**Build monitoring and inspection in 3D printing digital technology**

**Моніторинг та перевірка побудови в цифровій технології 3D друку**

**Мониторинг и проверка сборки в цифровой технологии 3D печати**

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*Адитивне виробництво має незаперечні переваги перед традиційними технологіями: відсутність геометричних обмежень, виготовлення деталей складної форми, можливість використання різних матеріалів. Але все ж таки для отримання якісного об'єкта необхідно правильно підібрати параметри друку. При 3D-друку виникає безліч різноманітних дефектів, що вимагає постійного контролю якості об'єкта. Онлайновий моніторинг якості деталей є необхідним для своєчасного, надійного та швидкого виявлення несправностей. У зв'язку з цим описуються системи якості через параметри стану та вихідні параметри технологічної системи.*

***Ключові слова****: адитивні технології, 3D-друк, метод FDM, онлайновий моніторинг, лазерна техніка.*

*Аддитивное производство имеет неоспоримые преимущества перед традиционными технологиями: отсутствие геометрических ограничений, изготовление деталей сложной формы, возможность использования различных материалов. Но все же для получения качественного объекта необходимо правильно подобрать параметры печати. При 3D-печати возникает огромное количество разнообразных дефектов, что требует постоянного контроля качества объекта. Онлайновый мониторинг качества деталей является необходимым для своевременного, надежного и быстрого обнаружения неисправностей. В связи с этим описываются системы качества через параметры состояния и выходные параметры технологической системы.*

***Ключевые слова:*** *аддитивные технологии, 3D-печать, метод FDM, онлайновый мониторинг, лазерная техника.*

*Additive manufacturing has undeniable advantages over traditional technologies: the absence of geometric constraints, the manufacture of complex shapes parts, the possibility of using different materials. But nevertheless, in order to obtain a high-quality object, it is necessary to choose the correct printing parameters. A huge variety of defects occurs in 3D printing, which requires constant quality control of the object. Online monitoring of part quality is essential for timely, reliable and fast fault detection. In this regard, the quality systems via 3D printing state and output parameters are described.*

***Key words****: additive technology, 3D printing, FDM method, online monitoring, laser technique.*

1. **Introduction**

The most commonly used 3D printing technology was fused deposition modeling (FDM) or fused filament fabrication (FFF). FDM printers use a thermoplastic filament, which is heated to its melting point and then extruded, layer by layer, to create a three-dimensional object. One of the key strengths of using the FDM technique is its compatibility to variety types of thermoplastic polymers. The most popular and stable materials are ABS (acrylonitrile butadiene styrene) and PLA (poly lactic acid). To date, FDM printers have shown the ability to print other thermoplastics including polycarbonates (PC), polystyrene (PS), polyamide, polyetherimide (PEI), and polyetheretherketone (PEEK). There is also a demand to build composite filaments by adding certain materials into polymer matrices, as they offer improved mechanical properties, biocompatibility or conductivity [1].

1. **Literature Review**

Today, the degree of development of the “smart factory” direction within the concept of “Industry 4.0” is an indicator of the country’s development aimed at increasing the competitiveness of its products. The key components of “Industry 4.0” includes: virtual and augmented reality in design [2], cloud technology, industrial internet of things, autonomous robots and cyber security computer integrated manufacturing [3, 4], measurement accuracy increasing [5], modeling and simulation [6], additive manufacturing based on 3D printing for complex-shaped parts [7], online monitoring based on laser techniques [8], artificial intelligence based on mechatronic systems [9], etc. The development of each of these components contributes to the development of the concept smart factory and is the basis for improving the system of training specialists [10].

