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Abstract- Direct material deposition (DMD), also called rapid manufacturing (RM), additive manufacturing (AM), or 3Dprinting, brings many changes and opens new ways of production to every industry that it enters [1-4]. DMD-AM is an innovative technology, which layer by layer "prints" objects from a variety of materials, performing shapes that are not achievable by traditional manufacturing technologies. DMDAM, which started as prototyping in plastics, now succeeds in processing metals. DMD-AM in metals, first of all, in titanium alloys, gives a possibility to implicate net-shaped, complex geometrical and light-weight objects. It also provides high mechanical and specific acoustic properties, even better than those obtained by traditional mass production methods, such as casting or machining.

Keywords: *additive manufacturing, 3d-printing, industrial design, titanium.*

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Benefits of Titanium Additive Manufacturing for Industrial Design Development. Trends, Limitations and Applications

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Abstract Direct material deposition (DMD), also called rapid manufacturing (RM), additive manufacturing (AM), or 3Dprinting, brings many changes and opens new ways of production to every industry that it enters [1-4]. DMD-AM is an innovative technology, which layer by layer "prints" objects from a variety of materials, performing shapes that are not achievable by traditional manufacturing technologies. DMD-AM, which started as prototyping in plastics, now succeeds in processing metals. DMD-AM in metals, first of all, in titanium alloys, gives a possibility to implicate net-shaped, complex geometrical and light-weight objects. It also provides high mechanical and specific acoustic properties, even better than those obtained by traditional mass production methods, such as casting or machining.

The goal of the current research is to investigate the prospects of 3D-printing as a novel instrument for professional industrial designers developing new products and applications.

However, DMD-AM has limitations that prevent the use of this technology for mass production.

The paper presents examples of successful novel applications of 3D-printing by Additive Manufacturing Center at Technion (Israel).

Keywords: additive manufacturing, 3d-printing, industrial design, titanium.

1. INTRODUCTION

The development of DMD-AM processes, includes the development of the process productivity, improvement of material properties, investigation of new alloys and development of modeling and free-form design. Industrial designers, as well as 3D-engineers and product developers, use this technology for making their design prototypes, to solve problems related to shape, lines and structure, together with their usability, mechanical properties, and functionality. The DMD-AM is widely used for presentation of new ideas and concept-designs to clients, to share their concept vision with other departments: sales, management, production or marketing [2, 3].

Moreover, implementation of metals additive manufacturing (M-AM) showed that 3D-printing techno-

logies could be used not only for prototyping but for product fabrication, with required high mechanical properties.

In [5] it is proposed that AM will perform revolution in manufacturing. Some enthusiasts of 3D-printing even predict that this technology will replace other traditional industries like casting and machining. As approval of these statements is the fact of successful application of DMD-AM in such specific life critical spheres as aerospace and production of bio-medical patient-specific titanium implants. In fact, for these applications, the DMD-AM has already become a production tool.

The DMD-AM provides many benefits for industrial design and manufacturing as shape/geometry form freedom, no tooling requirements, on-demand production, no minimum order quantities, extreme complexity, integration of multiple parts into one, no need of high-cost die-forms, and functionally graded materials (FGM).

Papers [5-8] demonstrate remarkable advantages provided by M-AM and its successful application in aerospace, automotive, medical and other specialized industries. Current work aims to show novel applications and potential of this technology for industrial design development and mass production of technologically new products.

a) Direct material deposition (DMD)

The DMD-AM has emerged as an efficient way to produce customized and fully functional parts from various materials [1, 3]. ASTM International (formerly American Society for Testing and Materials) standard defines AM freeform fabrication as: The layer upon layer process of joining materials to make objects from 3D-model, as opposed to traditional manufacturing technologies ascasting or machining [9]. The economic benefits of the use of AM for low series production are substantial as well since customization and single part production are easy to accomplish [10].

Numerous capabilities of M-AM have made it a flexible production method, compared to conventional machining, with enhanced efficiency to produce, for example, personalized bio-medical implants or aerospace components.

