BULLETIN of Cherkasy State Technological University

Journal homepage: https://bulletin-chstu.com.ua/en

Vol. 28 No. 4. 2023

UDC 621.791.7:004.932.046.78
DOI: 10.62660/2306-4412.4.2023.50-58

Features of application in critical structures of products made by fused deposition using 3D printing technology

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Abstract. The technology of hot-melt 3D printing has prospects for military equipment and other special applications, provided that necessary requirements for the quality, strength and durability of plastic components are met. However, there is a problem of insufficient accuracy and unexplored patterns of change in technological parameters during 3D printing, which makes it necessary to manufacture critical structures using plasma

Article's History: Received: 01.09.2023; Revised: 08.11.2023; Accepted: 18.12.2023.

Suggested Citation:
Tychkov, D., Bondarenko, Yu., Tuz, V., Sapozhnikov, S., & Shapovalova, D. (2023). Features of application in critical structures of products made by fused deposition using 3D printing technology. *Bulletin of Cherkasy State Technological University,* 28(4), 50-58. doi: 10.62660/2306-4412.4.2023.50-58.

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deposition technology. The main purpose of the article is to study and evaluate the features of using the fused deposition method in 3D printing technology for the manufacture of products that are critical special-purpose structures and require increased strength and durability. To achieve this purpose, the technology and means of 3D printing by fused deposition method (filament feed control system with a circular encoder) have been improved. It has been established that the use of the filament feed control system can reduce the number of visually detected defects on the surface of printed products by an average of 71.7%, but increase the amount of wire consumed by 13% and the average printing time by 15-17%, which is due to the lack of supporting structures for the resulting surfaces. The research conducted in this paper has shown an increase in delamination strength of elements of critical structures, such as brackets for mounting a laser rangefinder to the body of an unmanned aerial vehicle. With the help of the filament feed control system, the strength of these elements has increased from 27.4 (tensile) and 32.1 (compressive) to 38 (tensile) and 44.3 MPa (compressive). There is also a more than 2.7-fold increase in the number of dynamic load cycles during endurance tests. This study indicates greater dynamic stability and less fatigue of the elements manufactured by fused 3D printing using a filament feed control system. The results will have practical applications in various fields, including military applications

Keywords: additive technology; print quality; strength; endurance

INTRODUCTION

Gradual growth of product quality requirements is becoming an integral part of a competitive market. This relevance, however, is gaining new dimensions due to the use of non-standard technical and technological solutions that are becoming more common in modern manufacture of products. These non-standard solutions cannot always be effectively implemented using traditional methods and technologies. There is a tendency to use innovative approaches, such as 3D printing and other advanced technologies. These methods open up great opportunities for creating unique and complex products, but at the same time pose new challenges for manufacturers in terms of researching and optimising process parameters. Despite significant progress in this area, important patterns of change in technological parameters of the printing process and their impact on product quality and mechanical and operational characteristics remain insufficiently understood.

Traditional technologies are increasingly replaced by additive technologies and rapid prototyping methods that can be used for mass manufacture of products without the need for complex production planning and specialised equipment, which greatly simplifies the process of product formation due to more flexible approaches to production management, which has been written about by B.A. Praveena *et al.* (2022) and G. Prashar *et al.* (2023). Authors I. Gibson *et al.* (2021) noted that 3D printing technologies are increasingly being used in various fields of science and technology. For example, the introduction of such technologies in modern production allows to manufacture products of varying complexity and configuration, including fragments of various energy, aviation, rocket and space, and military equipment (e.g., quadcopters, unmanned vehicles, etc.) operating under high climatic and mechanical loads, according to T.D. Ngo *et al.* (2018). Existing 3D printing technologies often do not meet high accuracy requirements for products, especially those that are components of critical structures. This is due to the limited research, rapid prototyping technologies, and lack of information on methods for controlling the accuracy of parts during their manufacture, as pointed out by J. Kiendl and G. Chao (2020).

In general, despite the prevalence of 3D printing methods and tools that have been developed recently, the study of their performance in the manufacture of critical products remains relevant to many leading world-class scientists. For example, a team under the guidance of J. Huang (Huang *et al.,* 2022) proposed an algorithm for implementing a unidirectional slicing strategy that slices the product model in the Z-axis direction, perpendicular to the 3D printer platform. This algorithm, although simple to implement, requires a significant amount of time to complete. Due to the disadvantages of this algorithm, which also include high computational complexity and inaccuracy, it is proposed to use a direct slicing strategy using analytical models. This strategy slices the model without converting it from a surface model to a mesh one. This can improve the accuracy of cut contours and correct the shortcomings of the mesh model. These algorithms usually require the support of a commercial software kernel for computer modelling, as written about in the works of such researchers as R.P. Ferreira and A. Scotti (2021), F. Wang *et al.* (2021) and S. Sagar *et al.* (2021).