At the heart of modern scientific research is a systematic approach that provides for the allocation of three groups of parameters in any system under consideration [11]. The input parameters are determined at the pre-production stage based on a priori data. The state parameters are a consequence of the input parameters and the actual operating conditions of the system. Output parameters – to a greater extent relate to the quality of the products. Taking into account such a system representation, a model of technological grinding system can be represented as follows (Fig. 1). The model consists of the following state parameters: *Q'w, V'w, F, Т, AE*, where *Q'w* is the specific material removal rate in mm3/(s·mm), *V'w* is the specific material removal in mm3/mm, *F, Т, AE* are theforce, temperature, and acoustic emission signals.

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Fig. 1. Grinding system model (in fractional notations the input variables are listed in overseas [12] and domestic designations).

1. **Research Methodology**

This is a technology that has been patented by Stratasys, Inc. It allows the creation of detailed and intricate objects, small parts and specialized tools. FDM printers use a thermoplastic filament which is heated to its melting point and then extruded, layer by layer, to create a three dimensional object. One of the key strengths of using the FDM technique is its compatibility to variety types of thermoplastic polymers. The most popular and stable materials are ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid). To date, FDM printers have shown the ability to print other thermoplastics; including polycarbonates (PC), polystyrene (PS), polyamide, polyetherimide (PEI), and polyetheretherketone (PEEK). There is also a demand to build composite filaments by adding certain materials into polymer matrices, as they offer improved mechanical properties, biocompatibility or conductivity [13].

The advantages of the FDM method (Fig. 2, *a*) include easy handling, high printing speed, cost efficient, variety types of thermoplastic polymers, freeform fabrication without the use of expensive molds and tools, low cost of machines and consumables. The disadvantages of the FDM method include high rough surface finishing, presence of internal defects: internal pores, warping, clogging effect, delaminations, minor shrinking, non-smooth surfaces, weak mechanical properties, delamination and lower mechanical integrity.



Fig. 2. Schematic diagram of FDM (*a*) and FDM’s printing parameters (*b*) [1].

An important aspect that determines the quality of the printed object is the printing parameters of the 3D printer. Their optimal combination gives best surface quality, built rate and mechanical property. At least three groups of printing parameters must be considered to get high characterization of the final product of FDM and high productivity. The first group involves geometry parameters, the second – processing parameters, the third – structural ones (Fig. 2, *b*). For example, nozzle diameter and filament size are the geometrical parameters. Extrusion temperature, bed temperature, printing speed, build orientation, and setting of retraction are the processing parameters. Layer thickness, infill pattern, infill density, number of layers, raster angel, air gap, raster width, contour, and number of contours are the structural parameters.

1. **Results**

A large number of articles for the implementation of quality monitoring in 3D printing are devoted to the use of the following sensors: thermal camera, acoustic emission (*AE*) signal, current sensor, accelerometer, laser equipment, etc. The relevance of using the *AE* sensor for monitoring is due to its sensitivity to changes in friction, force, vibration of the elements of the 3D printer technological system and ease of embedding into original equipment. Because of *AE* signal is very sensitive and short period of time results in a lot of data. Thus, the *AE* signal collected by the sensors is measured as the *AE* arrives, and then certain characteristics are extracted [14-18]. Amplitude, counts, duration, absolute energy, signal strength and root mean square (RMS) can be such characteristics of the *AE* signal in a limited time interval in the time domain (Fig. 3).



Fig. 3. Measurement of an *AE* hit vs time and the typical time-domain features [18].

In the FDM method, the temperature fluctuations developed during the building process affects the final quality and mechanical properties of the fabricated part. In printed object there is an accumulation of thermal residual stresses and strains. When these stress and strain fields are accumulated to a certain level, it is possible distortion, warpage, and even possible part fabrication failure in the form of inter- or/and intra-layer delamination or cracking [19-20].

The test samples were made by the FDM method. The Creality Ender-3 printer with PLA filament has been used for the research. The samples were designed by software Autodesk Inventor Professional 2021. To generate the G-code for object printing the conversion of a CAD model into stereolithography (STL) format was made for the “Ultimaker Cura” slicer software (popular 3D printing software). The following KEYENCE equipment was used for profile analysis: LJ-8020 laser profiler and LJ -X8000A controller as a separate unit. Each measurement was repeated three times under otherwise equal conditions, the mean value was taken as the result of the measurement. The following data were obtained from comparative studies of contact (roughness R130 tester by Innovatest) and non-contact (LJ-8020 laser profiler by KEYENCE) methods for assessing object surface irregularities.

