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AZ ADDITÍV TECHNOLÓGIA ÉS A 3D NYOMTATÁS LEHETŐSÉGEI A KATONAI LOGISZTIKÁBAN, KÜLÖNÖS TEKINTETTEL AZ ADAM FÉMNYOMTATÁSRA ÉS A SZÁLERŐSÍTÉSŰ KOMPOZITOK NYOMTATÁSÁRA

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THE POTENTIAL OF ADDITIVE TECHNOLOGY AND 3D PRINTING IN MILITARY LOGISTICS, WITH REFERENCE TO ADAM METAL PRINTING AND THE PRINTING OF FIBRE-REINFORCED COMPOSITES

Abstract:

This paper will describe some modern additive manufacturing technologies and their potential applications and own related experiences, with a special focus on their use in the field of military logistics. It also will present 3D metal printing using ADAM technology, its application possibilities, the possibility and advantages of producing closed internal structures and cells, and the printability of high melting point metals. It will describe some of the options for printing composite plastic parts with combined chopped and continuous fibre reinforcement filament. The paper also presents the research results related to additive manufacturing technology achieved in the 3D printing laboratories of the Department of Military Technology, Faculty of Military Science and Officer Training, University of Public Service.

Keywords: *additive manufacturing, 3D printing, Atomic Diffusion Additive Manufacturing metal printing, printing of fibre-reinforced composites*

INTRODUCTION

3D metal printing is today's state-of-the-art manufacturing technology. Today, a wide range of additive manufacturing technologies are available to produce 3D printed parts.[1] As a result, 3D printing is gaining momentum in industry and the defence industry, as well as in military logistics. This article presents research results related to additive manufacturing technology achieved in the 3D printing laboratories of the Department of Military Technology, Faculty of Military Science and Officer Training, University of Public Service, mainly in the field of military logistics.

1 BACKGROUND

The main scientific problem to be solved in the field of military logistics is that, according to NATO's current understanding, the components of military equipment, including combat vehicles and other military vehicles, must be secured even in remote areas during the operations. However, the provision of spare parts cannot always be achieved from the stocks of specialised material deployed in the mission area. In addition, the supply of spare parts cannot always be guaranteed even in peacetime during the force's activities on home territory, especially for technical equipment that has been in service for decades. In such situations, some NATO member states, notably the United States and Germany, have in recent years started to customise and produce spare parts, including metal and plastic parts, as required, using additive manufacturing technology and 3D printing. The US forces are conducting additive manufacturing research at the following research laboratories and institutes:

- CCDC Army Research Laboratory,
- Naval Research Laboratory,
- Air Force Research Laboratory,
- Army Materiel Command Additive Manufacturing Centre of Excellence,
- U.S. Army Research, Development and Engineering Command - ARDEC.

A 3D-printer container was successfully deployed by air for research purposes in Spain during the 2017 NATO European Combat Airlift Exercise and the Australian Defence Force has already gone into service a containerised metal printer.[2]

Hungary's National Military Strategy 2021 stated that some new technologies, such as "the military application of 3D printing ... will fundamentally change the rules and procedures of current warfare."[3] 3D printing is a technology to be introduced in the Hungarian Defence Forces. The Hungarian Defence Forces are also represented in the European Defence Agency's 3D Printing for Military Logistics Applications R&D working group.[4] The Department of Military Technology is represented in the European Defence Agency 3D Printing for Military Logistics Project Working Group (Additive Manufacturing for Logistic Support Project Working Group), which last meeting was held in Stockholm (16-09-19 September 2024).

In 2022, the Faculty of Military Science and Officer Training of the University of Public Service acquired several 3D printers with different technologies, including a metal and a fibre-reinforced composite printer. The reason is that 3D printing is fixing its place today, both in the defence industry and in military logistics and logistic operations management, as well as in military higher education.[5] ADAM technology printing - the Markforged MetalX metal printer - was introduced to the US Army's military logistics toolkit in 2018.[6] The

Department of Military Technology began research with this type of Markforged MetalX metal printer in 2022. This paper describes the ADAM (Atomic Diffusion Additive Manufacturing) 3D metal printing technology used by the mentioned printer. It discusses the printability of high melting point metals, the possibilities of ADAM 3D printing and the impact of the emergence of these metals on the development of military technology. It discusses the possibilities and advantages of producing closed internal structures and cells. It also describes some of the possibilities for printing fibre-reinforced composite plastic parts.

