Development of equipment for composite 3D printing of structural elements for aerospace applications

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Abstract. Development of an industrial equipment prototype based on a multi-axial robotic arm KUKA KR3 R540 for composite 3D printing with continuous fiber is presented. Composite Filament Co-extrusion Anisoprint technology is taken as a basis of the equipment. The following advantages of the manufacturing equipment are presented in the paper: ability to produce parts of complex spatial shapes with complex spatial reinforcement; mold fabrication in a single process with a part manufacturing. Complex spatial composite structures manufacturing is demonstrated.

Keywords: structural elements, aerospace applications, bi-matrix composite, industrial equipment prototype, reinforcement with continuous fiber, lattice structures, 3D printing.

1. Introduction

Moving to digital manufacturing based on three-dimensional printing (3D printing) is one of the key focus of modern technologies. [1-5]. Already nowadays there exist parts of aircrafts and rocket and space structures made by 3D printing. The following examples can be mentioned: rocket engine nozzles (Lockheed Martin) [6], a fuel tank (RedEye and Lockheed Martin) [7], parts of F35 fighter engine (Northrop Grumman) [6], etc. Boeing Company uses numerically controlled machines that use the layer-by-layer fabrication method to produce more than 200 parts for 10 different aircrafts [8].

Evolution of Fused Filament Fabrication (FFF) is three-dimensional printing of composite parts reinforced with continuous fibers [9-14]. Specific mechanical characteristics of such materials significantly exceed the characteristics of materials obtained by other methods of 3D printing. Composite 3D printing has all advantages of FFF method. Main of them is capabilities of print head movement that provide flexible control of part reinforcement. This feature is not available for conventional manufacturing of composites. Only three-dimensional printing in space allows maximum utilization of advantages of reinforced composites and obtaining parts with high weight efficiency and high mechanical properties. The first results in composite 3D printing reinforced with continuous fiber appeared in 2013. Today both in the US and in Europe, many research centers and private companies are engaged in the development
of this branch of additive manufacturing [12-18]. However, current application of composites in industrial 3D printing is mostly limited by plastics filled with chopped fibers. Such materials possess much lower physical and mechanical properties than reinforced composites do [19]. There are additive manufacturing methods based on semi-extractive process with layer-by-layer placement of continuous fiber thermoplastic prepgs combined with machining [20]. Anisoprint suggests own method based on FFF process which is called Composite Filament Co-Extrusion (CFC) where reinforcing composite fiber and thermoplastic filament are simultaneously supplied into hot end [21]. Using thermoplastic polymers as a matrix eliminates the need for subsequent curing of a part after its printing. It enables fabricating parts of complex spatial shape due to solidification of the matrix during the printing process. This approach makes it possible to optimize reinforcement paths in accordance with acting loads. That allows obtaining parts of complex shapes, without resorting to post-processing that causes destruction and damage of reinforcing fibers [22]. The machining essentially reduces the strength and stiffness of composites. Examples of machining detrimental effects are shown in Figure 1 [23].

Despite the fact that 3D printing with continuous fibers is actively developing, currently there are no industrial solutions capable to fabricate composite parts of complex shape and complex spatial internal structure. This work is dedicated to development of multiaxial 3D printing equipment for manufacturing of composite parts reinforced with continuous fibers.

![Figure 1](image1.png)

**Figure 1.** Examples of the destruction of layered composite material during post-processing.

### 2. Prototype of Equipment for Composite 3D Printing

This article describes the development of the industrial equipment prototype for 3D printing of composite load-carrying structural elements reinforced with continuous fibers. A reinforcing fiber is used in the fabrication process of composite elements. During the printing process this fiber is fed directly into the printing head together with a thermoplastic polymer. The fiber is pre-impregnated with a special polymer composition [24]. Thus, the output is a bi-matrix composite. One matrix provides a reliable impregnation of the reinforcing fiber and its adhesion to the used thermoplastic. The other ensures coupling between such composite fibers.

Within the concept of additive automated digital manufacturing the developed equipment allows to fabricate aerospace and aviation structural elements of complex shapes and internal structure with high specific mechanical characteristics.

Main elements of the equipment prototype for composite 3D printing include: a non-removable load-bearing frame decorated with a protective casing; a multi-coordinate kinematic system based on an industrial robot; a print head manufactured and operated by Anisoprint technology.

The frame was designed in the Siemens NX / NX Nastran computer-aided design and engineering system. An analysis of acting loads to the prototype during the manufacturing process was made. A finite element (FE) analysis of the prototype frame with further optimization of the structure was also conducted.

The load was defined as a concentrated force applied at the cantilever end of the outstretched robotic arm and acting vertically down. The magnitude of the applied load was equal to 800N. It corresponded to the triple weight of the entire industrial robot with printhead payload. Multiplier 3 (three) was applied
as a safety factor, taking into account dynamic loading and possible accident loads. Several iterations of design refinement were performed until the final design was obtained. Goal of the design was minimum weight of the frame with satisfaction of the stiffness restriction. Final weight of the frame was 254 kg and maximum deflection did not exceed 0.1 mm under applied loading. The results of FE analysis for the chosen design are presented in Figure 2.

