IMPACT OF ADDITIVE MANUFACTURING IN MILITARY INDUSTRY

[1]Martin VÍTEK, [1]Jiří JELÍNEK, [1]Roman VÍTEK

[1]*University of Defence, Brno, Czech Republic, EU, martin.vitek@unob.cz*

https://doi.org/10.37904/metal.2024.4921

Abstract

Additive manufacturing and 3D printing is one of the most rapidly evolving industry branches nowadays. This technology brings possibility of creating new designs and materials which military industry could adopt with its benefits. 3D printing based on stereolithography method was invented in 1980s. In recent times it became more and more popular and affordable what powered up a development of these technologies and spread them into public environment. Making these technologies affordable contributed to creation of a large base of informed and experienced worker's. Additive technologies are also widely studied in many educational and scientific institutions. In this paper the impact and possibilities of use additive manufacturing in military industry mainly in terms of application of 3D printing in production of weapons and ammunition will be described. Technologies of 3D printing were listed according to normalization. Technological advancements in terms of printing methods and materials were studied. Prediction of possible usage was researched based on material studies and previous scientific papers aiming for different types of materials used in military industry like metals, composites, plastics, and explosives. Requirements on additive manufacturing technologies were defined for different types of production. Operational benefits for armed forces were also studied and finally challenges for future development of additive manufacturing in military industry were set.

Keywords: additive manufacturing, military industry, materials, explosives

1. INTRODUCTION

Additive manufacturing (AM) is defined as process of joining materials usually layer by layer guided by 3D model dataset [1]. Firstly was this technology patented in 1986 as method of stereolithography (SLA) [2]. Since that time there were developed seven technologies according to [1]. Mostly commonly known and publicly spread is Material Extrusion technology (MEX) mainly used for 3D printing polymers like polylactic acid (PLA) or acrylonitrilbutadienstyren (ABS). On industry bases there are more advanced technologies used adopting printing of composite materials or different types of metals. On scientific base there is also development of 3D printed explosives [3]. This could be useful for improving function and impact of ammunition and also could develop industrial use of explosives via special nano printed explosive structures.

Overall 3D printing brings possibilities of printing different structures and designs which is not possible to create by traditional subtractive and formative methods. In many types of use it could also bring better material characteristics like for example conductivity.

Affordability of 3D printers and printing materials also bring possibilities of using these technologies in operations of armed forces. There are some companies producing hardened 3D printers deployable with forces. In combination with more durable composite or fibre filled materials this could help logistics of armed forces and improve comfort of troops through personalised accessories and new spare parts on demand. As it can be seen 3D printing brings loads of benefits which in good way of use could bring enhancement of capabilities of our military industry and armed forces, so it is important to study these technologies and strategy of their use.

The aim of the paper is to predict the impact and possibilities of use additive manufacturing in military industry mainly in terms of application of 3D printing in production of weapons and ammunition. Prediction of possible usage was researched based on material studies and previous scientific papers aiming for different types of materials used in military industry like metals, composites, plastics, and explosives.

2. DEFINITIONS OF PRINTING TECHNOLOGIES

Additive manufacturing and 3D printing technologies are defined in [1]. Thera are seven technologies which each is suitable for different materials and has its own pros and cons. MEX is most widely used and mostly known method is filament deposition modelling (FDM), because its mostly spread in public for hobby modelers, prototyping, etc. This technology work filament string deposited through nozzle on printing table. Next technology is VPP with SLA, DLP (digital light processing) and others which working on base photocurable polymers. These two printing technologies are most affordable and doesn't need industrial facilities, but on the other hand are very limited in material possibilities which are mostly polymers or polymers filled with different powders and fibres.

For industrial use there are available other technologies which are direct energy deposition (DED), powder bed fusion (PBF), material jetting (MJT), sheet lamination (SHL) and binder jetting (BJT). These technologies are usable for wide variety of material and each technology provides different mechanical and printability properties and printing speed [4].

On side of additive manufacturing technologies there is method of cold spray. This method is not normalised as 3D printing technology, but it could be included in MJT. Cold spray work on acceleration of powder made from printing material which is deposited on printing area through nozzle and material fit there by its kinetical energy. Method of cold spray provides high printing speeds in maximum between 40 to 100 kg of printed material in an hour and provides possibility for multi-material printing [5].

3. PRINTING OF POLYMERS AND COMPOSITES

Polymers are macromolecule-based materials composed of large numbers of monomers, which create basic molecular structure of polymer substances. Synthetic polymers are produced as plastic materials, which are mostly used in additive manufacturing [6].

