

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

Vladimir V. Popov Jr<sup>1</sup>, Anastasia Kolomiets<sup>2</sup> and Gary Muller<sup>3</sup>

<sup>1</sup> Technion - Israel Institute of Technology

*Received: 11 December 2017 Accepted: 2 January 2018 Published: 15 January 2018*

---

## 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. 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).

---

*Index terms*— additive manufacturing, 3d-printing, industrial design, titanium.

## 1 Introduction

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

Papers [5][6][7][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.

## 2 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 3Dmodel, as opposed to traditional manufacturing technologies ascasting or machining [9]. The economic benefits of the use

41 of AM for low series production are substantial as well since customization and single part production are easy  
42 to accomplish [10].

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

46 The DMD-AM provides many benefits for industrial design and manufacturing as shape/geometry form  
47 freedom, no tooling requirements, on-demand production, no minimum order quantities, extreme complexity,  
48 integration of multiple parts into one, no need of high-cost die-forms, and functionally graded materials (FGM).  
49 The development of DMD-AM processes, includes the development of the process productivity, improvement of  
50 material properties, investigation of new alloys and development of modeling and freeform design. Industrial  
51 designers, as well as 3Dengineers and product developers, use this technology for making their design prototypes,  
52 to solve problems related to shape, lines and structure, together with their usability, mechanical properties, and  
53 functionality. The DMD-AM is widely used for presentation of new ideas and concept-designs to clients, to share  
54 their concept vision with other departments: sales, management, production or marketing [2,3].T : ? ? ?

55 At present, the focus has shifted towards manufacturing and production of finished and functionalized parts  
56 rather than prototyping [10][11][12]. Today various materials can be used in AM processes, i.e., metals, polymers,  
57 ceramics, organic tissues, and cells.

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

59 ? Waste reduction. For critical raw material, for example, for rare-earth elements it is especially relevant [13];  
60 ? No machining is needed, significantly reducing post-processing time and costs; ? An option of small material  
61 amount use, important for new materials testing and low-serial production; ? Freedom of rapid design/model  
62 development.

63 ? A possibility of function ability / lightweight structure improvement ? Personalized design; ? Manufacturing  
64 efficiency: to produce the assembled parts in one build; However, the capabilities of 3D-printing are still limited  
65 due to several reasons:

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

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

70 b) The additive manufacturing production cycle An additive manufacturing production cycle starts from the  
71 3D-designer's work, whose task is to realize the CAD-model of the future component (fig. ??). This 3D model is  
72 the basis for the production of the part. Initial shape, geometry, and internal properties can be designed directly  
73 at this stage. Then the model is transformed into a .stl-file and maybe sliced into layers (.amf format) for further  
74 manufacturing. The .stl format converts all internal and external surfaces into an array of triangles.

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

77 After finishing the building process, the part is removed for post-processing and testing. These procedures vary  
78 depending on the used AM process and the final part application. For the M-AM technologies as Selective Laser  
79 Melting (SLM) and Electron-Beam Melting (EBM © ), the first post-processing Fig. ??: A visual representation  
80 of the additive manufacturing principle procedure is support structures removal. There are several reasons to  
81 apply support structures: for heat transfer from the part and as gravity support.

### 82 3 c) 3D-printing of titanium alloys

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

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

## 89 4 II.

## 90 5 Application of Titanium Additive Manufacturing in Industrial Design

91  
92 Due to the material and process benefits, M-AM successfully use in different fields. Today many of them are  
93 short series units, with a high level of complexity, and a high level of customization.

## 94 6 a) Patient-specific titanium implants

95 M-AM techniques are beneficial for the production of patient-specific replacements. The main advantage is  
96 the possibility to customize personalized implants. Moreover, the development of lattice structures in medical  
97 implants becomes advantageous as it combines the mechanical strength, light weight performance, increases

---

98 the number of surfaces (for the interaction between titanium implants and muscular tissue), and minimizes  
99 replacement/shielding surface.

