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PERSPECTIVES AND DEVELOPMENT TRENDS FOR APPLICATION OF ADDITIVE TECHNOLOGIES IN MODERN DENTISTRY IN THE LIGHT OF INDUSTRY 4.0

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ABSTRACT

Additive manufacturing technologies (AMTs) offer a new approach for cost-effective production of goods and services and are therefore quite rightly included as part of the Fourth Industrial Revolution, Industry 4.0. Last years great attention is paid to the AMTs as technologies of the future development in many countries all over the world including the European Union. Depending on the availability of a good base of installed 3D printers and intellectual potential, the countries are divided into two groups: 1) leaders in the field of 3D printing technology and 2) countries with large bases of equipment, but lack of trained and qualified labor force. The aim of the present paper is to analyze the perspectives and development trends for application of additive technologies in modern dental medicine in the light of Industry 4.0.

The constant development of AMTs will accelerate their implementation in various fields and in particular in medicine/dentistry. The 3D printing technologies are first applied in dentistry, due to the possibility for fabrication of individual dental constructions. Currently, almost all world-renowned companies for production of dental materials and machines develop additive technologies and manufacture the corresponding equipment. According to the forecasts, the 3D printing is expected to be widely used in dental clinics and laboratories in the next 5-10 years.

The additive technologies most often applied in dentistry include stereolithography, fused deposition modeling, selective electron beam melting, selective laser melting/sintering and ink-jet printing. The great variety of materials used in these processes allow constructions with different purposes to be made for all areas of dental medicine - surgery, oral implantology, conservative dentistry, orthodontics and prosthetic dentistry.

1. INTRODUCTION

The man's desire to improve and perfect his conditions and way of life is the main engine of the technical progress. At the dawn of humanity, for the sake of survival, he first used the raw available materials given to him by the nature. The first roughly made blades date back to the Stone Age, i.e.then the first processing technologies appeared, which were based on the material removal (Fig. 1). This group of technologies are called nowadays "subtractive technologies". With the gradual development of the technologies during the Stone-Copper Age, the pure metals (copper, tin and gold) began to be mined and processed in a primitive way. The melting and alloying of copper and tin to obtain a new material - bronze, and the casting of details from this alloy defined an entire age - the Bronze Age. The improvement of technologies and the development of special furnaces for the iron extraction marked the transition to the Iron Age, in which, in addition to the creation and use of iron alloys, the transition from casting to forging the details took place. Tools and weapons begin to be manufactured. It can be said, that during the following centuries, until the beginning of the industrial revolution in 1750, the development of materials and technologies was almost equal. A number of new materials were obtained and technologies were developed both for their production and for manufacturing details and products from them - glass, porcelain, gunpowder, etc. Until then, the creation of new materials was based on the natural ones, and the development of technological processes was extremely slow.

A powerful impetus was given by the steam engine invented by James Watt at the end of the 18th century. Then the first lathes and drills appeared and the synthesis of new materials began - acids, bases, etc.It defined transition to themachine production, i.e.industrialization. During this period until the middle of the last century, new materials and technologies were constantly and rapidly developed, new areas for their application arose. Based on the CAD-CAM systems created in the 1970s, the automation of production was introduced in industrial enterprises. In the 1980s, the first 3D printing technology was developed, i.e.technology for manufacturing details by adding material. At that time, nanotechnology began to develop rapidly. Thanks to them, new nano-sized materials with unique properties was created. The extremely rapid development in

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the last 20 years of computer and communication systems led to the globalization of production.

From the beginning of the last century until now, the development of the new materials and technologies has been following an exponential law (Fig. 1). Nevertheless, there is always a mutual relationship between the new materials and the new technologies. On the one hand, new materials can be obtained through both existing and new technologies. On the other hand, the developed new technological processes require the creation of new materials in order to expand their field of application.In this way, over the years, the anticipatory development of the materials and technologies alternates.