Polymer printing is commonly used to enable creating sophisticated structures with usage of composite materials. Additive technologies create opportunities of creating the complex geometrical structures and hardly machinable materials, including ceramic structures etc. Ability to precisely shape these types of materials gives military industry a new way of composing ballistic equipment, for example printing different vehicle components and weapon accessories as spare parts which can be helpful especially in international operations or as personalized customization of some parts which could be beneficial for ergonomic use. Several cases of using FDM method on printing light vehicle parts, mostly propellers of light UAV's, have been recorded, as well as printing wings. Necessary parts to avoid supply chains can be easily manufactured with AM. Several armies of the world are currently implementing features of AM to their own infrastructure [7].

Problems with lower quality and durability of polymer-based printing materials could be avoided by using composite materials. In general, composite materials are multiphase materials, that are developed for specific purposes, commonly are known for their high durability, strength, and abrasive resistant abilities [6].

Composite structures have various purposes, rising form origin of their nature. Many composite materials found their use in ballistic protection, thanks to their strength and high resistivity in tough conditions. Printing composite materials is enabled with using specific printing methods, for example FDM and MJT [8]. One of the more successful ways is printing ceramic structures. This has been done with direct ink writing (DIW) method as part of MEX technology to create heterogenous structure consisted of two ceramic materials, combining their unique abilities. Structures developed with these methods show high strength of the material, which can have possible impact on developing protection systems in the future [9].

4. METAL PRINTING

Metals in AM are required to have specific abilities, such as corrosion resistance, very good mechanical abilities, or any other special functional properties. Their application originates than from type of metallic structure and their key abilities. AM of metals is being done with both metals and alloys, which gives a lot of space for possible future research on these types of structures [7,10].

Metallic structures are usually manufactured using selective laser melting (SLM), other types of laser AM or using method known as cold spray [9]. Also, MEX technology could be sufficient but usually need further thermal treatment of printed sample. Mechanical properties differ depending on selected AM technology. SLM prints has lower porosity and higher density than those produced by FDM and then cured. Hardnes and other mechanical properties are also better with SLM method. In all cases and types of 3D printing there is also problem of anisotropic behaviour cause by printing layer by layer [11].

Using variations of PBF, we can produce various types of metal alloys. Worth mentioning are aluminium and tungsten alloys, on which have been done studies so far [12,13]. Yet still more research and progress in industry has to be made. Various methods of implementing printing metal structures are being presently done. For instance, Australian military had done development project of with association with private company SPEE3D. Their cooperation showed important results, which should be look upon with further projects. Using cold spray method, important parts, even vehicle parts, can be printed in short time, in which it would have been resupplied. Shown results of printed parts proved their full functionality and reliability. Printing station can be also transported in tougher conditions, allowing it to print necessary part in places where needed [14].

5. EXPLOSIVES PRINTING

Explosives are materials able to rapidly transform their state from solid or liquid state to gas state in exothermic reaction which leads to large amounts of energy release. According to speed of reaction and energy output we divide explosive into two groups of high and low explosives [15]. Both groups are used in different ways mostly in ammunition. Low explosives are often propellants for rocket motors or guns, high explosives are used as main impact explosives and primers in ammunition projectiles.

According to several reviews [3,16] there has been done a lot of work in enhancement in printability of propellants and high explosives. Several technologies were used for propellant printing as VPP and MJT. For 3D printing are not used standard nitrocellulose propellants but two or more material composite propellants. Usually, a combination of high explosive powder and heatcurable or photocurable binder [3]. Power of these propellants is comparable to low energy propellants for example tank propellants.

Enhancing power of printed propellants could be done in two ways. One is enlarging of solid loadings of high explosives powder [17]. This leads on the other hand to higher viscosity and these substances are harder to print with VPP method which provides higher printing speed than MJT which is more suitable for high solid loadings like it was mentioned in. Other way to increase energy contain of printed propellants are energetic binders like APNIMO. This binder gives to burning of propellant its own energy and its use give better result than using standard photopolymers [18,19].

3D printing of propellants could bring better possibilities for creating structures that are not achievable by standard fabrication methods. Australian research brought mathematical models of using new types of propellant grains, which could for artillery increase muzzle velocity for 23 % with same maximal pressure or reduce maximal pressure in barrel for 35 % with same muzzle velocity [20]. This could bring new ways of reducing barrel wear or increasing penetration depth of kinetic anti-armour ammunition. Also printing with photopolymer binders has fewer internal defects than other binders which create vapours during their polymerization process like hydroxyl terminated polybutadiene (HTPB), which structure comparison with same printed photopolymer binded propellant [16].