Despite all the achievements and clear progress of this technology, there are currently a number of problems that limit the use of 3D printing technologies for the manufacture of high-precision and reliable products of critical structures. These problems include the lack of approaches to maintaining technological quality of moulded surfaces due to the lack of feedback in most 3D printing tools to determine the actual consumption of consumables, which can lead to a decrease in printing quality and the emergence of a number of defects (microcracks, non-compliance with the thickness of product elements, etc.) and, as a result, deterioration of mechanical performance of these products, according to A. Jennings (2022).

For this reason, solving the issue of improving such characteristics in critical structures of products manufactured by fused deposition using 3D printing technology is an urgent task to which this article is devoted. To achieve this goal, the article solves the following tasks:

- to analyse existing solutions among the methods and systems of fused 3D printing of critical products for military equipment and other special-purpose applications;
- to compare the results of the proposed method of product printing using an improved filament feed control system and the method of traditional fused deposition by 3D printing;
- to test the products obtained using different technologies for compliance with their mechanical strength and endurance under dynamic loads.

The main purpose of this article was to study and evaluate the features of applying the fused deposition method in 3D printing technology for the manufacture of products of critical special-purpose structures that meet increased requirements for their high strength and durability. Scientific novelty of this work is that the technology and means of 3D printing by fused deposition method, in which a filament feed control system, including a circular encoder, is used, and the use of which can significantly improve the quality of 3D printing of products, increase their mechanical strength and endurance to external dynamic loads, have been improved.

MATERIALS AND METHODS

Technological experiment to obtain prototypes of products was carried out on a fusion 3D printer developed and improved with the participation of the authors in the laboratory of additive technologies in instrumentation, created on the basis of the department of instrumentation of mechatronics and computerised technologies of Cherkasy State Technological University. Testing and verification of the results obtained for the selected printing modes were carried out on the Ender-3 V3 SE device (Creality, China) at the State Scientific Research Institute of Armament and Military Equipment Testing and Certification. Experimental verification of research results with the aim of their comparison was carried out using both proposed technologies (traditional one and authors' technology using the filament feed control system). Polylactic acid (PLA) material was used to print the products. The average feed rate of a wire with a diameter 1.75 mm was 3.0 (for traditional technology) and 1.8 mm/s (for the authors' technology), and the extruder movement speed was 30 mm/s. The data obtained were calculated using 3D printing software, Cura (Vijay *et al.*, 2022). The printing was performed with a layer of 0.6 mm, with 20% filling without supports.

Analysing the available solutions among the methods and systems for fused deposition of 3D printing, it should be noted that methods such as FDM (Fused Deposition Method) or FFF (Fused Filament Fabrication Method) are very common in the additive manufacturing industry. This is due to their ease of equipment modification, affordability, wide range of consumables, and the possibility of quick training, according to T.S. Xiong *et al.* (2022). When manufacturing products with a complex geometric structure or there is a need to meet special reliability requirements (especially for components of critical structures) using FDM method, some defects may occur, for example, the effect of segmented texture (Fig. 1). This problem manifests itself when the angle of inclination of the surface relative to the printing plane decreases, and the formed surface becomes less smooth.

Figure 1. Exterior view of the product (Boeing Insitu ScanEagle (USA) UAV compressor bushing) printed by fused deposition using 3D printing technology with a distinct segmented texture effect

Source: compiled by the authors

In addition to the aesthetic problem, the effect of segmented texture also negatively affects mechanical properties of products, such as strength, resistance to harsh environmental conditions, aerodynamics, resistance to perpendicular loads, and other aspects. To solve this issue, a reduction in the height of the vertical layer can be used, but this approach leads to an exponential increase in printing time. Therefore, another method is proposed, which is also considered to be one of promising areas for the development of FDM technology in general – a method of manufacturing curved layers, known as Curved-Layer Manufacturing (CLM) (Cao *et al.*, 2023). Compared to the standard fused deposition process, in which parts are manufactured layer by layer, curved layer method allows to avoid the effect of segmented texture on surfaces lying close to the horizontal by printing these areas using continuous solid layers (Fig. 2).