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At present, the focus has shifted towards manufacturing and production of finished and functionalized parts rather than prototyping [10-12]. Today various materials can be used in AM processes, i.e., metals, polymers, ceramics, organic tissues, and cells.

The benefits of the 3D-printing process summarized from [3, 5, 11] are:

- Waste reduction. For critical raw material, for example, for rare-earth elements it is especially relevant [13];
- No machining is needed, significantly reducing post-processing time and costs;
- An option of small material amount use, important for new materials testing and low-serial production;
- Freedom of rapid design/model development.
- A possibility of function ability / lightweight structure improvement
- Personalized design;
- Manufacturing efficiency: to produce the assembled parts in one build;

However, the capabilities of 3D-printing are still limited due to several reasons:

- High initial costs of 3D-printing professional machines and their maintenance;

- The cost of powder printing materials and complicity and a high cost of their production, for example, gas atomized spheroidal titanium powders;
- For the mass production, 3D-printing is still non-competitive with traditional production methods as casting, because of the relatively low productivity.

b) *The additive manufacturing production cycle*

An additive manufacturing production cycle starts from the 3D-designer's work, whose task is to realize the CAD-model of the future component (fig. 1). This 3D model is the basis for the production of the part. Initial shape, geometry, and internal properties can be designed directly at this stage. Then the model is transformed into a .stl-file and maybe sliced into layers (.amf format) for further manufacturing. The .stl format converts all internal and external surfaces into an array of triangles.

Components are manufactured by adding thin cross-section layers of a material on a top of each other to grow the parts according to a 3D CAD-model [1, 3].

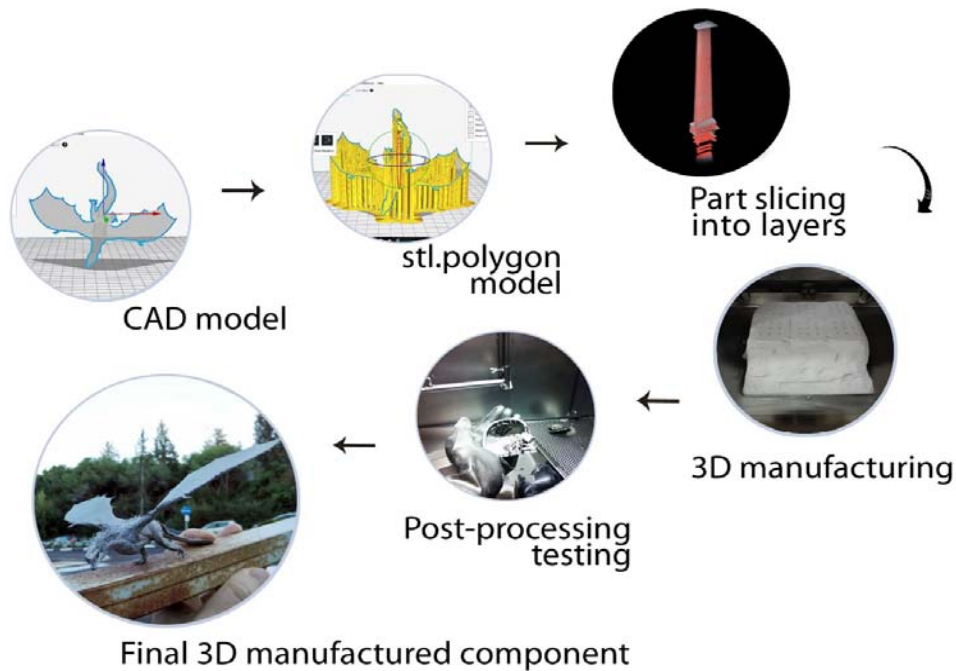


Fig. 1: A visual representation of the additive manufacturing principle

After finishing the building process, the part is removed for post-processing and testing. These procedures vary depending on the used AM process

and the final part application. For the M-AM technologies as Selective Laser Melting (SLM) and Electron-Beam Melting (EBM®), the first post-processing

procedure is support structures removal. There are several reasons to apply support structures: for heat transfer from the part and as gravity support.

c) *3D-printing of titanium alloys*

Ti-6Al-4V is the most traditional material for SLM and EBM[®] 3D-printing [15, 16]. It is used in the form of gas atomized spherical powder with the average fraction of 50 microns. High requirements for production and re-use of the powder are aimed to prevent the material oxidation, nucleation of satellites and distortions of the spherical shape of the particles.