Printing of high explosives is challenging in ways of high pressure and temperature sensitivity of these materials. With pure trinitrotoluene (TNT) and its mixtures is useable MEX printing technology due to sufficient difference between melting temperature and initiation temperature. Serie of papers referring about research done on MEX printing of hexogen (RDX) or octogen (HMX) and TNT mixtures showed that these high explosives are printable, and their printing could enhance mechanical properties of final sample compared to standard cast ones [21]. Another positive feature of 3D printing of high explosives is creating of gradient structures [22]. Shaped charges used as part of anti-tank ammunition created with gradient structure of explosive infill should have better armour penetration characteristics due to better impact of detonation wave on shaped charge liner [23].

6. 3D PRINTING IN MILITARY OPERATIONS

AM could bring up also many advantages for army logistic and deployed forces in military operations. Some studies on this topic were already done. According to [7] 3D printing would be beneficial mainly for creating spare parts on demand. This would affect sustainability of deployed forces and decrease time need for repair of damaged vehicles and equipment.

In these terms we have to focus on loads of dangers and challenges appearing with use of this technology on the battlefield. Spare parts need to be divided into several groups according to their printability with sources of the units and according to importance of spare part and danger created with eventual failure of this spare part. Deriving from categories of printed spare parts there should be categories of units with adequate equipment and supplies to fulfil needs of fighting units.

On the first level it could be small unit with capacity to print plastic materials and its upgraded versions with MEX technology printers. These printers should be durable according to use on frontlines. Second level on base of repair platoon should have ability of metal 3D printing similar to AM containers with coldspray method used for example in US army. On this level it should be emergence repair in case of lack of spare parts to rapid retrieve of combat capability of unit with expectation of replacing this printed spare part with stock one as soon as it will be possible according to combat situation. AM advantages on higher levels of army repairs could be discussed in future, but there should not be large lack of spare parts as in combat situations. Also, there is at the time expectation of lower durability and life span of printed spare parts, which need to be deeply studied and improved if want to use these parts long term repairs [7].

7. CONCLUSION

To conclude it can be said that AM could be used in military industry in several different ways. Some are helpful in achieving new shapes or inner structures of some parts of weapons and ammunition concluding in better functional properties or ergonomic use. On the other side even if the functional properties or durability of 3D printed spare parts will not be as good standard manufactured it can help logistic of armed forces in case of supply shortage.

In near future we can expect that there will be rising number of 3D printers in all industry. Though there are some implications where additively manufactured components are less effective or durable we shall test them and have prepared printing processes for case of emergency production increase in time of war state. In this case all 3D printing capacities in industry could be used until military industry will be able to increase its own output.

In terms of non-operational and peace situations AM should be used with all its benefits described in this paper but also in close cooperation with other types of manufacturing to enhance quality of military industry.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the specific research project 2024 "SV24-201 Modern technology in weapons and ammunition manufacturing" at the Department of Weapons and Ammunition, University of Defence in Brno, and by the Project for the Development of the Organization "VAROPS (DZRO VAROPS) Military autonomous and robotic assets" by the Ministry of Defence of the Czech Republic.

REFERENCES

[1] *EUROPEN ISO/ASTM 52900, Additive manufacturing - General principles - Fundamentals and vocabulary*. European Committee for Standardization, 2021.

[2] HULL, C. Apparatus for production of three-dimensional objects by stereolithography. US. 4,575,330. Applied Aug. 8, 1984. Patented Mar. 11, 1986.

[3] ZHANG, J., HE, K., ZHANG, D., DONG, J., LI, B., LIU, Y., GAO, G., JIANG, Z. Three-dimensional printing of energetic materials: A review. *Energetic Materials Frontiers*. 2022, no. 3, pp. 97-108.

[4] WIEBERG, A. *Towards Design Automation for Additive Manufacturing.* Licentiate's Thesis. Linköping University, 2019.

[5] RAOELISON, R.N., XIE, Y., SAPANATHAN, T., PLANCHE M.P., KROMER, R., COSTIL, S., LANGLADE, C. Cold gas dynamic spray technology: A comprehensive review of processing conditions for various technological developments till to date. Additive *Manufacturing*. 2018, vol. 19, pp 134-159.

[6] CALLISTER, W.D., RETHWISCH, D.G. *Materials Science and Engineering: An Introduction*. Hoboken: Wiley, 2010.