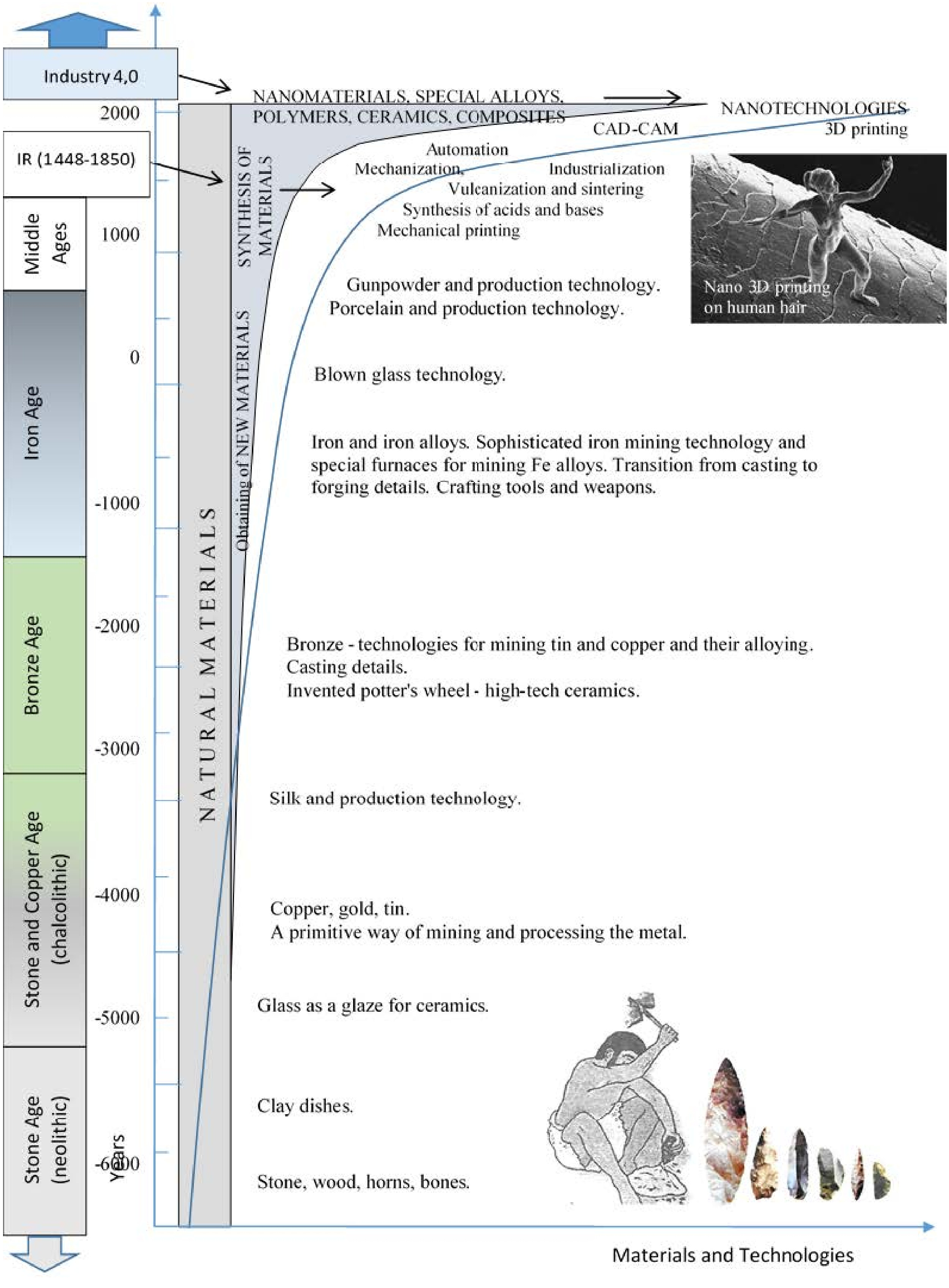


Fig. 1. Development of man, materials and technologies (IR – industrial revolution)

The development of dental medicine from ancient times to the present day moves together with the development of the technical progress [1, 2]. This is the main reason that the improvement and development of new dental materials and technologies for production of dental constructions has been carried out according to an exponential law in the last 40 years (Fig. 2) [3]. The processing technologies with application in dentistry are divided into five large groups depending on how an object is made: by plastic deformation, joining, manufacturing compact details, removing or adding material (Table 1).