![Figure 2. FE analysis results of 3D printing equipment prototype frame.](image)

The industrial robot KUKA KR3 R540 with a specialized software and hardware complex of movement control KR C4 Compact RP DC4 XI X55 10 was used as a multi-axial kinematic system. It was dictated by the highest accuracy of positioning and repeatability in its class of equipment, the absence of the hardware redundancy and the possibility of deep industrial integration into manufacturing processes. The printhead was installed on the interface of the robot. It worked according to the Anisoprint CFC process. The printhead had several features. The first one is a compact size. The second feature is an ability of cooling the print head input channels for stable supply of plastic filaments. The printing head has a special extruder nozzle to ensure the consolidation of the composite. The printhead had the following characteristics: maximum extruder heating temperature up to 400 °C; supported binder materials: PLA, ABS, PA (nylon), PET-G, PC, PEI. The 3D model and photo of the print head installed on the KUKA KR3 R540 robot is shown in Figure 3.

![Figure 3. 3D model and photo of the print head](image)

To achieve the maximum printing area of the multi-coordinate moving system the position of the industrial robot was chosen as "On the wall". A simplified functional block diagram of the equipment and placing of control system for the material supply are shown in Figure 4. All units are located on the support frame.
Figure 4. Functional block diagram of the equipment and placing of control system for the material supply on the frame.

The control system for the material supply consisted of the industrial controller Bosch Rexroth CML25 with I/o modules, the module for heating control via RS-485 Protocol and two-channel pulse-width modulation signal generation module. NFE02.1 module was used for line filters. HCS01.1E modules with brand-name MSM019B servo motor connection cables are used as drivers. At the same time, the controller drove the Thermodat modules intended to heat the nozzles of the printhead. Main advantages of the layout are compliance with the requirements of industrial operating standards, scalable hardware platform, standardized communication interfaces, the ability to connect high-grade human-machine interface components and I/O modules, etc.

Figure 5 shows the equipment prototype and CFC printing a branch pipe. The branch pipe was manufactured in one operation cycle.

3. Parts Manufacturing

For numerical control code generation, simulation of the printhead movement and reinforcement paths modelling were conducted in Rhinoceros 3D. Figure 6 shows the developed 3D model and the printing process of the part.

It should be noted that reinforcement of the part was made only within predefined zone. Such reinforcement can be realized either by applying trimming of reinforcing fibers, or by serpentine turns of the reinforcement paths. The second method was chosen to demonstrate capabilities of the technology. In this case, the serpentine turns are high curvature non-geodesic lines. Such layup cannot be carried out by conventional automated processes of composite manufacturing such as winding or automated fiber placement.

4. Discussion
Currently composite lattice structures are widely used in rocket and space industry. Such structures allow to fully utilize advantages of reinforced composites and reduce their basic drawbacks. It ensures their high weight efficiency in comparison with traditional composites and metal structures [25-28].

Figure 6. 3D model and Part printing.

Filament winding is mainly applied process for manufacturing of lattice structures. Ribs of the lattices corresponds to geodesic or quasi-geodesic lines. Shapes of the lattice structure as a rule are convex or close to convex. Figure 7 shows typical rocker and space structures. Irregular grids of complex structure and configuration can be evolution of anisogrid structures. Shapes of ribs of such structures are not restricted by geodesic and quasi-geodesic lines. The developed equipment for composite 3D printing allows manufacturing irregular composite lattice structures with complex shapes. It is not required application of expensive molds and tooling. Thus, the suggested technology can be considered as promising for manufacturing of lightweight aerospace structural elements of new generation [29-31].

Figure 7. Composite lattice payload adapter and spacecraft frame (CRISM).

5. Conclusions
The developed equipment makes possible manufacturing of composite structures with complex shape and internal structure. It allows effective distribution of acting loads through structural elements. That provides production of structural elements of high weight efficiency.

Anisoprint Composite Filament Co-Extrusion process is basis of the developed technology. It provides flexible control of fiber volume fraction in composite. Application of thermoplastic polymers as a matrix can be considered as one of the technology advantage in terms of increasing impact and crack resistance of manufactured composite parts.

Modern hardware components provide full automation for manufacturing of composite parts.

