METHODS OF QUALITY CONTROL FOR AEROSPACE PARTS, PRODUCED WITH 3D-PRINTING OUT OF COMPOSITE-REINFORCED POLYMERS

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Abstract. One of the features of parts, made from polymer composite materials, is that the part and material are both formed at once, when the part is being made. Complexity of interaction processes between matrix and reinforcing fiber makes it difficult to achieve prognosed characteristics of part due to possible imperfections of manufacturing processes and technology. Therefore, an important part of parts life cycle is quality control. Quality control can be destructive or non-destructive, the latter giving more information and insight on defects of the part itself and, possibly, at flaws in manufacturing technology. With the increase in popularity of use of additive manufacturing technologies, especially – FDM 3d-printing, in aerospace industry, there’s a need to improve the performance of parts. Benefits of FDM 3d-printing is the absence of need for specialized forming equipment and tools, especially for forming the parts with complex, topologically-optimized geometry and structure. One of the ways to improve printed parts performance and its physical properties is to use continuous fiber reinforcement. Because of need to control the state and position of the fiber in the part, quality control is also an important part of this type of additive manufacturing. Existing popular methods of quality control, used in polymer composite materials part manufacturing were reviewed. Also, the features and limitations, imposed by structure of printed parts and printing technology were reviewed as well, the differences of them and polymer composite parts made in traditional forming ways, were noted too. The destructive testing methods reviewed are tensile stress testing, bend testing and impact stress testing. The non-destructive quality control methods reviewed are visual, acoustic, radiological and ultrasound. Also, recommendations on their use on FDM 3d-printed parts were formed. As a result, visual and ultrasound methods were accepted as non-destructive methods of quality control, with need to perform destructive tests on sample parts as well. Also, as a promising method, thermography was proposed, yet because of the limitation of using it with high-temperature polymers, its utility is also limited.

Keywords: POLYMER COMPOSITE MATERIALS, 3D-PRINTING, REINFORCING FIBER, QUALITY CONTROL
контролю якості: статичне розтягування, статичний вигин, ударний вигин, візуальний, акустичний, радіографічний та ультразвуковий, також надані рекомендації та вказівки з використання їх для контролю якості деталей, виготовлених за допомогою FDM 3д-друку. Крім необхідності провести руйнівний контроль деталей-зразків, для неруйнівного контролю деталей, виготовлених 3d-друком з композиційних армованих матеріалів, найбільш дієвими обрано візуальний та ультразвуковий види контролю. Також, як перспективний був наведений термографічний метод контролю, але через обмеження по використанню лише для високотемпературних полімерів його доцільність обмежена.

Ключові слова: ПОЛІМЕРНІ КОМПОЗИЦІЙНІ МАТЕРІАЛИ, 3D-ДРУК, АРМУЮЧЕ ВОЛОКНО, КОНТРОЛЬ ЯКОСТІ.

Introduction

Use of parts, produced with additive manu facturing methods, including FDM/FFF 3d-printing, becomes more and more widespread. In aero space the benefits of additive manu facturing are the possibilities of cheap iterative development, using of COTS-technologies and materials, which allow to significantly lower the cost of end product. In a similar way, FDM/FFF 3d-printing can be used both for developmental prototypes, to test the construction for later use of the manu facturing methods [1], and for production of end units directly [2].

Aside from the methods of production, and important part of the parts lifecycle is quality control. There are destructive and non-destructive types of control, and non-destructive are usually employed before destructive. Non-destructive methods allow to get enough data to determine if the part is corresponding to design requirements. Destructive analysis is needed only when the properties of the material aren’t known or provided by material source. Also, destructive testing is required for determining the physical and mechanical characteristics of an end part when new manufacturing technologies or materials are used.

In the process of additive manufacturing from polymer materials, control methods similar to those used for polymer and composite materials obtained by traditional production methods are most often used.

Methods of destructive control are divided by the type of controlled parameter. The main methods are divided into: static stretching, static bending, impact bending (on notched samples) [3].

Static stretching, or tensile testing methods determine such parameters as proportionality limit, elastic limit, yield limit, strength limit and relative elongation. In these methods, tearing machines are used, material tests are performed on samples of a defined geometry, as per relevant standards [4].