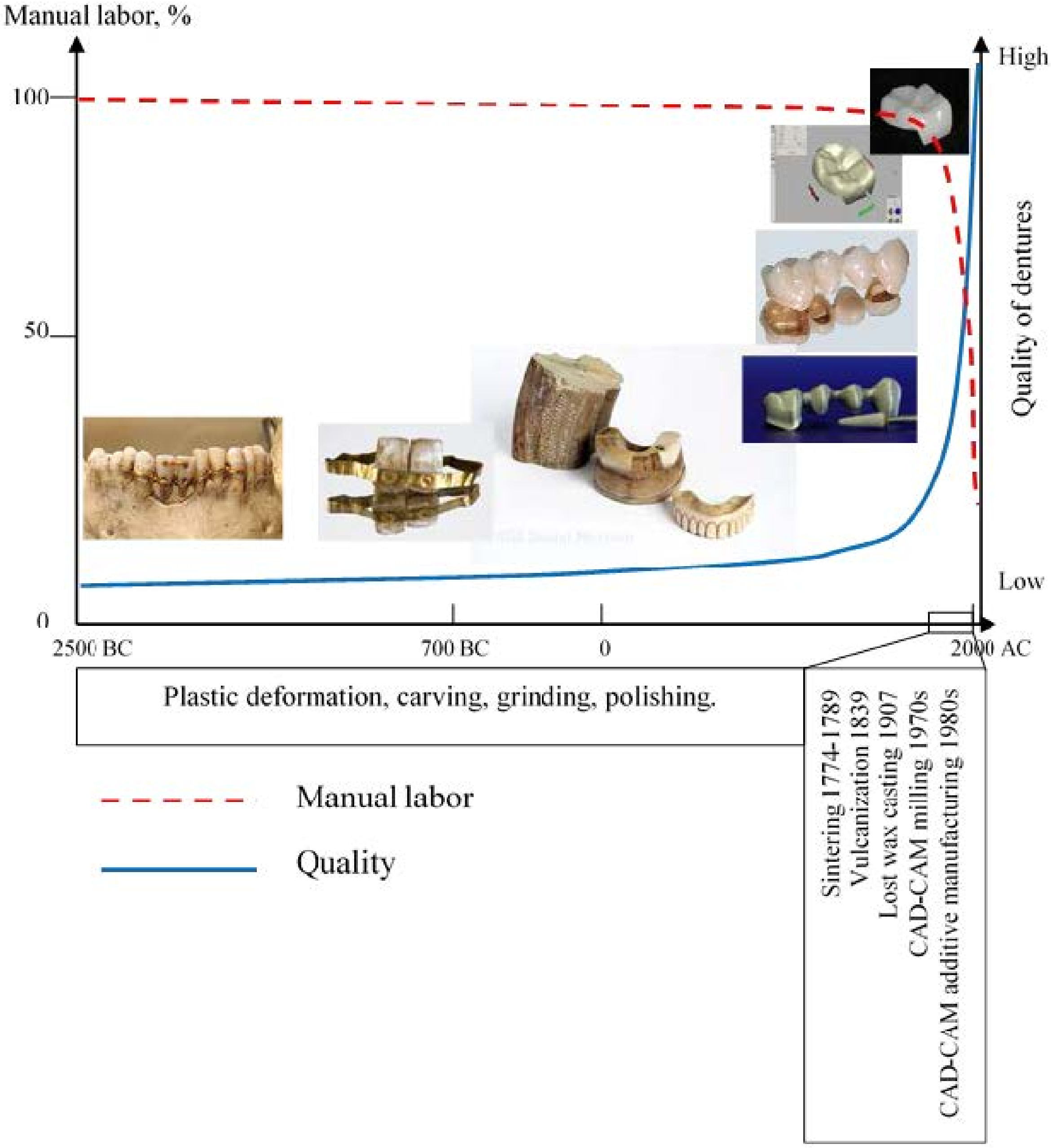


Fig. 2. Development of technologies for dentures manufacturing over the centuries and influence on the amount of manual labor involved and the quality of restorations [3]

The latter group of additive manufacturing technologies (AMTs) emerged in the 1980s when C.W.Hull created the first 3D printer working on the principle of stereolithography [4]. In the AMTs,at first, a virtual 3D model is created and then the object is built layer-by-layer by polymerization, melting or sintering the initial material until the whole detail is completed [5-8]. The greatvariety of technological processes used makes it possible to work with a wide range of materials – waxes, gypsum, polymers, composites, porcelain, puretitanium, Tiand Cr-Co alloys, austenitic steels. The absence of the need for forming, special or universal tools, typical for mostof other processes, allows to produce parts of complex shape with almost no waste. The machines for additive manufacturing are designed and integrated as a CAM module in modern CAD-CAM systems. This makes the production process easy controllable and guarantees high accuracy and qualityof the product. Due to these indisputable advantages, AMTs have been developing at high rates since their inception until today [7-9].

The aim of the present paper is to analyze the perspectives and development trends for application of additive technologies in modern dental medicine in the light of Industry 4.0.

Table 1 *Classification of technologies for manufacturing of dental constructions [3]*

Type of processing technologies	Temperature of the process	Technological process	Processed materials	Computer control
Plastic deformation	Room temperature	Bending	Metals and alloys	No
		Forging		
		Rolling		
		Drawing		
		Stamping		
Joining technologies	Room temperature	Screw joint	Metals, alloys, polymers, ceramics	
		Threaded joint		
		Bolt and nut		
	High temperature	Soldering	Metals and alloys	
		Welding		
Manufacturing compact details	High temperature	Vulcanization	Rubber	
		Casting	Alloys, ceramics	
		Pressing	Polymers, ceramics	
		Sintering	Ceramics	Yes
Subtractive technologies	Room temperature	Carving	Wood, ivory	No
		Cutting	Metals, alloys, polymers, composites and ceramics	
		Milling		
		Grinding		
		Polishing		
		CAD-CAM milling	Ceramics and metal alloys	CAD-CAM systems
	High local temperature	Laser ablation	ceramics	
Additive technologies	Room temperature	Stereolithography	Light curing polymers, ceramics mixed with light curing polymers	
	High local temperature	Fused deposition modeling	Thermoplastic polymers and waxes	
		Selective melting by electron beam	Metals and alloys (pure Ti, Ti-6Al-4V and Co-Cr alloys)	
		Selective laser sintering	Waxes, polymers, composites and ceramics	
		Selective laser melting	Metals and alloys (pureTi and Ti alloys, Co-Cr alloys, stainless steel)	
	Room temperature	Ink-jet printing	Light curing polymers, gypsum, ceramic suspension	

2. PERSPECTIVES AND DEVELOPMENT TRENDS OF ADDITIVE TECHNOLOGIES IN THE LIGHT OF INDUSTRY 4.0

According to the definition of the American Society for Testing and Materials (ASTM), additive technology is "a process, as opposed to subtractive manufacturing, in which the object ismanufactured from a 3D model by joining materials layer by layer" [5,7,10-12]. Additive manufacturing technologies have been initially used for production of prototypes and models of various products that is where the term "rapid prototyping" originates, which continues to be widely used both in our country and abroad.Other terms associated with this type of process are "rapid manufacturing", "freeform fabrication" or "layered manufacturing" [6, 8, 10, 13-15].