## 100 **7 b) Dental prosthetics**

101 SLM technology has better characteristics than EBM © in surface roughness and accuracy of small parts. Because  
102 of that fact, for dental prosthetics manufacturing, such as dental crowns and bridges, braces and aligners, usually  
103 use SLM-AM. In the same build, hundreds of personalized prosthetics can be manufactured by cost-efficient  
104 SLM-AM. SLMmanufactured dental implants (fig. ??) passed heat treatment and required testing for fatigue  
105 resistance.

106 The manufacturing of titanium dental implants is already serial production for some hospitals. Titanium and  
107 its alloy Ti-6Al-4V are well-known as structural materials. Such applications as medical technologies, chemical  
108 processing, sports, leisure, marine and aerospace all make use of the advantageous combination of properties of  
109 titanium materials. Compared to other metals, titanium and titanium alloys exhibit high corrosion resistance  
110 and high specific strength-to-weight ratio [14]. Today Ti-6Al-4V is the most widely used titanium alloy [15]. This  
111 alloy has a balanced combination of mechanical properties and workability and has been extensively researched  
112 [16]. Year 2018J © 2018 Global Journals a b

113 Fig. ??: a -tooth implant with lattice structured basis; b -implant's support system by EBM © c) Aerospace  
114 components Ti-6Al-4V became a very popular aerospace alloy because of high fatigue resistance. Fatigue  
115 resistance is critical for aerospace parts that work under cyclic loadings. Thus, the first goal for a new  
116 manufacturing technology was to prove that printed components have the same or maybe better mechanical  
117 properties than casted-machined parts.

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

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

## 124 **8 d) New tools manufacturing**

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

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

## 130 **9 III. Prospects of Additive Manufacturing for Industrial De- 131 sign**

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

## 134 **10 a) Automobile application: passengers and concept cars**

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

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

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

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

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

## 146 **11 b) Electronics and engineering manufacturing**

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

151 The case performed in fig. 5 is a newly designed component of a camera for direct nanomotion detection. The  
152 chosen material was Ti-6Al-V because of the unique combination of plasticity and strength of this alloy. EBM  
153 © process was used for the component manufacturing because of temperature conditions of this type of M-AM,

154 which provide the microstructure of a final component free from residual stresses and martensitic structures. After  
155 several iterations between 3D-engineer and industrial designer, the optimal light-weight shape was determined.  
156 The proposed solution is optimal for the serial production of such type of cameras.

## 157 12 c) Complex research systems

158 Fig. 6 presents the components for the electropolishing system of titanium EBM © -printed parts for the needs  
159 of Corrosion Laboratory at Technion. EBM © has specific advantages:

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

## 163 13 Global Journal of Researches in Engineering ( ) Volume 164 XVIII Issue II Version

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

## 169 14 d) Art and musical instruments

170 According to successful experience of rapid plastic prototyping of musical instruments, there is a significant  
171 potential of titanium DMD-AM for this application. Metal instruments have a more sonorous, piercing sound.

## 172 15 Titanium DMD-AM provides the following benefits:

173 ? Bio-compatible non-allergic material; ? Unique acoustic properties;

174 ? High mechanical properties -lightweight, plasticity, strength; ? Unique design possibilities for development  
175 of the product ; ? Personalized instruments: for professional musicians with their specific techniques. From the  
176 internet search, it may be found just several examples of M-AM of musical parts. One of them laser-manufactured  
177 aluminum electric guitar [19]. However, this work is interesting mostly from the esthetic point of view. In this  
178 work the advantages of aluminum as a lightweight or non-corrosive material were not utilized. Moreover, electric  
179 guitar doesn't use the acoustic properties of the printed metal. 3D-printing in metals allows manufacturing of  
180 exclusive souvenirs (Fig. 7), unique art-objects, netshape art installations (Fig. 8) and even jewelry. Moreover  
181 M-AM maybe combined with other techniques as machining, air-brushing (Fig. 8b), coating, assembling, etc.

