UDC 006.91:681.2:531.7 DOI: 10.24027/2306-7039.1.2018.134056

Analysis of the capability of the national measurement standards of Ukraine for assurance of traceability in the field of additive manufacturing

P.I. Neyezhmakov, V.V. Skliarov, A.V. Prokopov

National Scientific Centre "Institute of Metrology", Myronosytska Str., 42, 61002, Kharkiv, Ukraine
vladimir.skliarov@gmail.com

Abstract

The national measurement standards from the point of view of traceability of the results of measurement in additive manufacturing in Ukraine are considered in the paper. The metrological characteristics of the national primary measurement standards in the field of geometric, temperature, optical-physical and time-frequency measurements, which took part in international comparisons within COOMET projects, are presented. The accurate geometric, temperature, optical-physical and time-frequency measurements are the key ones in controlling the quality of additive manufacturing. The use of advanced CAD/CAE/CAM systems allows to simulate the process of additive manufacturing at each stage. The problem with the classification methods is that some processes have a complex (hybrid) manufacturing technology, for example, sintering is combined with AM or the use of laser welding, followed by processing on a milling or turning machine. In accordance with the areas of the technology of additive manufacturing, the ways of improving the national measurement standards of Ukraine for the growing needs of metrology of additive manufacturing are considered.

Keywords: additive manufacturing, metrological assurance, traceability, modeling, national measurement standard.

Received: 16.03.2018 Edited: 20.03.2018 Approved for publication: 25.03.2018

1. Introduction

Additive manufacturing (AM) is the process of creating the three-dimensional objects of almost any geometric shapes based on a digital model. AM is based on the concept of constructing an object by adding layer-upon-layer of material that repeat the contours of a three-dimensional object model. Additive manufacturing ensures the manufacturing of complex and multifunctional parts without waste, which allows to save money and manufacturing resources significantly.

The implementation of additive manufacturing, which goes from the prototype and the experimental technology to the completed technology, leads to a higher demand for methods and technology of measurement, evaluation and verification of both AM processes and AM parts, as well as raw materials used in manufacturing processes. The roadmaps for AM, reflecting the views of more than 100 industry stakeholders [1, 2], point to the urgent need of improving the stability of the process, product quality, the use of raw materials of the corresponded composition and properties, and the standardization of additive manufacturing technologies.

The key elements of standardization are the creation of a database of materials with corresponding properties and technological processes of their combination [1]. AM has a high potential for cost-efficient manufacturing of complex parts in small outputs and even in the creation of a single unit. Primary manufacturing requires a detailed study of the raw materials and the process of construction (printing) to control manufacturing within tolerances in design.

There are many ways of classification for AM technology. The approach to classification in accordance with the basic area of technology is popular: whether this process uses laser radiation; metal or polymer; sintering of material particles or melting of building material is used. Another approach to this is the classification depending on the type of material from which the object is printed.

ASTM International (American Society for Testing and Materials) is an American international organization, which develops and issues voluntary standards for materials, products, systems, and services, has identified 7 main areas of additive manufacturing that consist of several technologies that are further developed and refined. In addition, multicomponent hybrid technologies that combine the process elements as defined in ASTM F2792 [3] are being developed. According to the standard ASTM F2792, these areas differ by the principle of construction of the three-dimensional