Conventional production, which constitutes 16% of the world economy, is at the limit of its transformation [16]. Additive manufacturing technologies will ensure more cost-effectively production of goods and services tailored to consumer needs. They are part of the new technologies of the Fourth Industrial Revolution, Industry 4.0, and that is why they have received a lot of attention in recent years.

As of 2017, the USA is the world leader in the field of AMTs, followed by Germany, the Republic of Korea, Japan, England, Singapore, Canada, Sweden and France [16]. These countries form the group of leaders in the field of 3D printing technology. They have a good base of installed 3D printers, intellectual potential and are already at the stage of their widespread adoption. The aspiration in Germanyis the AMTs to become key technologies of Industry 4.0. The second group includes countries such as Australia, China, Italy, Malaysia, Taiwan, Spain, Russia, the Czech Republic and Turkey. They have large bases of equipment, but they do not meet certain macroeconomic factors such as the way of management, training and availability of qualified labor force.

In recent years, Korea, Italy, England, Germany, France and Singapore have seen the fastest development in the field of AMTs. The Arab countries (Saudi Arabia and the UAE) should not be neglected either. The latter's aspiration is to become a world leader in Industry 4.0 with priority development of the new technologies and 3D printing in particular. A “Dubai 3D Printing Strategy” has been developed to make the country a global hub for 3D printing technologies by 2030. Great attention is also paidto the AMTs as technologies of the future development in the countries of the European Union [17]. In addition to their advantages and applications, the need for the creation and introduction of European and international standards in this area is noted. On the basis ofthe long-term constant analyses, in 2013 a road map was developed for the AMT standardization activities to ensure their successful development in the future.

Since 1993, “Wohlers Associate” has published annual reports on the state of the industry [18]. Forthe first time in 2004, definitions of 3D printing, types of technological processes for layered manufacturing, materials used, possible applications and their development in different countries around the world are given in them. According to the 2017 report, the industrial application of AMTs grew by 17.4% in 2016 compared to the previous year, with the number of companies producing 3D printing equipment rising to 97 compared to 62 in 2015 and 49 in 2014. The market volume of products produced in 2016 through AMTs was 6.063 billion dollars, with 11% or 667 million dollars representing the share of medical and dental products (Fig. 3) [19]. From the very beginning of the implementation of additive technologies, their application in the field of medicine/dentistry occupies the 3rd place, and in recent years, their share in the industry and aircraft construction has increased.It is expected that by 2025, the production of AMTs in the world markets will reach 7 billion dollars. According to the “IDTechEx” research, the development of new applications of 3D printing technologies will continue until 2020, and in areas that are not yet very popular, such as bioprinting [20]. The constant development of AMTs by big business will accelerate their implementation in various fields and in particular in medicine.