[7] BOER, J., LAMBRECHTS, W., KRIKKE, H. Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain. *Journal of Cleaner Production*. 2020, vol. 257, article no. 120301.

[8] COLORADO, H.A., CARDENAS, C.A., GUTIERREZ-VELAZQUEZ, E.I., ESOBEDO, J.P., MONTEIRO, S.N. Additive manufacturing in armor and military applications: research, materials, processing technologies, perspectives, and challenges. *Journal of Materials Research and Technology*. 2023, vol. 27, pp. 3900-3913.

[9] PELZ, J.S, KU, N., SHOULDERRS, W.T., MEYERS, M.A., VARGAS-GONZALEZ, L.R. Multi-material additive manufacturing of functionally graded carbide ceramics via active, in-line mixing. *Additive Manufacturing*. 2021, vol. 37, 2021, article no. 101647.

[10] GARCIA-AVILA, M., PORTANOVA, M., RABIEI, A. Ballistic performance of a composite metal foam-ceramic armor system. *Procedia Materials Science*. 2014, vol. 4, pp. 151-156.

[11] KLUCZYNSKI, J., JASIK, K., LUSZCZEK, J., SARZYNSKI, B., GRZELAK, K., DRAŽAN, T., JOSKA, Z., SZACHOGLUCHOWICZ, I., PLATEK, P., MALEK, M. A comparative investigation of properties of metallic parts additively manufactured through MEX and PBF-LB/M technologies. *Materials*. 2023, vol. 16, no. 14, article no. 5200.

[12] LUI, E.W., MEDVEDEV, A.E., EDWARDS, D., QIAN, M., LEARY, M., BRANDT, M. Microstructure modification of additive manufactured Ti-6Al-4V plates for improved ballistic performance properties. *Journal of Materials Processing Technology*. 2022, vol. 301, article no. 117436.

[13] KRISTOFFERSEN, M., COSTAS, M., KOENIS, T., BRØTAN, V., PAULSEN, C.O., BØRVIK, T. On the ballistic perforation resistance of additive manufactured AlSi10Mg aluminium plates. *International Journal of Impact Engineering*. 2020, vol. 137, article no. 103476.

[14] 3Dprint.com. *Australian Military 3D Prints Over a Dozen Armoured Vehicle Parts in the Field*. [online]. 2021 Available from: https://3dprint.com/286608/australian-military-3d-prints-over-a-dozen-armoured-vehicle-parts-in-the-field/.

[15] PRAKASH, J.A. *High Energy Materials*. Weinheim: Wiley-VCH, 2011.

[16] TAN, B.J., MO, H.C., LU, X.M., DUAN, B.H., CHEN, S.L., LIU, N. Research progress on photocurable 3D printing of propellants and explosives. *Journal of Physics: Conference Series*. 2023, vol. 2478, no. 3, article no. 032082.

[17] NAYA, T., KOHGA, M. Influences of particle size and content of HMX on burning characteristics of HMX-based propellant. *Aerospace Science and Technology*. 2013, vol. 27, pp. 209-216.

[18] LI, M., YANG, W., XU, M., HU, R., ZHENG, L. Study of photocurable energetic resin based propellants fabricated by 3D printing. *Materials & Design*. 2021, vol. 207, article no. 109891.

[19] DUNJU, W., CHANGPING, G., RUIHAO, W., BAOHUI, Z., BING, G., FUDE, N. Additive manufacturing and combustion performance of CL-20 composites. *Journal of Materials Science*. 2020, vol. 55, no. 7, pp. 2836-2845.

[20] DOLLMAN, B., HART, A., JOHNSTON, I., PRIOR, C. *Advanced Munitions: 3D Printed Firepower*. Edinburgh: Defence Science and Technology Group, 2018.

[21] ZONG, H., GUO, C., WANG, Z, GUO, R, ZHOU, H., HAO, G., REN, H., XIAO, L., JIANG, W. Preparation of TNT/HMX-based melt-cast explosives with enhanced mechanical performance by fused deposition modelling (FDM). *Journal of Energetic Materials*. 2022, pp. 1-19.

[22] ZHOU, X., MAO, Y., ZHENG, D., ZHONG, L., WANG, R., GAO, B., WANG, D. 3D printing of RDX-based aluminized high explosives with gradient structure, significantly altering the critical dimensions. *Journal of Materials Science*. 2021, vol. 56, pp. 9171-9182.

[23] CARLUCCI, D.E., JACOBSON, S.S. *Ballistics: Theory and Design of Guns and Ammunition*. CRC Press, 2013.