Figure 2. Exterior view of the product (Boeing Insitu ScanEagle (USA) UAV compressor bushing) printed by the curved layer method using solid layer 3D printing technology

Source: compiled by the authors

The method of non-planar 3D printing allows to reduce or even eliminate the need to print supporting structures necessary for the construction of overhanging parts of the product, which leads to additional material and time consumption for the manufacture of parts. To improve operational and mechanical (strength) characteristics of products manufactured by the fused deposition method using 3D printing technology, it is proposed to use a filament feed control system, the exterior view of which is shown in Figure 3.

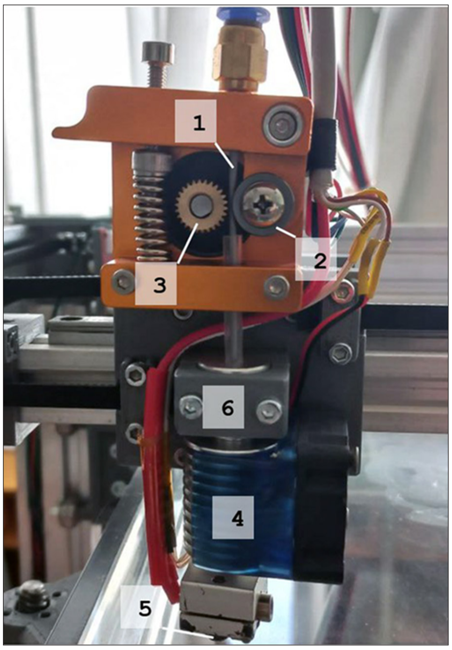

Figure 3. Exterior view of the filament feed control system together with the extruder

Notes: 1 – filament, 2 – measuring rollers, 3 – toothed filament feed rollers, 4 – heating unit, 5 – nozzle, 6 – circular encoder mechanism

Source: compiled by the authors

The principle of operation of the control system is as follows: filament 1 is fed from the bay (not shown in the figure) through special toothed rollers that act as measuring elements and activate the circular encoder mechanism 6 of the filament flow metring unit. When a command is received to start 3D printing on the device, the filament preheated by the heating unit 4 is directed through the nozzle 5 to the area where the 3D product is formed using the feed motor (not shown). Simultaneously with the start of the feed motor, toothed filament feed rollers 3 and measuring rollers 2 start feeding the filament 1 through the measuring device. If the filament slips in feeding devices into the heating and printing zone, a reduction in the required filament volume is taken into account using encoder 6. In this case, the control programme recalculates to reduce the filament feed rate, which ensures the required operational and mechanical characteristics of elements of critical structures.

RESULTS AND DISCUSSION

The strength and durability of the obtained products under dynamic loading were evaluated by testing the developed device in real conditions. For this purpose, the consumption metring mechanism of consumable material – filament – was proposed and tested (based on the developed automatic control system (Andriienko *et al.*, 2019)). This mechanism made it possible to control the supply of consumables to the working area with high accuracy (over 95%) and speed (the reaction time to a change in the wire feed rate is 250-480 ms). A comparison of the results of the proposed method of printing the product using the filament feed control system and the method of traditional fused deposition by 3D printing is shown in Table 1.

Table 1. Comparison of printing process parameters using the proposed technology with the filament feed control system and traditional technology

Printing process settings	**By technology using the filament feed control system**	**Using traditional technology**
Number of samples / printed surface area, m^2	12/0.34	12/0.34
Number of visually detected surface defects	61	216
Length of wire consumed, m	230.8	201
Weight of consumed material, kg	0.292	0.247
Printing time, min	128.2	111.6

Source: compiled by the authors

Table 1 shows that with the use of the control system, the number of visually detected defects decreases by 71.7%, from 216 to 61. At the same time, the amount of wasted wire increases by 13%, which for these products amounts to 247 (for products manufactured with traditional technology) and 292 grams (for products manufactured using the technology with a filament feed control system). Since there are no supporting structures for resulting product surfaces, the total length of printing segments (and, consequently, the wire used) also increases, which leads to an increase in the average printing time by 15-17%.