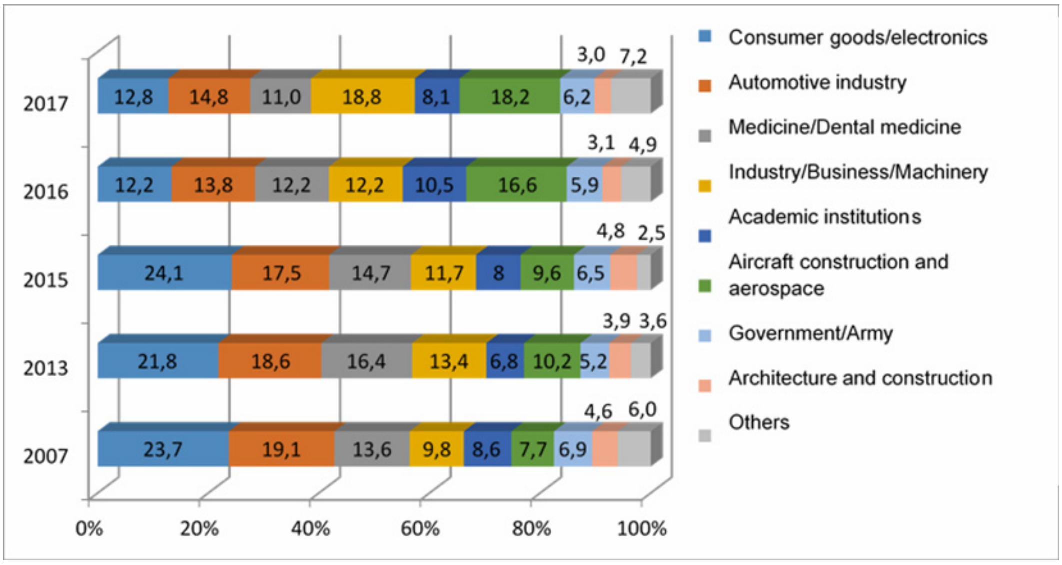


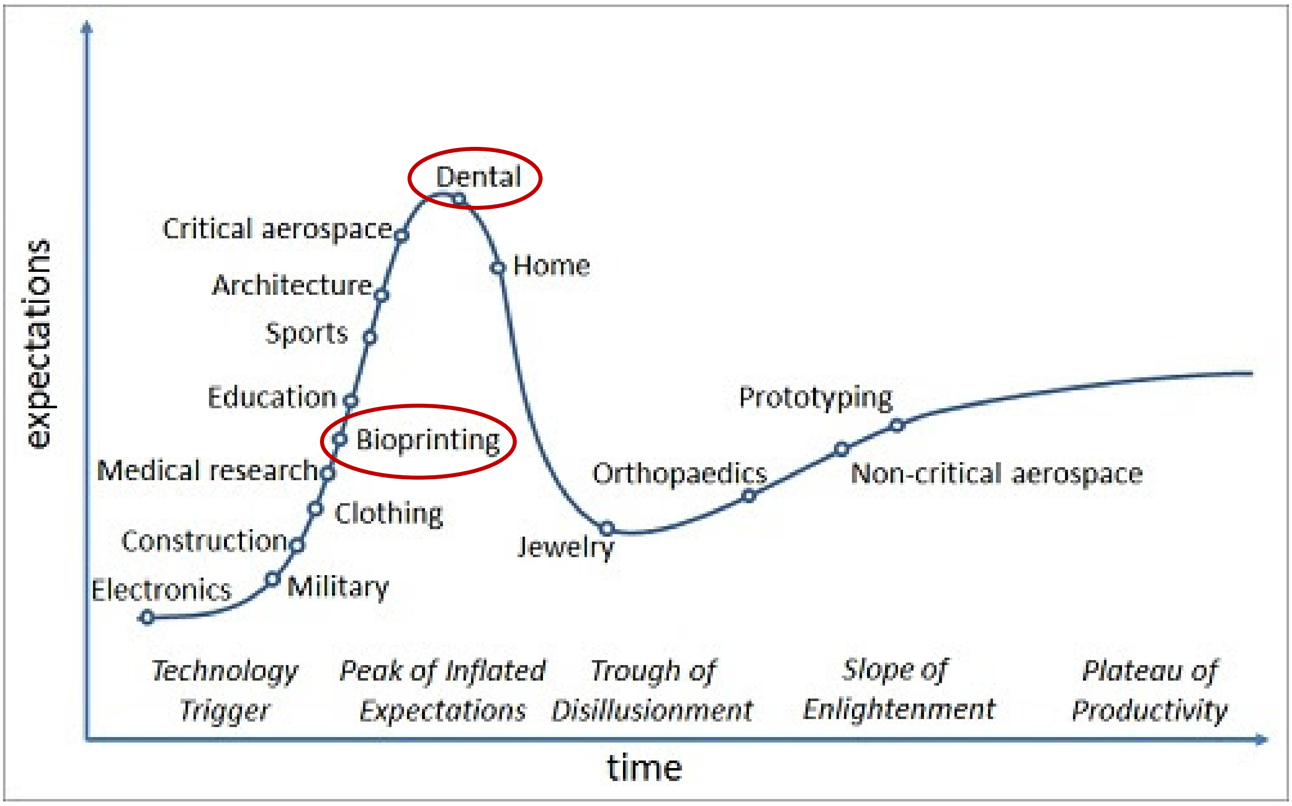
Fig. 3. Application of additive manufacturing technologies in various sectors [19]

The above trends are confirmed by Gartner's study of the development cycle of 3D printing technologies [21], which graphically presents their emergence and maturity. According to him, the trend for the development of a technology consists of five steps (Fig. 4):

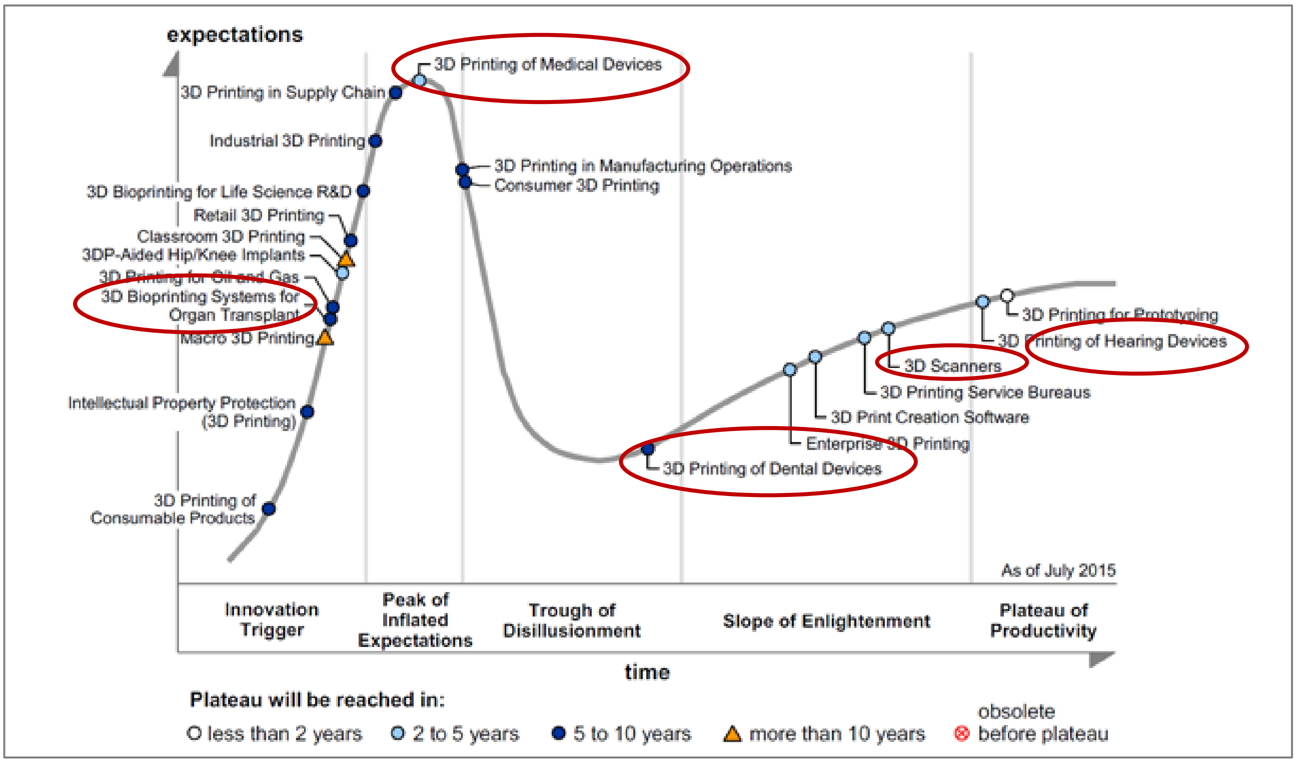
- To be on the rise, when great interest is shown in it due to its high potential;
- To be at the top of the expectations directed at her;
- The expectations begin to decrease due to difficulties encountered in the process of verification and confirmation of its authenticity;
- As a result of successful assimilation, expectations for the new technology again increase, but more slowly;emergence of second and third generation products intended for consumers;
- In the final stage of development, the technology enters the plateau of real production.