Titanium and its alloy Ti-6Al-4V are well-known as structural materials. Such applications as medical technologies, chemical processing, sports, leisure, marine and aerospace all make use of the advantageous combination of properties of titanium materials. Compared to other metals, titanium and titanium alloys exhibit high corrosion resistance and high specific strength-to-weight ratio [14]. Today Ti-6Al-4V is the most widely used titanium alloy [15]. This alloy has a balanced combination of mechanical properties and workability and has been extensively researched [16].

Components from titanium alloys are complicated to process by traditional machining or milling, due to a relatively low thermal conductivity.

II. APPLICATION OF TITANIUM ADDITIVE MANUFACTURING IN INDUSTRIAL DESIGN

Due to the material and process benefits, M-AM successfully use in different fields. Today many of them are short series units, with a high level of complexity, and a high level of customization.

a) *Patient-specific titanium implants*

M-AM techniques are beneficial for the production of patient-specific replacements. The main advantage is the possibility to customize personalized implants. Moreover, the development of lattice structures in medical implants becomes advantageous as it combines the mechanical strength, light weight performance, increases the number of surfaces (for the interaction between titanium implants and muscular tissue), and minimizes replacement/shielding surface.

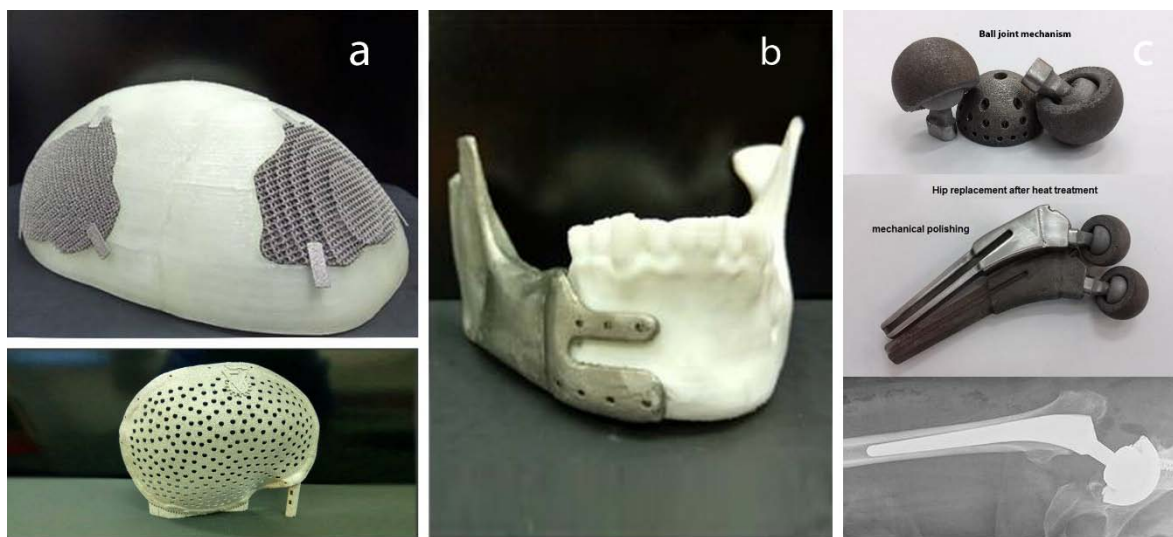


Fig. 2: Examples of EBM[®] medical implants manufactured by AMC Technion: a -cranial recovery lattice structure inserts; b - preliminary variant of the mandibular implant; c -hip replacement implants