Static bending methods are used to determine such parameters as the bending angle and to specify the modulus of elasticity. These methods use press machines with attachments such as a double-stand and mandrel bender, a V-stand and mandrel bender, and a vise bender. [5].

Impact strength is determined by impact bending methods. These methods use a pendulum coper.

Methods of non-destructive testing are divided according to the type of physical principles, which are used to carry out the testing. The main methods are divided into: visual, acoustic, radiographic, ultrasonic and impedance-ultrasound [6].

Visual control methods include inspections with the naked eye, size measurements, and the use of inspection and measuring microscopes. Visual methods also include surface preparation methods for control.

Acoustic control methods include manual and automatic shock-acoustic tests (the so-called "coin tap test") and thermo-acoustic emission tests.

Radiographic research methods are divided into neutron, X-ray and gamma radiography.

Ultrasonic research methods use ultrasonic waves and are divided into transmitted radiation methods and reflected radiation methods. Impedance methods are a subspecies of ultrasonic and consist in recording the resonance of the part under the influence of high-frequency vibrations.
Formulation of the research problem

The purpose of the work is to determine and analyze the methods suitable for the study of parts and products made by the methods of additive technologies from composite materials.

The specifics of the quality control of such parts is that additive manufacturing technologies, namely FDM 3d-printing, create a multi-layered, heterogeneous structure, the arrangement of elements in which strongly depends on the printing settings. Even when using the same settings, the same materials from different suppliers or batches can affect the appearance and geometry of structures. Such features make it difficult to control products because they make it difficult to distinguish defects from features of structure generation. Printing settings also affect the accuracy of defect detection, due to the possible complexity of measuring technologically determined structures and sizes [7]. Also, unlike traditional composite materials, where the density and porosity of the layers can vary depending on the stacking of the layers, the amount of binder and the strategy of its application, FDM 3d-printing forms almost monolithic walls and structures in the places where the infill walls pass. Another problem is the presence of technological pores and cavities, which requires the creation of "maps" of infill walls and considering the location of variable layer density in places of roundings and chamfers.

Presence of rein for cingfiber in plastic filament also adds certain features on quality control. Dueto technological specifics of FDM 3d-printing, the position of fiberin singular line, deposited by the nozzle, maynot correspond to fiber position in previouslays, which canbe misinter pretedas false positive esign of a defect. Also, position of rein for cingfiberin filamentmay changewithlengths. Sumof thefactors may hinder the inter pretation of control device’s readings.

Solution of the research problem

Taking into account the features of FDM 3d-printed parts and the features imposed by the presence of composite reinforcing fiber in the plastic, the abovementioned control methods will be evaluated in the context of compliance with both sets of factors. Various options for the orientation of the layers of the part relative to the control device will also be considered.

Tensile testing is possible for specimen parts of various sizes and configurations, but the most commonly used are models that conform to testing standards for metals. The first thing to consider is that the strength of the material and the strength of each individual part produced by FDM 3d-printing are different. Tensile strength depends on technological parameters of printing, such as temperature[8]of the nozzle or layer orientation, infill thickness [9]. In addition, strength is also affected by the infill pattern, shell thickness, the quality of the infill-to-shell bond, and the degree to which the shell is overlapped by the infill. Considering the presence of reinforcing fiber in the parts, during tensile tests, the destruction of the main polymer material may occur while maintaining the integrity of the fiber with its debonding from the polymer matrix. This indicates that the strength limit of the product is equal to the strength limit of bonding the main polymer with the reinforcing fiber.

Bend testing [10] is performed with flat sample parts. In bending for flat samples, when the layers are located parallel to the neutral plane of bending, a more critical role is played by the bond strength between the individual layers, which, as a rule, is always less than the strength in the plane of the layers. The presence of reinforcing fiber plays a minor role in increasing flexural strength. However, when the layers are arranged so that the load is applied in the plane of the layer, the influence of the reinforcement on the strength depends on the angle of infill walls and the angle of the shell pattern.