The analysis made in 2014 (Fig. 4-a) shows that the application of AMTs in dentistry is at the top of expectations, and that of bioprinting is at the beginning of the trend.In just 3 years – until 2017 (Fig. 4-b) the 3D scanners are already in relatively wide use, followed by the production of dental constructions. According to the forecasts, the 3D printing is expected to be widely used in dental clinics and laboratories in the next 5-10 years. At the peak of expectations is the trend for 3D printing of medical devices and surgical implants, and at the dawn of development are systems for 3D bioprinting of organs for transplants.

For the last 6 years until 2020, the 3D printed products in the field of healthcare have grown by 15.6% in global markets, which for 2020 represents about 1.13 billion dollars [22]. The most widely used technological processes from 2012 to now are photopolymerization (stereolithography) and selective laser melting (SLM), followed by fused deposition modeling (FDM)and selective electron beam melting (SEBM) (Fig. 5). Stereolithography (SLA) is applied to make accurate bio-models mostly in scientific organizations and reached 140 million dollars in 2013. The SLM process is used to manufacture orthopedic implants.It is undergoing the fastest development and from 2014 to 2020 its application growth is about 16%.



a.



b.

Fig. 4. Development cycle of 3D printing technologies for 2014 (a) and 2017 (b) [20,21]

Due to the uniqueness of the individual dental constructions, the 3D printing technologies are first applied in dentistry, where they find a wide field of expression [23].Currently, almost all world-renowned companies for production of dental materials and machines develop additive technologies and manufacture the corresponding equipment (Fig. 6) [24].

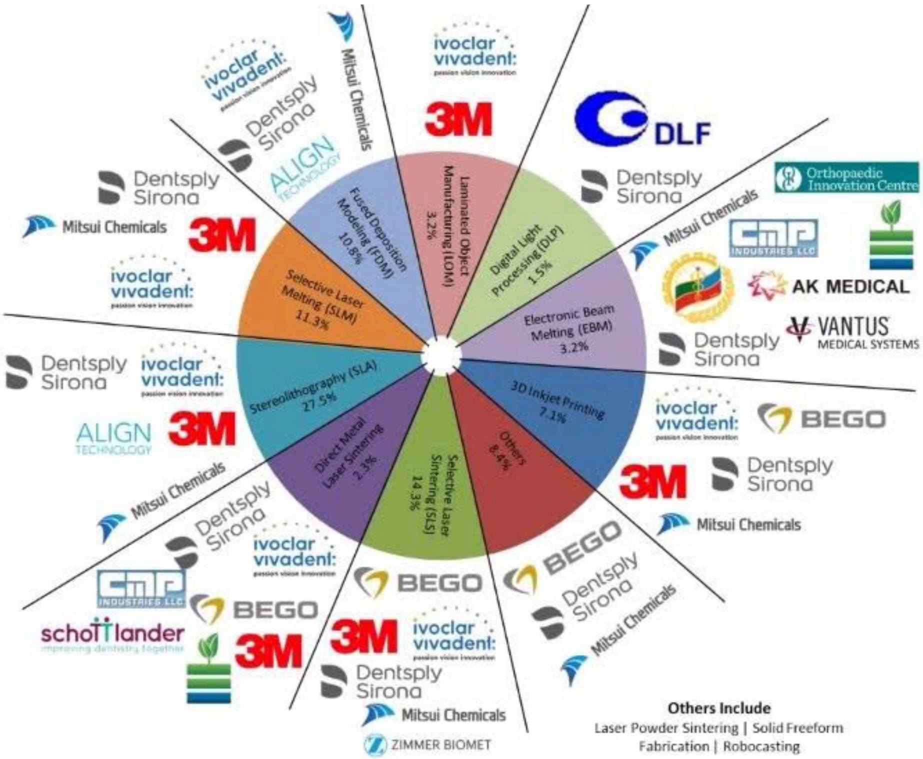


Fig. 5. Additive technologies with application in medicine [22]