Figure 2 demonstrates the EBM[®]-manufactured samples of cranial, mandibular and hip replacement implants. The "bone"-part is printed from ABS plastic to provide a surgeon the opportunity to try the implant on a plastic model and see if it fits well, how to fix it, what screws to use, etc.

b) *Dental prosthetics*

SLM technology has better characteristics than EBM[®] in surface roughness and accuracy of small parts. Because of that fact, for dental prosthetics

manufacturing, such as dental crowns and bridges, braces and aligners, usually use SLM-AM. In the same build, hundreds of personalized prosthetics can be manufactured by cost-efficient SLM-AM. SLM-manufactured dental implants (fig. 3) passed heat treatment and required testing for fatigue resistance.

The manufacturing of titanium dental implants is already serial production for some hospitals.

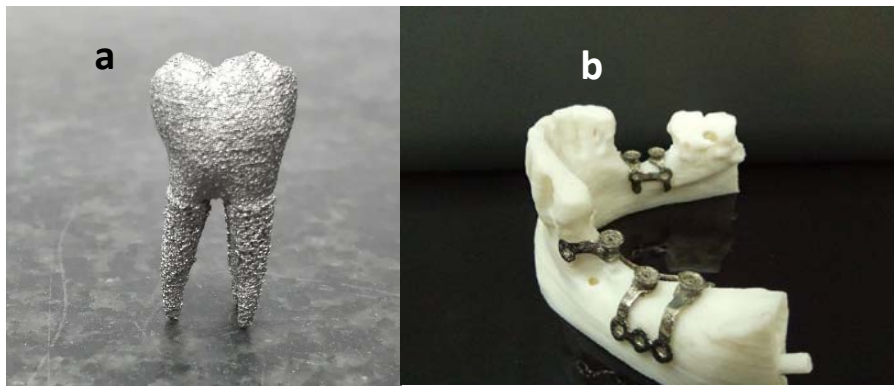


Fig. 3: a - tooth implant with lattice structured basis; b – implant's support system by EBM®

c) *Aerospace components*

Ti-6Al-4V became a very popular aerospace alloy because of high fatigue resistance. Fatigue resistance is critical for aerospace parts that work under cyclic loadings. Thus, the first goal for a new manufacturing technology was to prove that printed components have the same or maybe better mechanical properties than casted-machined parts.

Today titanium DMD-AM for aerospace application develops rapidly. The components that are already in airplanes are mostly non-critical parts, with light weight design and lattice structure. New bionic shaped parts save weight as the material is put only on stress points.

The next stage for 3D-printing of aerospace components is to perform an approving technology that will enable prediction of mechanical properties and microstructure of the printed products. That will allow manufacturing also critical parts that should be stable under cyclic loadings.

d) *New tools manufacturing*

Rapid tooling is an M-AM of new or some specific tools. It is a combination of traditional and novel fabrication methods. For example, cutting tools can be printed from tool steels. The main advantage in the fabrication of these tools through the AM is the fast production where the design can be easily changed and improved [5].

DMD-AM maybe also used for specific surgeon tools production. Because of biocompatibility of the material, such titanium-based 3D-printed tools do not need deep sterilization. Moreover, surgeons usually have their techniques, and here 3D-designers can help to produce some new tools for their work.

Benefits of DMD-AM as manufacturing of lattice structures, net-shape surfaces, and internal channels are also relevant for rapid tooling production.

III. PROSPECTS OF ADDITIVE MANUFACTURING FOR INDUSTRIAL DESIGN

As it was already said above, the critical safety application of 3D-Printing, as bio-medical and aerospace applications, are already well-known and rapidly develop.