Figure 4 shows the results of test printing of products of critical structures, namely mounting brackets made of PLA plastic, obtained at a print speed of 60 mm/s using a 0.2 mm nozzle. When using the filament feed control system (Fig. 4b) with a 0.2 mm nozzle and a higher printing speed (80 mm/s), the quality of the solid surface is much better, and printing artefacts observed when using traditional technology are almost completely eliminated. The authors suggest that obtaining high-quality and reliable products is possible with a further increase in printing speed under conditions of controlled filament supply and adjustment of its operating temperature. The decrease in the quality of printing the edges of a product with a sharply defined geometry in 3D printing using traditional technology is associated with the occurrence of internal mechanical stresses due to faster cooling of the filament (associated with a lower printing speed) and, as a result, peeling and cracking of the applied solid material. In contrast to traditional technologies, 3D printing with the filament feed control system, which is carried out at a 30-35% higher speed, provides better adhesion between the layers of the applied material and, thus, greater adhesion strength and fewer internal and surface defects.

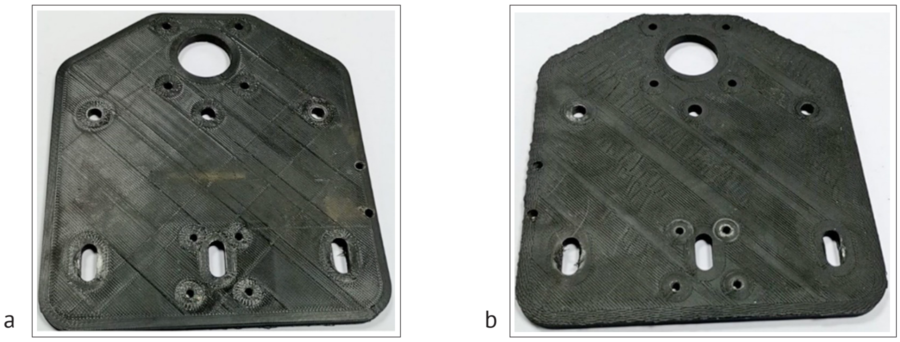

Figure 4. Exterior view of samples (brackets for mounting the laser rangefinder to the UAV body)
Notes: a – printed using traditional technology, b – printed using the technology with the filament feed control system
Source: compiled by the authors

The authors D. Chakraborty *et al.* (2022) presented a surface-based parametric tool generation method for rapid prototyping technology, known as layer-by-layer modelling with curved layer deposition. This method allows the deposition of curved layers instead of traditional flat layers in FDM (Fused Deposition Method), which can improve the quality of thin curved parts. However, this method, according to the authors, is developed mainly for thin parts, and the algorithms presented in this paper are theoretical. Researchers Y. Li *et al.* (2022) used the method of slicing with curved layers to preserve the features of a complex surface. Genetic algorithms that passed curved layers through clusters of object features to reduce the number of curved layers were proposed. This method is mainly suitable for thin parts and hollow shells, so no experiments were conducted with products. Thus, in contrast to the applied method of 3D printing using the filament feed control system, the use of the methods proposed above is impractical due to practical unconfirmation of the results of the proposed solutions, as well as the lack of information (even theoretical one) on how to improve mechanical characteristics of parts printed using the proposed technologies.

Mechanical characteristics of parts (in particular, strength and endurance to dynamic mechanical loads) manufactured using the fused deposition method by 3D printing were investigated by N. Elmrabet and P. Siegkas (2020), M. Algarni (2021) and M. Doshi *et al.* (2022). At the same time, studies on the compliance with tensile and compressive strength of the printed product according to the methodology proposed by J. Sedlak *et al.* (2023) showed the following. According to classical technology, the delamination strength of bracket samples was 27.4 (tensile) and 32.1 MPa (compressive), while according to the technology using the filament feed control system, these values were 38 and 44.3 MPa, respectively, and approached the ultimate tensile and compressive strength of a solid material (for PLA plastics, the latter are 50-70 and about 60 MPa, respectively), which was a positive result. Experimental results indicate a significant improvement in mechanical properties of such parts compared to parts made by layer-by-layer surfacing.

When these products were tested for endurance under dynamic mechanical loads at load amplitude of 30 MPa and cyclic frequency of 5 Hz, the following was established. The first signs of fracture (local delamination and cracking in the product) appeared on the samples of brackets produced by traditional 3D printing technology after 4.680 load cycles, while the samples produced by the technology proposed in this paper withstood 12.960 cycles before the appearance of signs of fracture, which proves greater dynamic stability and lower fatigue of the products manufactured by this technology.

The hot melt technology of 3D printing opens up opportunities for its use in military equipment and other specialised industries, provided that it meets the required standards of quality, strength and durability of plastic parts. At the same time, there is a problem of insufficient accuracy and unexplored patterns of change in technological parameters during 3D printing. This problem can be solved by creating critical structures using plasma deposition technology. One way to overcome these difficulties is to conduct a detailed study and optimise printing process parameters to achieve the highest quality and efficiency of manufactured products. Such an approach will simultaneously expand the scope of the technology and ensure its successful use in highly demanding military and special applications.