Impact strength [11] can be carried out on parts of different layer orientations. It should be considered that with some orientations of the layers, local strengthening and compaction of the layers is possible in the place of the modeled notch. The coefficient of effective reinforcement is lower due to the presence of a notch, which causes greater asymmetry in the failure of the sample.
Methods of visual control [12], such as dimensional measurements, naked eye inspection or microscopes can be used to analyze the surface of the part, they do not have penetrating power even if (partially) transparent plastics are used to manufacture the part. Visual methods allow qualitative detection of the entire range of surface defects, and when using measuring microscopes, micrometers, or calipers, a quantitative assessment of the size of defects is also possible. Also, when inspecting the parts, it is possible to control the presence of exposed reinforcing fibers in single lines or layers. If visual control is carried out on the cut parts, it makes it possible to detect internal defects inherent in FDM 3d-printing, such as: delamination of the wall perimeters, delamination of top and bottom shell layers, defects of the connection of the infill and the outer shell, breaks or delamination of the infill walls, the presence foreign inclusions in infill cavities or in shells, etc. When examining the side surface of the parts (perpendicular to the layers), a qualitative and quantitative assessment of the height of the layers and their defects, if any, is possible. Before research using microscopes, in the process of preparing a section or cut of the part, it is necessary to follow the temperature regime of the technological processes, to prevent heating of the material to or above the glass transition temperature. At the same time, many plastics react negatively to uneven cooling or heating, so the method of cooling of part must be uniform. Liquid cooling is also not advised in many cases. Contrary to the recommendations for the preparation of metallographic samples and cuts[13], it is undesirable to cut with abrasive wheels, especially in the case of plastics with high hardness, brittleness (for example, PLA or plastics after hardening or coating). Cutting should be done with saws, cutters, non-abrasive cutting discs. After cutting the sample, it is necessary to remove burrs and material residues from the infill cells. Grinding and polishing for many types of plastics is carried out dry, with wiping the surface of the sample with ethyl alcohol or isopropyl alcohol while changing the grain size of the grinding material. The use of polishing or grinding pastes/powders is not recommended. Etching of the cut after mechanical processing is not carried out, nor is it recommended to use solvents such as acetone or kerosene for wiping or washing the surface of the sample. When preparing the cut, one should also take into account the features of the presence of reinforcing fiber in the plastic, namely: when cutting and grinding, do not allow the fiber to tear out; do not allow clogging of the fiber with grains of grinding material; for wiping, use substances inert to the fiber material; do not allow loosening, swelling or wetting of the fiber from the wiping substance.

Acoustic testing[14]have little utility and accuracy of results for parts obtained by FDM 3d-printing methods. Impact-acoustic tests, such as the coin tap test, which is widely used in aviation to investigate composite panels, are practically impossible to apply to printed parts due to their much higher hollowness. Even when using print modes that provide high infill percentages and thick shells, the acoustic difference between defective and normal areas is very small. The reason for this is that the structure of the part is an array of separate elementary, single lines, and acoustic waves at frequencies that are generated in the process of impact-acoustic tests are too scattered at the boundary of separation of single threads to maintain a diagnostic effect. Also, the stiffness and "tension" of the shell of the printed part is too small for acoustic resonance. Thermo-acoustic studies cannot be used due to the requirements of heating parts above the glass transition temperature of most plastics.

Radiography studies [15]studies are well suited for multilayer structures. Computed tomography methods are especially suitable for researching parts made by the FDM 3d-printing method. There are many examples of industrial tomography machines that have high resolution, the possibility of adjusting the scanning power depending on the material of part, and, depending on the software of the tomograph, and the possibility of dimensional measurement of the internal and external dimensions of the parts [16]. From the point of view of need to control parts with
reinforcing fiber, it is necessary to take into account the degree of transparency of each specific type of fiber for the type of radiation used, and if necessary and possible, treat the fiber with radiation contrast substances at the stage of manufacturing filament for 3d-printing. Radiographic studies, namely computer tomography, can be used to study details at an arbitrary angle, both in the cutting mode and in the mode of generating a three-dimensional model. Disadvantages of radiographic methods include the impossibility of conducting on-site research without preparation; increased danger of research without the use of appropriate means of protection for others; high cost of machines.