To extend the spectrum of M-AM in the current research is presented by the successful examples of implementation of the technology by Additive Manufacturing Center at Technion.

a) *Automobile application: passengers and concept cars*

The automobile giants like BMW, Nissan, Ford, Rolls Royce, etc. are already utilizing AM for some car components production. Metal and plastic materials are both used.

According to Wohler's Report 2016, motor vehicle sector is already the third one that successfully used DMD-AM as a series production.

However, because of advantages (specific design of unique parts) and disadvantages (low productivity) of DMD-AM, the 3D-printing of parts of concept cars and formula motor cars is rapidly developed.

Figure 4 demonstrates the EBM® manufactured parts of exhaust gases system for Formula Technion cars. The new design and manufacturing technique enabled to decrease weight up to 3 kg.

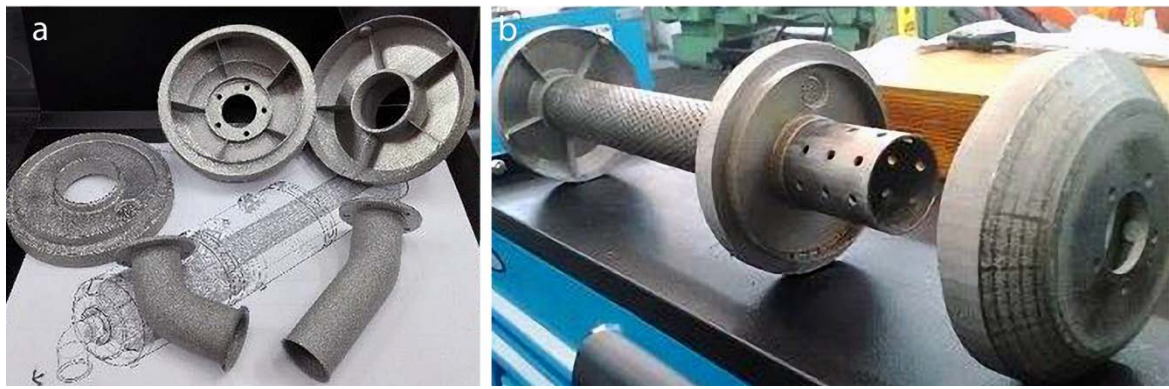


Fig. 4: EBM® manufactured parts of exhaust gases system for Formula Technion car

There are still limitations for mass production by M-AM for automotive application:

- Big volume parts manufacturing. Today ORNL [17] already uses the extrusion jetting technology for big volume parts fabrication from composites. However, EBM®/SLS/SLM metals AM techniques are still limited by the inner chamber size.
- Material price. The high requirements to atomized powders for metals printing make their cost too high compared to materials used in traditional industries.
- Lack of scientific base. Because of novelty of the AM industry, there is a lack of specialists, physicists, engineers, and lack of basic scientific knowledge of physics of the DMD-AM processes.
- Production time. The time of manufacturing by M-AM machines is still uncompetitive with casting. It is a problem for high series production.

b) Electronics and engineering manufacturing

There are several reasons for growing interest in the engineering manufacturing sector to different M-AM technologies. M-AM provides architecture simplification, capability to print integrated parts in one component, no geometry restrictions, and easy manufacturing development. A new product design reduces resources leading to cost reduction.

The case performed in fig. 5 is a newly designed component of a camera for direct nano-motion detection. The chosen material was Ti-6Al-4V because of the unique combination of plasticity and strength of this alloy. EBM® process was used for the component manufacturing because of temperature conditions of this type of M-AM, which provide the microstructure of a final component free from residual stresses and martensitic structures.