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

## 184 16 Conclusion

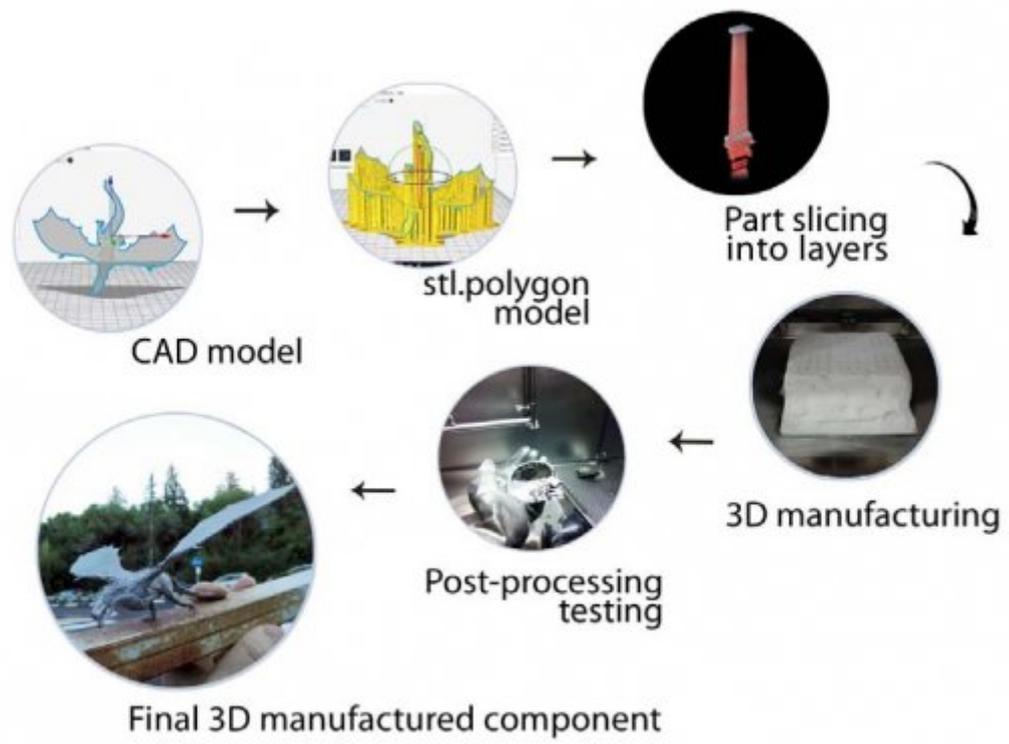
185 The paper presents the use of the 3D-printing as a new instrument for industrial designers for developing  
186 new products and applications. The marketing prediction of the future development of titanium DMD-AM in  
187 industrial design is very positive. Today there are decades of 3D-machines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

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

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

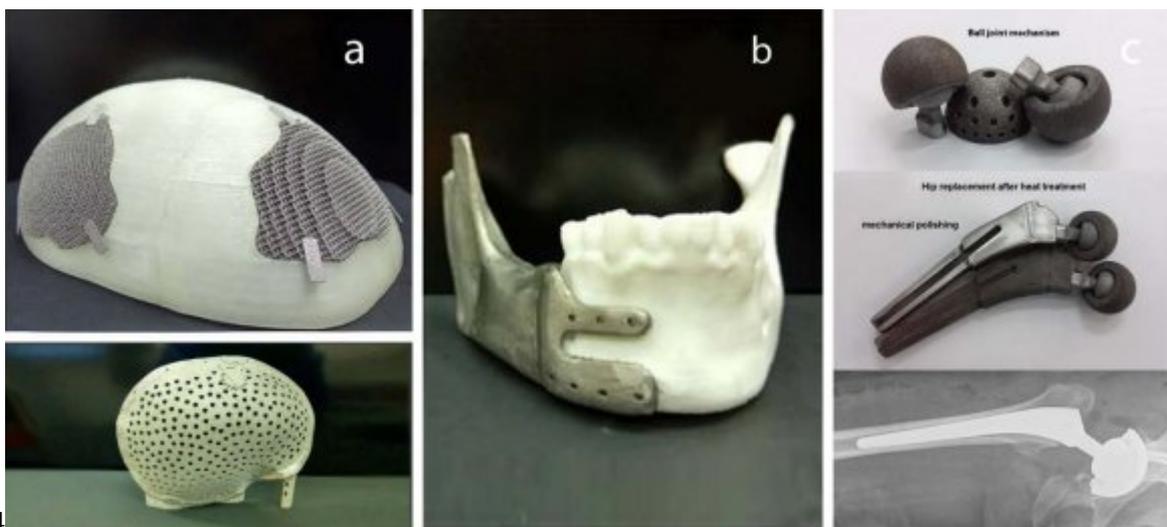
## 199 17 Global

200 1



2

Figure 1: Fig. 2 :