On the metal reference specimen (Ra = 3.34 μm with tolerance ± 3 %):

Instrument and error…………… Ra, μm Rz, μm

LJ-X8020 laser profiler………… 2.481 12.365

Roughness R130 tester ………….. 3.250 12.170

Error (to the R130 tester), % …… 23.7 1.6

On the plastic sample made of polylactic acid (PLA):

Instrument and error…………… Ra, μm Rz, μm

LJ-X8020 laser profiler………… 8.119 38.203

Roughness R130 tester ………….. 4.510 22.800

Error (to the R130 tester), % …… 80.02 67.56

Therefore, the roughness parameters obtained on the metal surface of the reference specimen (when 4 mm evaluation length) using contact (roughness R130 tester) and non-contact (LJ-8020 laser profiler) devices are close: Ra 3.250 μm and Ra 2.481 μm, as well as Rz 12.170 μm and Rz 12.365 μm. Relative error for the metal reference specimen is no more than 24 % while for the sample made of polylactic acid the relative error is more than 80 %.

There are several factors to make the measurement errors due to the error influences [21]. Some of them are given below.

1. Temperature influence. When the laser sensor is commissioned a warm-up time of at least twenty minutes then it is required to achieve uniform temperature distribution in the sensor. If measurement is performed in the micron accuracy range, the effect of temperature fluctuations on the sensor holder must be taken into account. However, due to the positive damping effect of the heat capacity of the sensor, sudden temperature changes are only measured with delay.

2. Mechanical vibrations. If the sensor is to be used for resolution in the µm to sub-µm range, special care is to be taken to ensure stable and vibration-free mounting of both sensor and target. This implies the inverse possibility of measuring micro-displacements caused by vibrations (the magnitude of vibrations), other things being equal.

3. Movement blurs. If the object being measuring is fast moving and the measuring rate is low, it is possible that movement blurs may result. That is why it is necessary select a high measuring rate during high-speed control operations.

4. Surface roughness. Laser-optical sensors detect the surface using very small laser spot. In contrast, a tactile, for example, using the Renishaw probe, detects a much larger area on the measurement object. In case of traversing measurements, surface roughness of 5 µm and more lead to an apparent distance change.

5. Color differences. Because of intensity compensation, objects color difference affect the measurement result slightly. But such color differences are often combined with different penetration depths of the laser light into the material. Different penetration depths then result in apparent changes of the measuring spot size mentioned above. That is why color differences in combination with penetration depth changes may lead to measuring errors.

1. **Conclusions**

1. The roughness parameters obtained on the metal surface of the reference specimen (when 4 mm evaluation length) using contact (roughness R130 tester) and non-contact (LJ-8020 laser profiler) devices are close: Ra 3.25 μm and Ra 2.481 μm as well as Rz 12.17 μm and Rz 12.365 μm. Thus, the contact (roughness R130 tester) and non-contact (LJ-8020 laser profiler) methods of control of standard integral parameters of surface roughness for a reference metal specimen give similar results. Relative error is no more than 24 %.

2. Similar studies on plastic objects are accompanied by much larger errors of the non-contact optical method (LJ-8020 laser profiler) compared to the contact method (roughness R130 tester): 65.96% and 76.32% for Ra and Rz integral roughness indicators, respectively, i.e. with the relative error that is more than 80 %.

3. Plastic’s color differences are the most important error influences. Because of intensity compensation, objects color difference affect the measurement result slightly. But such color differences are often combined with different penetration depths of the laser light into the material. Different penetration depths then result in apparent changes of the measuring spot size mentioned above. That is why color differences in combination with penetration depth changes may lead to measuring errors.

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