815_Development_aspects_of_incremental_technology_in_engineering_industry_applications [Accessed: 18 May 2023]. DOI:10.15199/148.2016.5.2.

[22] Laureijs, R E., Roca, J. B., Narra, S. P., Montgomery. C., Beuth, J.L., Fuchs, E. R. H., 2017. Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes [online] [in:] Journal of Manufacturing Science and Engineering, 139 (8). Available at: https://doi.org/10.1115/1.4035420 [18 May 2023], 081010-1 - 081010-9.

[23] Loska, A., Palka, D., Bień, A., Substelny, K., 2022. A way of supporting the servicing of production machines using reverse engineering and 3D printing techniques [online] [in:] Technologia i automatyzacja montażu, 1/2022. Available at: https://doi.org/10.7862/tiam.2022.1.3 [Accessed: 18 May 2023], 28-36.

[24] Lyons, J.G., Devine, D.M., 2019. Additive Manufacturing: Future Challenges [online]. In: Devine, D. (eds) Polymer-Based Additive Manufacturing. Springer, Cham. Available at: https://doi.org/10.1007/978-3-030-24532-0_12 [18 May 2023], 255-264.

[25] Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., Hui, D., 2018. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges [online] [in:] Composites Part B: Engineering, 143. Available at: https://doi.org/10.1016/j.compositesb.2018.02.012 [Accessed: 18 May 2023], 172-196.

[26] OPTOMEC presentation, AM Village 2nd preparation meeting, Prague 12-13.04.2023.

[27] Parts of a 3D Printer [online]. Available at: https://3dinsider.com/3d-printer-parts/ [23 April 2023].

[28] Scott, J. (Project Leader), Gupta, N., Weber, Ch., Newsome, S., 2012. Additive Manufacturing: Status and Opportunities, IDA, March 2012 [online]. Available at: https://cgsr.llnl.gov/content/assets/docs/IDA_AdditiveM3D_33012_Final.pdf [Accessed: 23 April 2023].

[29] Ślusarczyk, P., Technologie przyrostowe [online]. Available at: https://www.3dwpraktyce.pl/wp-content/uploads/2017/12/Druk-3D-diagram.pdf [Accessed: 27 October 2022].

[30] SPEE3D Will Work With British Army To Develop Their Additive Manufacturing Capabilities [online]. Available at: https://www.spee3d.com/resources/?resource=brochures [Accessed: 28 April 2023].

[31] Standard Terminology for Additive Manufacturing Technologies. ASTM F2792-12a [online]. Available at: http://web.mit.edu [Accessed: 24 March 2023].

[32] The materials presented during the European Military Additive Manufacturing Symposium, European Defence Agency, Bonn, 12-13 October 2021.

[33] Vayrea, B., Vignata, F., Villeneuvea. F., 2012. Designing for Additive Manufacturing [online]. Available at: https://doi.org/10.1016/j.procir.2012.07.108 [Accessed: 18 May 2023]. 45th CIRP Conference on Manufacturing Systems 2012 Athens, Greece 16-18 May 2012, 632-637.

[34] Wright, I., 2023. British Army taps SPEE3D's additive manufacturing for unplanned repairs, April 12 [online]. Available at: https://www.engineering.com/story/3d-printing-is-the-british-armys-new-secret-weapon [Accessed: 25 April 2023].

[35] Wu, B., Myant, C., Weider, S. Z., 2017. The Value of Additive Manufacturing: Future Opportunities [online]. In: Institute for Molecular Science and Engineering, Briefing Paper, 2. Available at: https://spiral.imperial.ac.uk/bitstream/10044/1/53611/2/IMSE-AMN%20The%20value%20of%20additive%20manufacturing-future%20opportunities.pdf [Accessed: 18 May 2023].

[36] Wysoczański, A., Kamyk, Z., Yvinec, Y., 2021. Analysis of the possibility of employing 3D printing technology in crisis situations [online]. In: Technical Transactions, 8. Available at: https://doi.org/10.37705/TechTrans/e2021008 [Accessed: 18 May 2023].

[37] Yang, S., Tang, Y., Zhao, Y. F., 2015. A new part consolidation method to embrace the design freedom of additive manufacturing [online]. In: Journal of Manufacturing Processes, 20 (3). Available at: https://doi.org/10.1016/j.jmapro.2015.06.024 [Accessed: 18 May 2023], 444–449.