For the replacement of some parts with 3D printed sub-parts, the degree of mechanical stress, or the resulting thermal loads, life cycle requirements, etc., clearly require the manufacture and use of metal parts. For example, the US Marine Corps (USMC) Weapons Engineering Workshop in Okinawa also uses a Markforged MetalX metal printer for this purpose - the same type is used for its military logistics metal printing research by the Department of Military Technology.[6] In the last two years, the department has 3D printed about 200 different machine parts and test pieces with this type of machine.

One of the 3D printers purchased by the Faculty of Military Science and Officer Training is a MarkForged Onyx One composite printer with fibre-reinforced plastic technology. The combination of advanced material technology and additive manufacturing technology used in this printer allows for the replacement of automotive metal parts with lower specific gravity plastics, as well as the flexible production of replacement parts. Nowadays, some advanced 3D plastic printers can incorporate continuous glass fibre, carbon fibre or Kevlar fibre reinforcement into the printed product, with the possibility of adding chopped carbon fibre reinforcement to the base material too (e.g. ABS-CF). 3D printing of chopped fibre-reinforced plastics or continuous fibre-reinforced composite plastics gives a new way to produce material with strengths close to some light metals. The strength properties of such a composite plastic machine part, manufactured by additive manufacturing techniques, reinforced with both continuous and chopped fibre-reinforcement are favourable - especially for the loads imposed by the plane of filament reinforcement. Taking all this into account, it can be hypothetically assumed that there is a set of automotive components for which the substitution of metal by 3D printed plastic. The possibility of replacing metal parts with plastic 3D printed parts should therefore be explored, for the following advantages:

- lower structural mass,
- lower production costs,
- shorter production time compared to 3D printing of metal parts,
- good corrosion resistance without the need for post-treatment.[1]

The Department of Military Technology has 3D printed about 100 different machine parts in two years with a MarkForged Onyx One fibre reinforced composite printer.

2 THE ATOMIC DIFFUSION ADDITIVE MANUFACTURING METAL 3D PRINTING TECHNOLOGY

The materials that can be used for ADAM technology are tool steels, stainless steel, heat-resistant Inconel (e.g. Inconel 625 or 718) or copper. The ADAM metal printing process is capable to build of:

- complex geometries such as closed-cell internal structure machine parts (e.g. with giroid filling, complex holes),
- printing high melting point metals (e.g. inconel - nickel containing heat-resistant alloy) (e.g. turbine blades, exhaust valves, rocket engines, heat exchangers),
- printing low melting point metals (e.g. copper),
- rapid replacement of raw materials,
- avoiding of unhealthy metal powder pollution.

Other metal printing technologies (e.g. powder bed) are not, or less suitable to offer these advantages.

Atomic Diffusion Additive Manufacturing (ADAM) is a 3D manufacturing process that involves three steps: printing, washing and sintering. The Markforged Metal X 3D metal printer with ADAM technology extrudes metal powders bonded to a polymer matrix using a traditional fused deposition method like plastic FDM printing. There is a second head in the printer that prints a thin ceramic partition layer to form supports that are built up to support the fabrication. The ADAM printer produces printed objects layer by layer from a metal powder bonded with thermoplastic polymer and wax using Eiger software. During the software-controlled printing process, due to shrinkage of the sintering phase in the furnace, the model is printed in a larger size, as calculated. After the printing and a wash phase this metal powder mixed into the polymer and wax binder will be melted.

The printed ‘green’ part is placed in a binder removal component washing station. In this station the binder wax is extracted from the workpiece by washing it mechanically in a heated (50-54°C) and the solvent is circulated for 12-23 hours. The Eiger software calculates the expected washing time in relation to the thickness of the part when slicing. After printing, a mass measurement is taken, followed by another mass measurement after the washing time has elapsed, which is recorded in the software. The difference of these mass measurements should be matched by a calculated weight loss. If the mass loss is not sufficient the operator should start another wash until the desired mass loss is achieved. (If the wash duration does not the sufficient time that may cause wax clogging in the sintering furnace.) Then, during the washing phase in the Tergo Cleaning Fluid, only the wax content is dissolved out of the green part, the remaining polymer content holds the ‘brown’ part together until sintering. The polymer burns out only in the sintering furnace, in the first phase of the firing cycle, the 'debinding' phase. Any remaining waxy binder from the washing process burns out of the part during sintering.