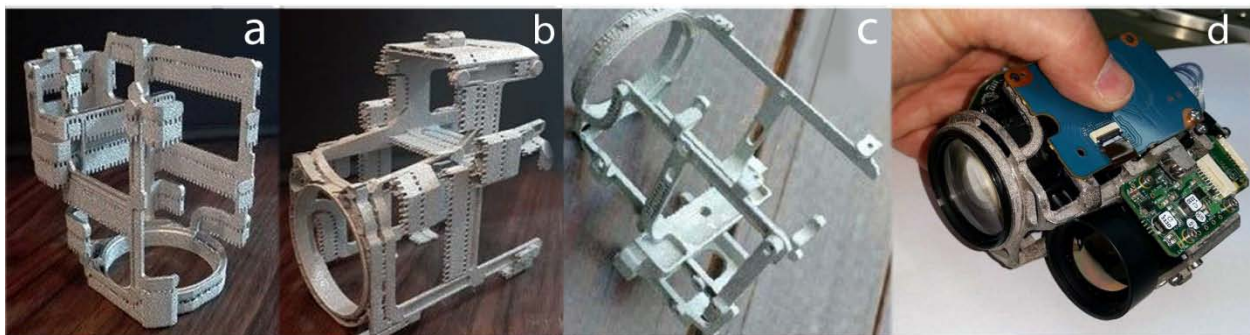


Fig. 5: The titanium EBM® manufactured body of a nano-camera Nanomotion Ltd.:

- a – direction of manufacturing; b –component with support structures; c –component without support structures; d – camera assembled in a newly printed titanium body.

After several iterations between 3D-engineer and industrial designer, the optimal light-weight shape was determined. The proposed solution is optimal for the serial production of such type of cameras.

c) Complex research systems

Fig.6 presents the components for the electro-polishing system of titanium EBM®-printed parts for the

needs of Corrosion Laboratory at Technion. EBM® has specific advantages:

- EBM® runs in high-temperature and high-vacuum conditions [15,18], which provides material microstructure clean of gas inclusions and free from residual stresses. Such production conditions have no need for any post-processing as heat treatment.



- Because of high-temperature conditions, the powder surrounding the printed component is strongly sintered. This phenomenon provides printing with fewer support structures compared to laser printed parts.
- The high-vacuum conditions are critical for production components for working in the aggressive environment. These electrode components are to work in the electrolyte and should have high corrosive resistance.

d) *Art and musical instruments*

According to successful experience of rapid plastic prototyping of musical instruments, there is a

significant potential of titanium DMD-AM for this application. Metal instruments have a more sonorous, piercing sound.

Titanium DMD-AM provides the following benefits:

- Bio-compatible non-allergic material;
- Unique acoustic properties;
- High mechanical properties – lightweight, plasticity, strength;
- Unique design possibilities for development of the product ;
- Personalized instruments: for professional musicians with their specific techniques.

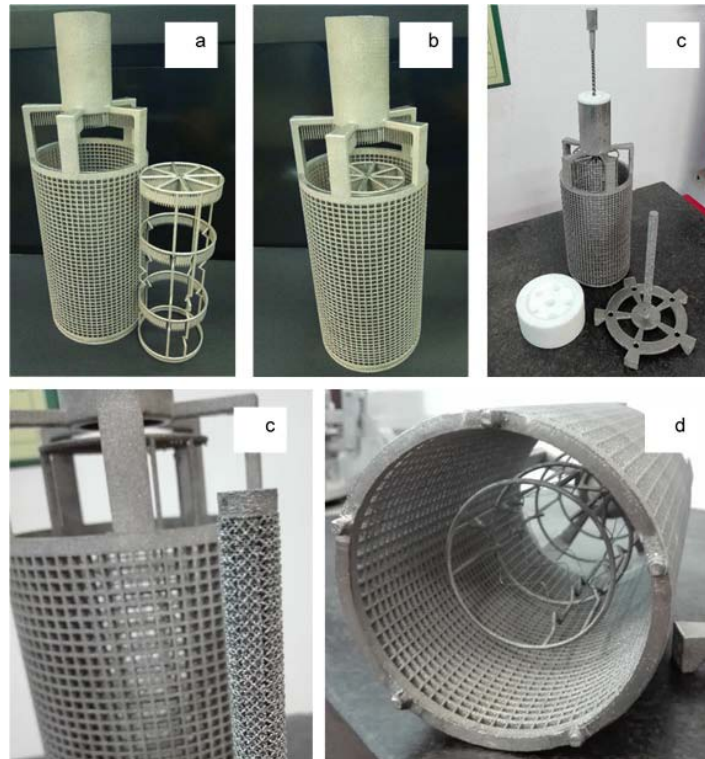


Fig. 6: a - as-built parts of a system with support structures; b - the combined components; c - resolution of lattice structures of an electrode; d - inside the system: the inner dispenser for samples.