44

Figure 2: Figure 4 JFig. 4 :



Figure 3: Fig. 5 :



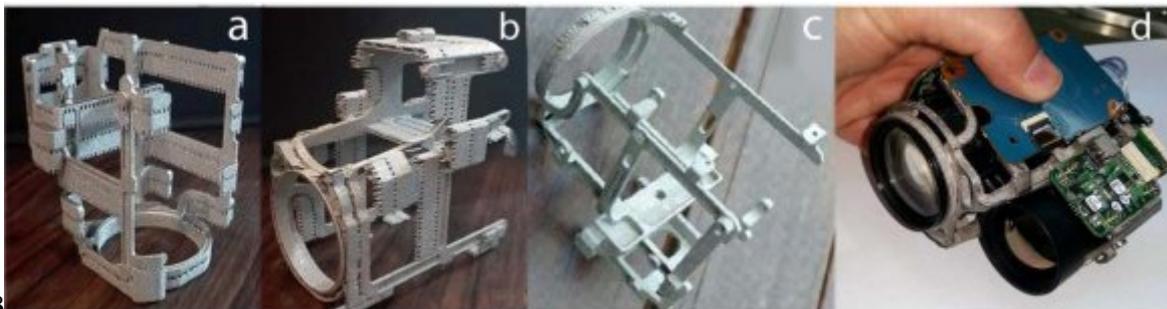
6

Figure 4: Fig. 6 :



7

Figure 5: Fig. 7 :



8

Figure 6: Fig. 8 :



Figure 7:

### 201 .1 Acknowledgments

- 202 You may contact the corresponding author for any additional information and access to the original tests' results.  
203 This research did not receive any specific funding. The authors want to thank prof. Andrey Koptuyug and prof.  
204 Ezri Tarazi for fruitful discussions and advice that helped to improve this paper.
- 205 [Lütjering and Williams ()] , G Lütjering , J C Williams , Titanium . 2007. Berlin: Springer -Verlag. p. . (2nd  
206 Edition)
- 207 [Koptuyug et al. ()] 'Additive Manufacturing for Medical and Biomedical Applications: Advances and Challenges'.  
208 A Koptuyug , L Rännar , M Bäckström , M Cronsakar . *Materials Science Forum* 2014. p. .
- 209 [Herderick ()] 'Additive manufacturing of metals: A review'. E Herderick . *Materials Science and Technology*  
210 *Conference and Exhibition 2011, MS and T'11*, 2011.
- 211 [Hao and Mellor ()] 'Additive manufacturing: a framework for implementation'. L Hao , S Mellor . *International*  
212 *Journal of Production Economics* 2014. (149) p. . (Journal Article)
- 213 [Saetre] *Development of Additive Manufacturing Technology: Implications on the design process and the*  
214 *transportation industry, moving from prototyping to production*, E Saetre .
- 215 [Popov et al. ()] 'Effect of Hot Isostatic Pressure treatment on the Electron-Beam Melted Ti-6Al-4V specimens'.  
216 V Popov , A Katz-Demyanetz , A Garkun , G Muller , E Strokin , H Rosenson , L Li . 10.1038/srep36212.  
217 *Procedia Manufacturing* 2016. 21 p. 36212. (Sci. Rep.)
- 218 [Fanelli (2016)] *Hear Heavy Metal, the World's First 3D-Printed Aluminum Guitar*, D Fanelli . [https://www.](https://www.guitarplayer.com/gear/hear-heavy-metal-the-worlds-first-3d-printed-aluminum-guitar)  
219 [guitarplayer.com/gear/hear-heavy-metal-the-worlds-first-3d-printed-aluminum-guitar](https://www.guitarplayer.com/gear/hear-heavy-metal-the-worlds-first-3d-printed-aluminum-guitar)  
220 Sep, 2016.
- 221 [How 3D Printing is Changing Product Design and Manufacturing] *How 3D Printing is*  
222 *Changing Product Design and Manufacturing*, [https://www.cadcrowd.com/blog/](https://www.cadcrowd.com/blog/how-3d-printing-is-changing-product-design-and-manufacturing/)  
223 [how-3d-printing-is-changing-product-design-and-manufacturing/](https://www.cadcrowd.com/blog/how-3d-printing-is-changing-product-design-and-manufacturing/)
- 224 [Alpay (2012)] *Implications of additive manufacturing applications for industrial design profession from the*  
225 *perspective of designers, thesis for MSc degree*, E Alpay . September 2012.
- 226 [Kirchner ()] *Mechanical properties of Ti-6Al-4V additively manufactured by electron beam melting*, A Kirchner  
227 . EuroPM2015.
- 228 [Kamsky and Kolomiets ()] 'Our future in additive manufacturing'. G V Kamsky , A A Kolomiets . *Materials*  
229 *of the XII International Scientific and Practical Conference «Science without borders -2016*, 2016. 19 p. .  
230 Sheffield Science and Education LTD (Technical sciences)
- 231 [Horn and Harrison ()] 'Overview of current additive manufacturing technologies and selected applications'. T J  
232 Horn , O L A Harrison . *Science Progress* 2012. 95 (3) p. .
- 233 [Morris ()] 'Personal Fabrication and the Future of Industrial Design'. J A Morris . *Idsa.org* 2007.
- 234 [Popov et al. ()] 'Prospects of additive manufacturing of rareearth and non-rare-earth permanent magnets'.  
235 V Popov , A Koptuyug , I Radulov , F Maccari , G Muller . 10.1016/j.promfg.2018.02.199. [https:](https://doi.org/10.1016/j.promfg.2018.02.199)  
236 [//doi.org/10.1016/j.promfg.2018.02.199](https://doi.org/10.1016/j.promfg.2018.02.199) *Procedia Manufacturing* 2351-9789. 2018. 21 p. .
- 237 [Holmström ()] 'Rapid manufacturing in the spare parts supply chain'. J Holmström . *Journal of Manufacturing*  
238 *Technology Management* 2010. 21 (6) p. .
- 239 [Mcdonald et al. ()] *Rapid Prototyping Casebook*, J A Mcdonald , C J Ryall , D I Wimpenny . 2001. Wiley.
- 240 [Rapidtoday ()] *Rapid Prototyping Struggles to Find Niche in Art, Design*, Rapidtoday .  
241 10.1016/j.promfg.2018.02.102. <https://doi.org/10.1016/j.promfg.2018.02.102> 2012. p. .  
242 (Accessed September 4. Rapidtoday)
- 243 [Kamsky et al. ()] 'Review of the main producers of 3d-machines for metals, characteristics of the machines, and  
244 directions of development'. G V Kamsky , A A Kolomiets , V V Popov . *Research Journal of International*  
245 *Studies* 2016. p. .
- 246 [Standard ()] Astm Standard . *ASTM F2792 -12a, Standard Terminology for Additive Manufacturing Technolo-*  
247 *gies*, (West Conshohocken, PA) 2012. ASTM International.
- 248 [Stratasys] Stratasys . [http://web.stratasys.com/rs/objet/images/SSYS-WP-AeroTrends-03-13-FINAL.](http://web.stratasys.com/rs/objet/images/SSYS-WP-AeroTrends-03-13-FINAL.pdf)  
249 [pdf](http://web.stratasys.com/rs/objet/images/SSYS-WP-AeroTrends-03-13-FINAL.pdf) *Additive Manufacturing Trends in Aerospace: Leading the Way*,
- 250 [Antonysamy and Microstructure ()] *texture and mechanical property evolution during Additive Manufacturing of*  
251 *Ti-6Al-4V alloy for aerospace applications. A thesis submitted to the University of Manchester for the degree*  
252 *of Doctor of Philosophy in the faculty of Engineering and Physical Sciences*, A A Antonysamy , Microstructure  
253 . 2012.