References
[1] Fo F G A and others 1970 Fiber Composite Materials Ed. D M Frantsevich and D M Karpinos (Kiev: Naukova Dumka) p 403
[2] Kobets L P and Gunyaev G M 1974 Structural plastics Ed. E B Trostyanskaya (Moscow: Khimiya) p 304
[3] Konkin A A 1974 Carbon and other heat-resistant fibrous materials (Moscow: Khimiya) p 304
[4] Sayfulin R S 1983 Inorganic Composite Materials (Moscow) p 304
[5] Lubin D ed. 1988 Composite Materials Reference translation from English book I, 2. (Moscow: Mashinostroyeniye) p 448
[6] Aizinson I L and others 1988 The main directions of the development of composite thermoplastic materials (Moscow: Khimiya) p 48
[7] Kelly A and Rabotnov J ed. by 1983 Handbook of composites 1-4 (Amsterdam: North Holland)
[8] Bourell D, Leu M and Rosen D Roadmap for Additive Manufacturing - Identifying the Future of Freeform Processing 2009 The University of Texas at Austin Laboratory for Freeform Fabrication Advanced Manufacturing Center TX
[9] Guo N and Leu M 2013 Additive Manufacturing: Technology, Applications and Research Needs Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology Rolla 8 3 215-43
[10] Jayakumar A 2014 Why the aerospace industry is investing in 3-D printing The Washington Post
[11] Cohen D, Sargeant M and Somers K 3-D printing takes shape 2014 https://www.mckinsey.com/ businessfunctions/operations/our-insights/3-d-printing-takes-shape access: nov. 2019
[12] Orbital Composites Electronic resource https://www.orbitalcomposites.com/ access: nov. 2019
[13] Matsuzaki R, Ueda M, Namiki M and other 2016 Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation Scientific Reports
[14] 3D Printer Using Continuous Carbon Fiber Composite Materials Electronic document http://www.jscm.gr.jp/3Dprinting/images/introduction_CFRP3Dprinter.pdf access: nov. 2019
[15] Composites 2.0 Electronic document https://www.rs.tus.ac.jp/composites2/ access: nov. 2019
[16] Frank van der Klift, Koga Y, Todoroki A, Ueda M and other 2016 3D Printing of Continuous Carbon Fibre Reinforced Thermo-Plastic (CFRTP) Tensile Test Specimens Open Journal of Composite Materials 6 18-27
[17] +LAB Electronic resource http://www.piulab.it/projects/cont Erinuo-fiber-composites access: nov. 2019
[18] Invernizzi M, Natale G, Levi M, Turri S and Griffini G 2016 UV-Assisted 3D Printing of Glass and Carbon Fiber-Reinforced Dual-Cure Polymer Composites Materials Materials 9(7) 583
[19] Zelensky E S, Kuperman A M, Gorbatkina Y A, Ivanova-Mumzhieva V G and Berlin A A 2001 Reinforced plastics - modern structural materials Journal of the Russian Chemical Society D 1 Mendeleev XLV 2
[20] Zhiyo A, Schwil H and Frolov M 2015 Thermoplastic carbon plastics: Special unidirectional materials for aircraft engineering II international technological forum "Innovations. Technologies. Production" (Rybinsk)
[21] Demkovich N A, Volkov I A and Yablochnikov E I 2016 The use of numerical modeling systems when introducing new production technologies Engineering and mechanical engineering 18 4(3) 459-63
[22] Chvalun S N, Novokshonova L A, Korobko A P and Brevnov P N 2008 Polymer-silicate nanocomposites: physicochemical aspects of in situ polymerization synthesis Journal of the Russian Chemical Society D I Mendeleev LII 5 52-7
[23] Wisnom M R The role of delamination in failure of fibre-reinforced composites. Philos Trans A Math Phys Eng Sci. 2012 Apr 28;370(1965):1850-70
[24] Adumitroaei A, Antonov F, Khaziev A, Azarov A, Golubev and Vasiliev V 2019 Novel Continuous Fiber Bi-Matrix Composite 3-D Printing Technology Materials Materials 12(18) 3011
[25] Vasiliev V 2009 Composite Pressure Vessels: Design, Analysis, and Manufacturing (Bull Ridge Publishing) p 704
[26] Kondakov I 2016 Development and validation of methods for calculating the strength analysis of mesh composite fuselage structures Civil Aviation High TECHNOLOGIE 19 06 137-46
[27] Azarov A V, Antonov F K, Vasiliev V V, Golubev M V, Krasovskii D S, Razin A F, Salov V A, Stupnikov V V and Khaziev A R Development of a two-matrix composite material fabricated by 3D printing. Polym Sci D 2017;10(1):87–90
[28] Azarov A, Antonov F, Golubev M, Khaziev A and Ushanov S 2019 Composite 3D printing for
the small size unmanned aerial vehicle structure *Composites* Part B *169* 157–63

[29] Reznik S V, Prosuntsov P V and Azarov A V 2015 Substantiation of the structural-layout scheme of the mirror-space-antenna reflector with a high shape stability and a low density per unit length // J. Eng. Phys. Thermophy. 88(3) pp. 699-705. DOI:10.1007/s10891-015-1239-x

[30] Reznik S V, Prosuntsov P V and Azarov A V 2015 Modeling of the temperature and stressed-strained states of the reflector of a mirror space antenna // J. Eng. Phys. Thermophy 88(4) pp. 978-983 DOI:10.1007/s10891-015-1273-8

[31] Reznik S V, Prosuntsov P V, Mikhailovsky K V and Shafikova I R 2016 Material science problems of building space antennas with a transformable reflector 100 m in diameter // IOP Conference Series: Materials Science and Engineering 153(1) 012012. – 10 p. DOI: 10.1088/1757-899X/153/1/012001