Fig. 7: 3D-printed art-objects and souvenirs.

However, until now there were no widely reported successful experiments in M-AM. It may be explained by the high-cost of the machines and metallic powder for AM.

From the internet search, it may be found just several examples of M-AM of musical parts. One of them laser-manufactured aluminum electric guitar [19]. However, this work is interesting mostly from the esthetic point of view. In this work the advantages of aluminum as a lightweight or non-corrosive material were not utilized. Moreover, electric guitar doesn't use the acoustic properties of the printed metal.

3D-printing in metals allows manufacturing of exclusive souvenirs (Fig. 7), unique art-objects, net-shape art installations (Fig. 8) and even jewelry. Moreover M-AM maybe combined with other techniques as machining, air-brushing (Fig.8b), coating, assembling, etc.

AM gives new ideas to designers, enables the use of 3D-printing for creating final customers products, and also specific printed molding forms, for example, for jewelry production.

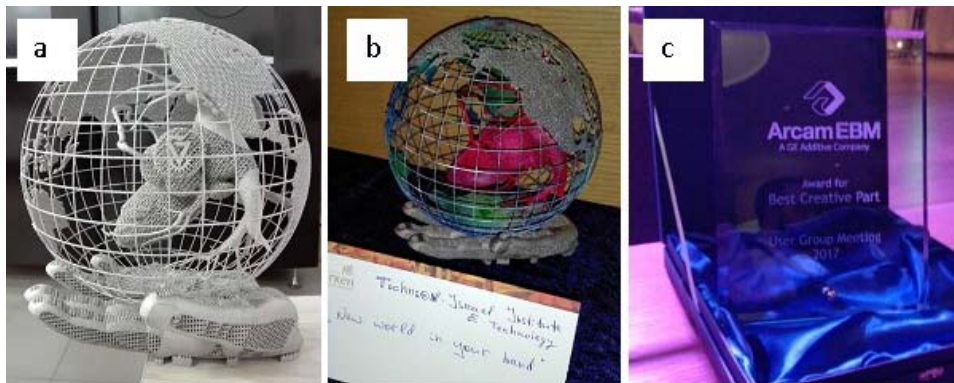


Fig. 8: a - as-built EBM[®]-manufactured work for Arcam UGM2017 competition; b - the airbrushed final part; c –"Best Creative Part" award for the EBM[®]-manufactured airbrushed object produced by AMC Technion.

IV. CONCLUSION

The paper presents the use of the 3D-printing as a new instrument for industrial designers for developing new products and applications. The marketing prediction of the future development of titanium DMD-AM in industrial design is very positive. Today there are decades of 3D-machines producers [20], who provide different processes for different materials.

Titanium alloys, because of the combination of high mechanical properties, fatigue resistance and corrosion resistance, provide interest to titanium 3D-printing not only for medical, aerospace, or automotive applications but also for specific engineering systems, electronics and even for musical instruments.

Many researchers believe [3, 21] that DMD-AM will shape the future of production and will stimulate new development in engineering and manufacturing processes. However, it is already clear that M-AM could not replace traditional fabrication technologies like casting at all. DMD-AM has its niche [3, 21-22] where it is uncompetitive: low-serial production of highly complicated geometrical lightweight parts. And first of all, it is design and development of new products and applications. And here AM becomes an instrument for industrial designers for prototyping new products, and

to develop them up to final net-shape products with specific mechanical properties.

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You may contact the corresponding author for any additional information and access to the original tests' results.

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