The part is sintered in a heat treatment furnace to achieve the quality of the casting. During this process, the 'brown' washed parts are placed on the ceramic plate of sintering furnace, and are sintered in the furnace for about 22-27 hours at a temperature of ~1300°C depending of the material. The part is sintered at this temperature in an argon shielding gas to obtain the final part. However, the technology has a peculirity, however, in that the sintering process not only reduces the volume of the finished model, which can even deform it on certain geometries. The risk of deformation highly increases above a length-to-height ratio of 1:6. When using this technology, the print can suffer a shrinkage of up to 7-9% compared to its original size (depend on the type of the material), which is compensated with a calculated print size tolerance by the Eiger design software. The sintering time is thus increased to about 37 hours, but the possibilities for improving the material properties are extended. Heat treatment of the component can of course also be carried out in a separate heat treatment furnace, if required. The manufacturer provides recommendations on the heat treatment parameters. In the sintering furnace all non-metallic additives are burnt out of the model, and argon shielding gas protects the metal from reacting with oxygen. In the final phase of sintering, the argon gas is mixture containing 2.4% hydrogen is used in the furnace. The residual plastic contents that burn out of the sintered part are removed with the gases. The effect on strength of the orientation of the sintered part produced by ADAM technology has also been studied in detail by researchers.[7] Thus, overall, both the limitations and potential of the technology are documented, and its characteristics are well-known.

Parts made with ADAM technology are suitable for further machining, surface treatment or even for strength enhancement by heat treatment. The name ADAM technology refers to the important feature whereby printing is carried out layer by layer using metallic filament, which, however, fuse together during sintering to form a homogeneous product, guaranteeing essentially the same strength characteristics in all directions. The use of 3D metal printing with ADAM technology is advantageous for heat-resistant, difficult-to-cast and difficult-to-machine alloys especially. These alloys, for example the Inconel are heat-resistant up to around 700-1000 °C. Inconel IN625 has a tensile strength of 920 MPa, bending strength of 670 MPa, elongation at break of around 40%, and a heat resistance up to 1000 °C.[8] The application of Inconel is equally important for turbine components in gas turbines and turbochargers.

One of the key areas for the development of 3D metal printing is the development of printable metallic materials from a materials science perspective, and the expansion of the palette. High melting point metals play an important role in the production of turbine blades, gas turbine gas speed governors and gas jet control arms, rocket engines, exhaust valves, heat exchangers. In addition, stainless steel, tool steels, and copper can be printed using ADAM technology, for which the range of materials is currently being expanded and developed.

3 3D PRINTING OF FIBRE-REINFORCED COMPOSITES

Nowadays, in the field of plastics printing, we can consider the FDM/FFF (Fused Deposition Modelling) technology as the most common one. In plastic 3D printing, we distinguish between homogeneous plastic and fibre-reinforced plastic products. Widely used filaments for this technology, e.g. PET, PETG, ASA, ABS and Nylon, can be admixture with short cut carbon fibres as additives in the polymers in quantities of around 15-20%. By adding short cut fibres - glass fibre or carbon fibre - at this rate, the bending strength can be increased by a factor of two to three in a 3D printed structural element. Another new possibility in additive manufacturing is the continuous fibre reinforcement of plastics, as nowadays not only micro-sized fibres can be mixed into the base material, but also additional continuous fibre reinforcement can be added to the construction layers, further improving the strength properties (even if only in one dimension).

The 3D printing of fibre-reinforced plastics, both chopped and/or continuous fibre-reinforced offers a new material with strengths approaching those of some lightweight metals. It has been known since the 1970s that 30% glass fibre reinforced polyamide increases in density by only 20%, while its specific tensile strength more than doubles.[9] For today the mechanical properties of different fibres in 3D printed plastic composite structures has extensively investigated and the effect of glass fibre on bending strength has been found to be beneficial, among other things. [10] It is also known that polyamide samples reinforced with 20% short carbon fibre show a 50% improvement in tensile strength, in addition to better adhesion between printed layers.[11]

Combining the two technologies - short carbon fibre reinforcement and continuous fibre reinforcement - in a printed polyamide product is an obvious solution. Nowadays, some advanced 3D plastic printers can incorporate continuous glass fibre, carbon fibre or Kevlar fibre reinforcement into the printed product, which can also be backed with a chopped carbon fibre reinforcement. The strength properties of such a composite plastic machine part, manufactured using additive manufacturing technology, reinforced with both continuous fibre reinforcement and staple fibre reinforcement, are extremely favourable - especially for in-plane loads supported by fibre reinforcement.