Identified positive aspects can be applied to improve technical characteristics of other products where it is important to ensure dynamic stability and durability. The results of the study can become the basis for further research aimed at improving and optimising 3D printing processes to increase the productivity of manufacturing high-quality parts. It should be borne in mind that the implementation of the findings can contribute to the development of innovative solutions in manufacturing, in particular in the field of new materials and technologies. Thus, this study opens up wide opportunities for the use of advanced approaches in the production and development of high-tech products.

CONCLUSIONS

The article analyses the existing solutions among the methods and systems of fused 3D printing of critical structures for military equipment and other special-purpose applications, which shows the prospects of using this technology provided that necessary requirements for manufacturing quality, mechanical strength, and endurance to external dynamic loads of elements of critical plastic structures are met. It has been established that with the application of the technology using the filament feed control system, the number of visually detectable defects on the surface of the printed product is reduced by an average of 71.7%. At the same time, the amount of wire consumed increases by 13%, and due to the lack of supporting structures for the resulting product surfaces, the total length of printing segments (and, accordingly, the wire consumed) also increases, which leads to an increase in the average printing time by 15-17%. An increase in delamination strength of critical structural elements (for example, brackets for mounting a laser rangefinder to the UAV body) from 27.4 (tensile) and 32.1 MPa (compressive) when such elements are produced using the classical technology to 38 (tensile) and 44.3 MPa (compressive) when producing such elements using the technology with the filament feeding control system, as well as an increase of more than 2.7 times in dynamic load cycles (load amplitude is 30 MPa; cyclic frequency is 5 Hz) for elements of critical structures obtained using the control system during their endurance testing are shown. This proves greater dynamic stability and lower fatigue of such elements and opens up the prospect of using products made by fused deposition by means of 3D printing technology with the filament feed control system in critical structures, including military applications. Further promising research in scientific direction stated in this paper may be devoted to the study of tactical, technical and operational characteristics of the resulting products when they are actively used under critical loads and effects of aggressive environments.

ACKNOWLEDGEMENTS

The authors thank the journal's anonymous reviewers and the handling editor for helpful comments on an earlier draught. Content and any remaining errors are the sole responsibility of the authors.

CONFLICT OF INTEREST

None.

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Особливості застосування у відповідальних конструкціях виробів виготовлених методом осадження плавленням за технологією 3D-друку

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Анотація. Технологія термоплавкого 3D-друку має перспективи для військової техніки та інших спеціальних застосувань за умови дотримання необхідних вимог до якості, міцності та довговічності пластикових деталей. Однак існує проблема недостатньої точності та недосліджених закономірностей зміни технологічних параметрів під час 3D-друку, що зумовлює необхідність виготовлення відповідальних конструкцій з використанням технології плазмового осадження. Основною метою статті є вивчення та оцінка особливостей використання методу осадження плавленням в технології 3D-друку для виготовлення виробів, які відносяться до відповідальних конструкцій спеціального призначення і вимагають підвищеної міцності та довговічності. Для досягнення поставленої мети було вдосконалено технологію та засоби 3D-друку методом плавкого осадження (система контролю подачі філаменту з круговим енкодером). Встановлено, що використання системи контролю подачі філаменту дозволяє зменшити кількість візуально виявлених дефектів на поверхні надрукованих виробів в середньому на 71,7%, але збільшити кількість витраченого дроту на 13 % і середній час друку на 15-17 %, що пов'язано з відсутністю опорних конструкцій для одержуваних поверхонь. Дослідження, проведені в даній роботі, показали підвищення міцності на розшарування елементів відповідальних конструкцій, таких як кронштейни для кріплення лазерного далекоміра до корпуса безпілотного літального апарату. За допомогою системи керування подачі філаменту міцність цих елементів зросла з 27,4 МПа (при розтягуванні) і 32,1 МПа (при стисненні) до 38 МПа (при розтягуванні) і 44,3 МПа (при стисненні). Також більш ніж у 2,7 рази збільшилася кількість циклів динамічного навантаження під час випробувань на витривалість. Це дослідження свідчить про більшу динамічну стійкість і меншу втому елементів, виготовлених методом термоплавкого 3D-друку з використанням системи керування подачі нитки. Результати матимуть практичне застосування в різних галузях, в тому числі у військовій сфері

Ключові слова: адитивна технологія; якість друку; міцність; витривалість