Ultrasonic studies use elastic high-frequency vibrations that either pass through the part and are received on the opposite side, or are reflected from the internal elements of the part (cavities, defects, inclusions) and are received on the same side[17]. Parts obtained by the FDM 3d-printing method have a high degree of internal hollowness, which in most cases makes it impossible to use the method of passing waves through, except for cases of study parallel to the shell walls. The method of research by wave reflection allows to evaluate: the actual thickness of the shell, the integrity of the layers of the shell, adhesion defects of the layers. When conducting ultrasonic studies, attention should be taken to the preparation and condition of the surface with which the sensor will interact – the cleanliness and roughness of the surface should ensure the most complete and reliable contact. This is especially critical for upper surfaces, bridges, surfaces that were printed on supports, curved and rounded surfaces with a large layer thickness and zones of the beginning and end of the trajectory of printing a layer. Based on the requirement to control parts and products with reinforcing fiber, ultrasonic methods can be used to qualitatively assess the uniformity of fiber distribution in the surface layers of the part, due to the effect of reducing the apparent thickness of the shells compared to the actual thickness due to the reflection of part of the wave front from the fiber.

Thermographic methods can be distinguished among promising methods of control of printed parts with composite fiber reinforcement. They consist in local heating of parts and analysis of temperature distribution using thermal imaging technology. Due to the fact that the reinforcing fiber has a heat capacity different from that of the polymer, it is possible to observe the distribution of the fiber in the surface layer of the shell of the part, perpendicular to which observation and heating are carried out. Also, the presence of defects in the adhesion of the shell and infill can be characterized by the thermal pattern of the joints of the shells with the infill walls. The limitation of this method is the possibility of its use only for polymers with a high glass transition temperature and the danger of thermal deformation of the part due to uneven heating and cooling. The use of machine vision systems for automating visual control is also becoming widespread. The use of high-resolution cameras, an image processing algorithm with the help of artificial intelligence and multispectral analysis (simultaneous monitoring in, for example, the visible and infrared spectrum) makes it possible to conduct quality control directly in the process of printing the part. For example, the Penelope system[18][19], which was developed for use with Laser Powder Bed Fusion (LPBF) 3d-printing technology, allows to control the condition of the part, print quality and correct defect areas during the process of synthesis of the part. This system consists of a high-resolution imaging system with a pixel size of 20 μm, a printer-mounted illumination system, and an infrared camera. Another important component of the system is a device for removing damaged/defective areas of the layer. It is a surface grinding wheel with an abrasive disk mounted on a carriage. With the help of this device, according to the conclusions of the monitoring system regarding the quality of the printed layers, the defective material is removed, the layer is locally corrected, and the printing process is resumed. A similar system can also be integrated into an FDM printer, with the possibility of installing a
grinding or milling device directly in the same fixture together with the print head.

Scientific novelty
A review, evaluation and analysis of existing quality control methods, widely used for the study and testing of polymer composite materials, was carried out, taking into account the features and limitations of FDM 3d-printing technology. The analysis and evaluation of these methods was also carried out from the point of view of greater heterogeneity of the structures of the parts, which is caused by the ratio of the reinforcing fiber to the main polymer and the hollowness of the parts, inherent to the technology.

Conclusion
During the analysis of destructive quality control methods, it was determined the need to conduct tests of samples for yield strength, bending and impact toughness to determine the actual physical and mechanical characteristics of materials and parts obtained by FDM 3d-printing. It is especially important to carry out such tests during the development of new PCMs synthesized by FDM technology, or the development of the technology for manufacturing final products. In another case, the strength of the finished part will be determined taking into account its design, internal structure, and the method of fiber reinforcement. Therefore, it is desirable to determine the strength characteristics of the finished part for a selected sample from a batch of products on special machines, which will allow obtaining more reliable data for predicting the characteristics of further parts manufactured with the same technological parameters. Also, for non-destructive quality control of parts made by FDM 3d-printing from polymer materials with continuous fiber reinforcement, it is most appropriate to use visual and ultrasonic control methods. The limitations of each of them require further consideration of the features of quality control of typical parts and surfaces, additional tests and the creation of recommendations for research methods. Recommendations for surface preparation and grinding for visual quality control using microscopes were also formed and provided.

References
2. Руйнуючий та ушкоджуючий контроль// ЗНУ. URL: https://moodle.znu.edu.ua/pluginfile.php/887971/mod_resource/content/1/%D1%80%D1%83%D0%B9%D0%BD%D1%96%D0%B2%D0%BD%D0%B8%D0%B9%20%D0%BA%D0%BE%D0%BD%D1%82%D1%80%D0%B0E%D0%BB%D1%8C.pdf (reference date18.12.2023).
8. H. Gonabadi, A. Yadav, S. J. Bull. The effect of processing parameters on the mechanical characteristics of PLA produced

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