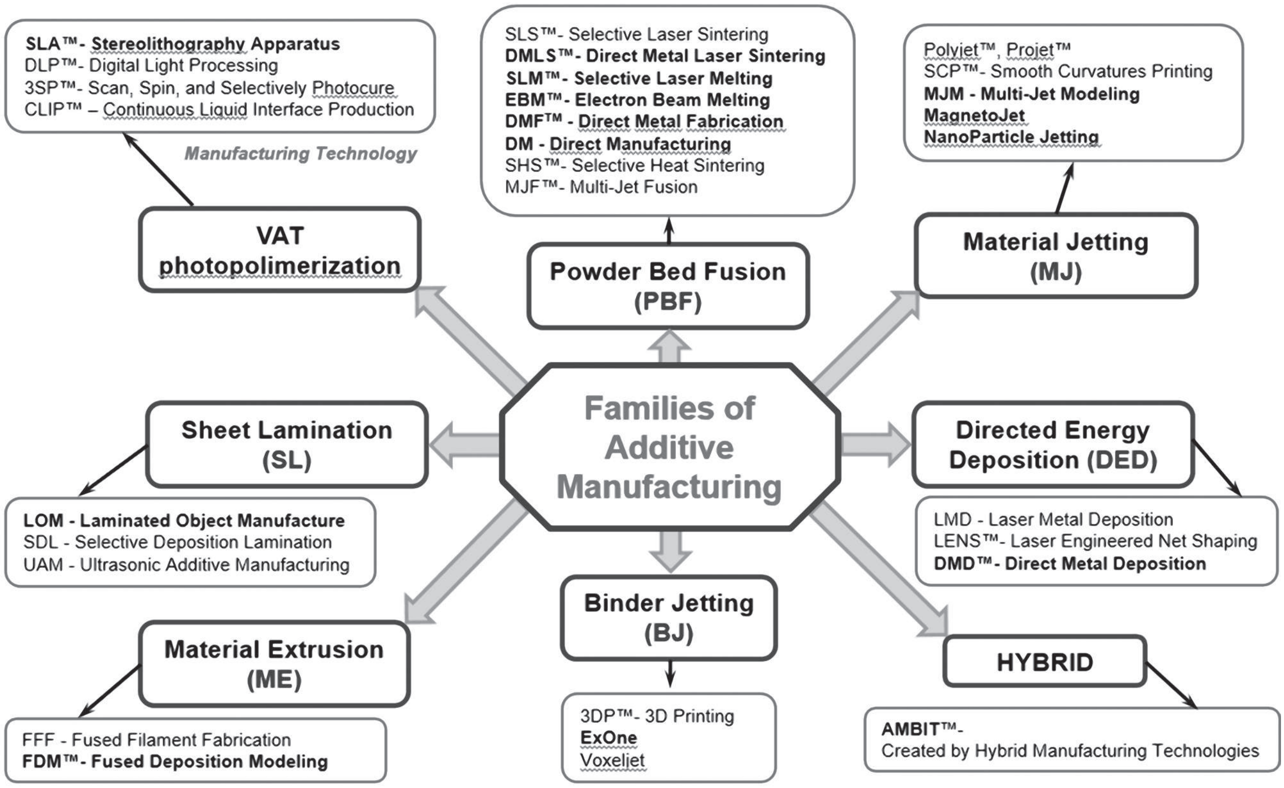

Fig. 1. Areas of additive manufacturing

object, the type of material used and the ways for further use (Fig. 1).

At present, the most common are the following AM technologies (shown in bold in Fig. 1):

- Stereolithography (Stereo Lithography Apparatus — **SLA**);
- Selective Laser Sintering (**SLS**) or Direct Metal Laser Sintering (**DMLS**);
- Selective Laser Melting (**SLM**);
- Electron Beam Melting (**EBM**) or Direct Metal Fabrication (**DMF**), as well as Direct Manufacturing (**DM**);
- The technology of Multi Jet Modeling (**MJM**);
- The technology of 3D printing of sand forms (Binder Jetting — **ExOne**);
- Laminated Object Manufacturing (**LOM**);
- Fusing Deposition Modeling (**FDM**) or Directed Energy Deposition (**DED**);
- Direct Metal Deposition (**DMD**) technology;
- Atomic Diffusion Additive Manufacturing (**ADAM**);
- **MagnetoJet** technology is a jet metal printing based on magnetic hydrodynamics, namely the ability to control molten metal using magnetic fields;
- **NanoParticle Jetting** is a technology for injection of nanoparticles, which involves the use of special sealed cartridges with a solution that contains a suspension of metal nanoparticles;
- **AMBIT** is a hybrid laser welding technology combined with a mechanical machining with software control.