The Department of Military Technology uses Markforged Onyx Pro printer for composite printing. The technology of the Markforged Onyx Pro printer is FFF (filament-drawing) type, its feeder is a double gear, wear-resistant, a composite-ready construction. It is also capable of printing continuous filament reinforced workpieces. It can create closed cells with various fillings (e.g. giroid). The workplace size is 320×130×160 mm, the created layer thickness is 100 - 200 µm. The power consumption is up to 350 W. Recommended printer head temperature 210 - 220 °C and hotbed temperature 60 °C. The device is also capable of printing continuous fibre reinforced - glass fibre reinforced - workpieces. The largest fibre-reinforced Onyx (polyamide) plastic composite printer currently available from Markforged is the FX-20, with a working area of 525 mm x 400 mm x 400 mm - which may already be suitable for some industrial-scale component manufacturing needs.

The PA6 Onyx composite filament used contains small, short carbon fibres, which allows for significant load capacity and component durability, while the temperature tolerance of the component can be increased to over 130-140 °C. The PA base material is thus suitable to produce components and brackets in the engine compartment of motor vehicles. Onyx matrix material characteristics: nylon (PA6 polyamide) with short, chopped carbon fibre reinforcement (tensile strength is 40 MPa, bending strength is 90 MPa).[12] The continuous fibre reinforcement is placed, in the x-y plane only. The tensile strength of the glass fibre applicated is 240 MPa. The maximum strength of a matrix fibre composite structure with glass fibre reinforced base material is 200 MPa, while for high strength HSHT (High Strength High Temperature) glass fibre it is 400 MPa. The more advanced Markforged printers achieve 550 MPa strength with continuous carbon fibre reinforced Onyx substrate. Strength testing of these Onyx filament types has also been validated by the Institute of Additive Manufacturing Technology at a Hungarian university.[13]

Based on literature data, the strength of composite 3D printed Onyx parts with short and continuous fibre reinforcement can be further improved by topological optimization.[14]

The Markforged Onyx Pro composite printer used by the Department of Military Technolgy has created an opportunity to test the replacement of metal parts with plastic. Researchers from the University of Public Service modelled, fabricated and tested the usability of 3D printed, continuous glass fibre and short-cut carbon fibre reinforced, high-strength, heat-resistant Onyx polyamide composite parts on a coolant pipe of a vehicle cooling system. The mechanical behaviour of the component, its chemical and thermal resistance, and its resistance to resonance have been tested in field usage. During the experiments, the composite coolant tube successfully replaced the metal coolant tube.

4 3D PRINTING RESULTS AT THE THE DEPARTMENT OF MILITARY TECHNOLOGY

In the last two years, the Military Technology Department has 3D printed more than 300 different machine parts and test pieces with Markforged MetalX metal printer and Markforged Onyx One composite printer machine.

The most important metal-based printed components were the following:

- 220 metal test specimens, including 33 dices of 17-4PH stainless steel V1 material,
- metal gears (D2 shear-steel),
- VR simulation system 3D printed metal quick-fitting elements (8 parts, printed in 17-4PH stainless steel V1 material with hollow fill),
- various metal brackets, coupling elements (17-4PH stainless steel V1 material, printed with hollow core),
- tool (socket wrench) with hexagonal coupling element (made of 17-4PH stainless steel V1 material, printed with hollow core),
- Rába truck exhaust valve (made of D2 shear-steel with hollow design),
- 8 mm metal plates (made of D2 shear-steel and solid copper),
- several other metal parts for motor vehicles.

The most important printed fibre-reinforced plastic material parts, (mainly Onyx PA6 continuous glass and carbon fibre-reinforced composite) were the following:

- Unimog truck small and large rear light sockets,
- Unimog truck radiator hose support clamp,
- UAV propeller (Onyx PA6 high strength continuous glass and cut carbon fibre reinforced composite material);
- other fibre reinforced composite automotive parts, tools, and wrenches.

In addition to these, many partly composite and plastic (mainly PLA) 3D printed educational models were produced for the department:

- a clutch actuating cylinder (PLA) for a Rába clutch,
- a planetary gear for a Rába clutch,
- instructional model of an internal combustion engine piston and sectional model,
- instructional model of an internal combustion engine valve and sectional instructional model,
- instructional model of a spring,
- instructional model of an injection pump pressure valve for diesel engine,
- springs, snap joints,
- lithophane experimental fixture, etc.

Summary and lessons learned

This paper has investigated some of the modern additive manufacturing technologies and their potential applications and experiences in the field of military logistics, and the following conclusions can be drawn:

- The ADAM metal printing process can produce complex geometries, closed-cell internal structure machine parts, by using high and low melting point metals,
- ADAM technology allows to change used metal in very short time,
- During the sintering phase of the ADAM technology, the printed layers are fused into a homogeneous product, guaranteeing essentially the same strength characteristics in all directions,
- The printing of combined fibre-reinforced composite plastic parts with short staple fibres and continuous filament offers the possibility of replacing some metal parts with fibre-reinforced composite,
- Replacing parts with plastic 3D printed parts is advantageous due to the lower structural weight, lower manufacturing cost, shorter manufacturing time compared to 3D printing of metal parts, and favourable corrosion resistance,
- Because of its heat and chemical resistance, thermal stress and resonance resistance of the 3D printed, continuous glass fibre and short-cut carbon fibre reinforced, high-strength, heat-resistant Onyx polyamide composite component can be suitable to replace metal car parts,
- - 3D printing can be used to ensure some kind of spare parts supply even in remote areas and during military operations.