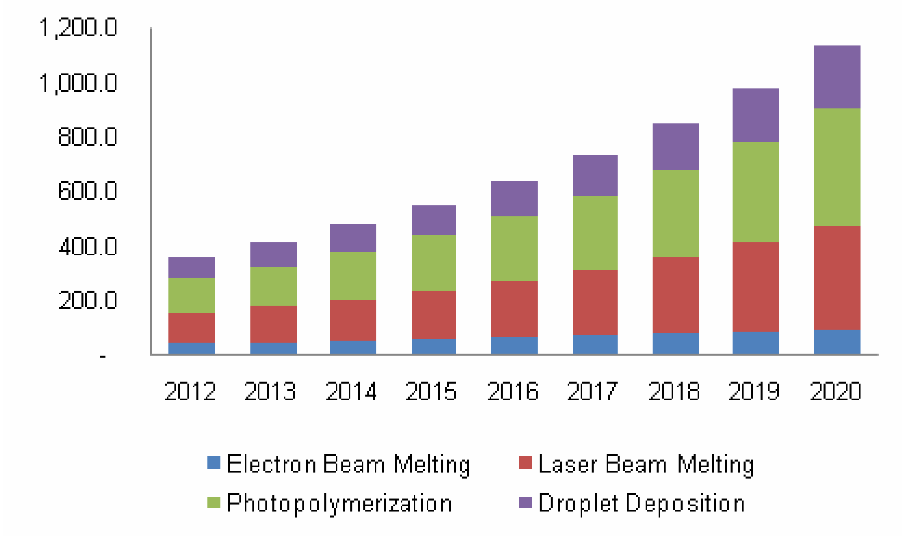
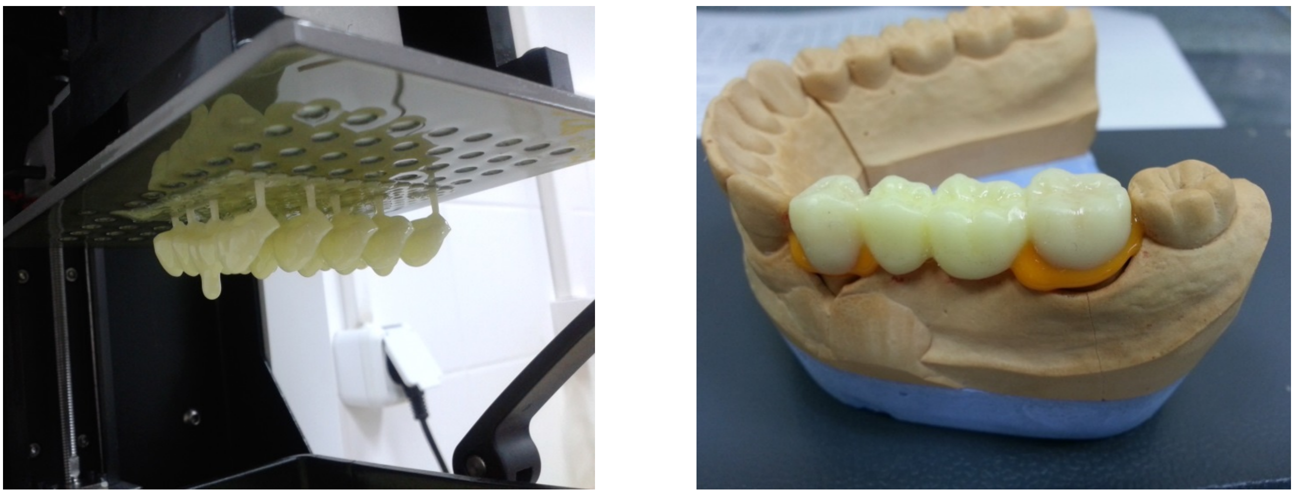


Fig. 6. 3D printing – technological processes – dental industry [24]



a *b*

Fig. 7. DLP stereolithography – a) and temporary dental bridge, produced by DLP SLA – b)

3. APPLICATION OF ADDITIVE TECHNOLOGIES IN MODERN DENTISTRY

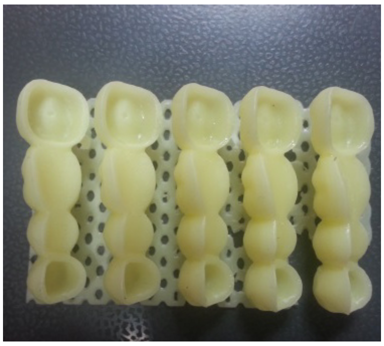
Among the wide variety of additive technologies, the stereolithography, fused deposition modeling, selective electron beam melting,selective laser melting, selective laser sintering (SLS) and ink-jet printing (IJP) are most often applied in dentistry [5, 11, 25, 26]. Constructions with different purposes can be made with their help for all areas of dental medicine - surgery, oral implantology, conservative dentistry, orthodontics and prosthetic dentistry [27-32].