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PHOTOS (ALL PHOTOS TAKEN BY THE AUTHORS)

Figure 1. 3D metal printing laboratory with ADAM technology: the printer in the left corner, the washer in the foreground, sintering furnace, and the gas supply system in the background

Figure 2. Removal of printed metal parts made by ADAM technology from the sintering furnace

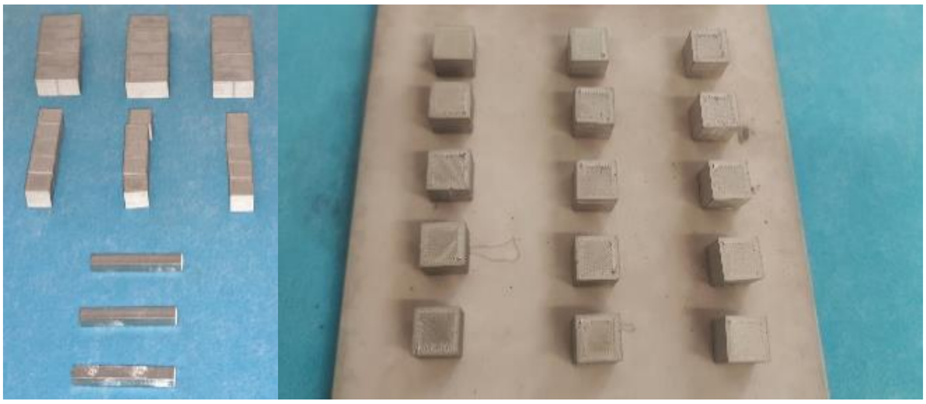

Figure 3. Printed specimens for checking dimensional accuracy

Figure 4. Manufacturing of standardised material test specimens

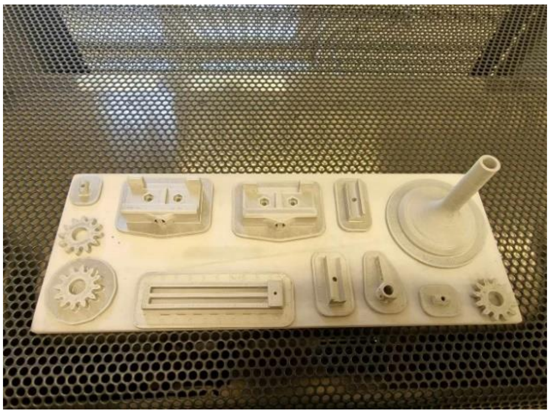

Figure 5. Various machine components (gear, coupling, valve, etc.) on the ceramic tray of the sintering furnace

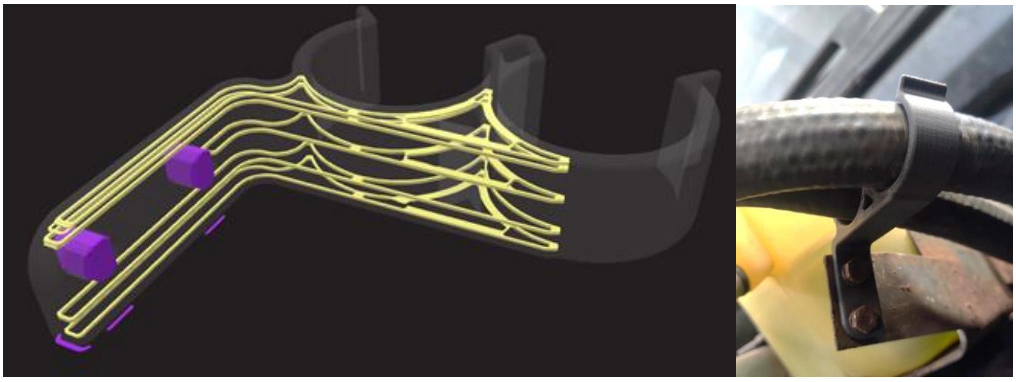

Figure 6. Coolant pipe support for cooling system of motor vehicles printed from Onyx fibre reinforced composite

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