Light curing polymers and composites, based on polymethyl methacrylate (PMMA), are used in the process of stereolithography. As a light source, a laser beam can be used, working by scanning the area, or other types of lighting, in particular an LED, that irradiates the projection once. In that case, the process is calleddigital light projection stereolithography (DLP SLA) [33-37]. Based on the type of materials, the SLA technology is used in dentistry for production of: models to replace plaster casts in prosthetic dentistry and orthodontics;individual impression trays and denture bases;surgical guides for implants;temporary crowns and bridges (Fig. 7), as well as patterns for casting dental constructions from metals and alloys [5, 11, 36-41].

In manufacturing details by fused deposition modelling, a greater variety of polymers are used - acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonates, polycaprolactone, polyphenylsulfones, as well as waxes. The process consists of extruding filamentary thermoplastic material through a heated nozzle or injecting the material from a reservoir [7, 8, 34, 42-44]. The application of the constructions made by FDM is determined by the type and strength of the materials used and by the quality of the surface of the objects. In dentistry, this process is mainly used for manufacturing polymeric (Fig. 8) and duplicating models and less for wax casting patterns [8, 11, 42, 44-51].

Inkjet printing technology closely resembles the way a classic inkjet printer works, which is where the other widely used term "3D printing" comes from. But here, instead of ink, different liquids are used: aqueous solutions of dyes, binders, suspension of ceramic particles [5, 7, 11, 48, 52].In some variations of this process, liquid polymer is used, and each layer is irradiated and polymerized by UV light [48]. Devices have been developed that work with several printing heads on the principle of multi-jet printing [53]. Due to the wide variety of materials used and the relatively high quality of the surfaces in some of the processes, both plaster and polymer dental models, orthodontic and implant guides, mouth andsleep apnea splints as well as dental zirconia restorations can be produced. It is important to mention that the 3D printed ceramic constructions are subsequently sintered.

In the selective electron beam melting technology, powders of biocompatible metals or alloys such as pure titanium, Ti and Co-Cr alloys or stainless steelsare melted layer by layer in vacuum until the object is built [54-58]. This process allows fabrication of constructions with a predetermined porosity and is mainly used for production of individual implants for orthopedics and maxillofacial surgery [7, 54]. Due to the relatively high surface roughness (Ra up to 25 μm), SEBM is not recommended for denture frameworks and crown/bridge infrastructures [5].



a

b

c

Fig. 8. Polymeric dental bridges produced by different 3D printing processes: DLP stereolithography – a), laser stereolithography – b) and fused deposition modelling – c)

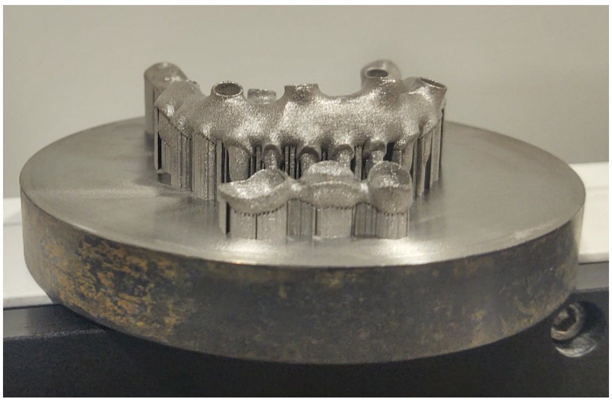


Fig. 9. Frameworks for metal-ceramic dentures, manufactured of Ti6Al4V alloy be selective laser melting

The technology of selective laser sintering/selective laser melting (Fig. 9) is analogous to that of SEBM, except that a laser is used as a source of highly concentrated energy [6, 11, 59]. Differentiation of the two processes takes place depending on the material that is used. Objects made of polymers or ceramics are manufactured by selective laser sintering, and those made of metals and alloys by selective laser melting [6, 7, 57, 59-63]. Since they offer possibilities to work with almost the entire range of dental materials, these processes are widely used in dentistry.Facial prostheses, functional skeletons and individual matrixes for tissue engineering from polymers and composites can be produced by SLS, and by SLM - dental implants and individual implants for maxillofacial surgery with dense or porous structure [27, 32, 64-71], infrastructures for dental crowns and bridges (Fig. 9), as well as frameworks for partial dentures made of metals and alloys [72-79].

4. CONCLUSION

Additive manufacturing technologies offer a new approach for cost-effective production of goods and services and are therefore quite rightly included as part of the Fourth Industrial Revolution, Industry 4.0. Great attention is paid to the AMTs as technologies of the future development in many countries all over the world including the European Union. Depending on the availability of good base of installed 3D printers and intellectual potential, the countries are divided into two groups: 1) leaders in the field of 3D printing technology and 2) countries with large bases of equipment, but lack of trained and qualified labor force.

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The additive technologies most often applied in dentistry include stereolithography, fused deposition modeling, selective electron beam melting, selective laser melting/sintering and ink-jet printing. The great variety of materials used in these processes allow constructions with different purposes to be made for all areas of dental medicine - surgery, oral implantology, conservative dentistry, orthodontics and prosthetic dentistry.

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