At present, AM manufacturing machines have sufficient control over the printing parameters to ensure that the manufactured object remains within the tolerances of the design specifications during manufacture. The geometric accuracy of AM products can only be assessed by measuring the critical parameters of the product. Internal structures are completely inaccessible and require the use of non-destructive testing methods to assess the quality of production [4]. To improve the process of obtaining quality products, additional knowledge of the process details is required, which should be based on reliable measurement of the parameters of the printing process. Assuring the traceability of measurement results to SI units during the production process is a guarantee of quality improvement at the level of manufacturing technology. The only way to determine the internal dimensions of an AM component is to destroy the sample area and use the usual coordinate measurement methods using a Coordinate Measuring Machine (CMM). X-ray computing tomography (XCT) provides a unique way of nondestructive assessment of the internal zones and structures of parts manufactured by AM, and is increasingly used by AM industry for assessment of the relevant products [5]. Complex geometry and various materials in the product result in systematic errors in measurement results, which limits the XCT's ability to perform accurate measurements of AM parts.

Existing technologies and methods of additive manufacturing, which are available today, require metrological support for:

- geometric parameters;
- roughness parameters;
- temperature parameters;
- laser radiation power;
- the time modes of the processes used.

According to the technological process and the type of material used, the rate of construction of the object and the rate of material addition (extruder pressure) for the next layer of the material is chosen.

The objective of the paper is to consider and show the connection of the technologies with the national measurement standards of Ukraine. The existing national measurement standards of Ukraine in the field of geometric, temperature, optical-physical radiation and time and frequency are analyzed, with the purpose of determining the ways of their further improvement in order to meet the growing demands of Industry 4.0 and Additive Manufacturing.

2. The ranges of measurement in additive manufacturing

Since AM is based on the concept of constructing an object through the sequential application of layers of a material, the main parameter that characterizes the accuracy of constructing an object is the thickness of the layer of material from which the object is constructed, that is, the layer of application. Thus, the accuracy of 3D printing is the minimum allowable layer height printed by 3D printer. Modern FDM 3D printers can provide a thickness of up to 20 μm. The fusing deposition modeling of the object enables the measurement of roughness parameters R_a, R_z and R_{max} of not worse than 50 μm. In addition, an important element of the final stage of AM is to reduce the roughness of the surfaces of the constructed object. The reduction of roughness of the object is performed using appropriate solvents or laser polishing, which reduces roughness to 1,4μm that can not be achieved by mechanical processing [6–8].

Analyzing AM technology, it should be noted that almost all technologies have modes of temperature influence on the process of reproduction of the object — sintering, melting, fusing deposition, adhesion, handling of molten metal. Thus, almost all additive manufacturing technologies have corresponding temperature modes of manufacturing, that is, it is important to measure the temperature of the material and the temperature modes in 3D printer case. The range of temperature modes is within the melting and heating up of the materials, it is maintained in the range from 200 ^{0}C (for polymers) to 3150 ^{0}C (for titanium), in addition, it is important to measure the temperature when the gradual cooling of the object during hardening (corresponding requirements to the cooling time) [9, 10].

Technologies for the use of laser systems for sintering powders of various types of metals, such as titanium, stainless steel, inconel, aluminum, cobalt-chromium alloy, copper, iron, gold and silver deserve the greatest attention in terms of future application in high-tech modern industries. The use of laser systems imposes appropriate requirements on the power and duration of laser radiation, since the materials for the construction of the object have different physical and chemical properties [9, 10]. The lasers provide high intensity and high-collimated energy beam that can move very fast and have programmable control using directional mirrors. Since AM requires that the material in each layer be strengthened and joined to the previous layer, lasers are an ideal tool as the laser energy provides mechanisms for the material transformation of the material. There are two types of laser applications in AM: cutting and heating. When using photopolymer resins (plastics, polymers), it is necessary to measure the wavelength of laser radiation, which ensures the hardening of the liquid resin, or the high quality cutting of the material. The usual wavelength of such a laser is in the ultraviolet range, but other frequencies may be needed for manufacturing. To heat the material, the requirement is that

Table 1

AM characteristics	Range of values of AM characteristics
Minimum permissible height of the printing layer, μm	5 to 20
Minimum surface roughness of the object, μm	2 to 5
Temperature of additive manufacturing, 0C	200 to 3150
Laser radiation power, W	70 to 15000
Wavelength of laser radiation, nm	360 to 1064
Laser beam travel speed, m/min	0.2 to 60
Time of effect of laser radiation, ms	2 to 6
Viscosity at 100 ^{0}C, *centipoise* (cP)	1 to 200
Material density, kg/m^3	1 to 2380 (molten Aluminum at 800 ^{0}C)
Pressure, MPa	10 to 20

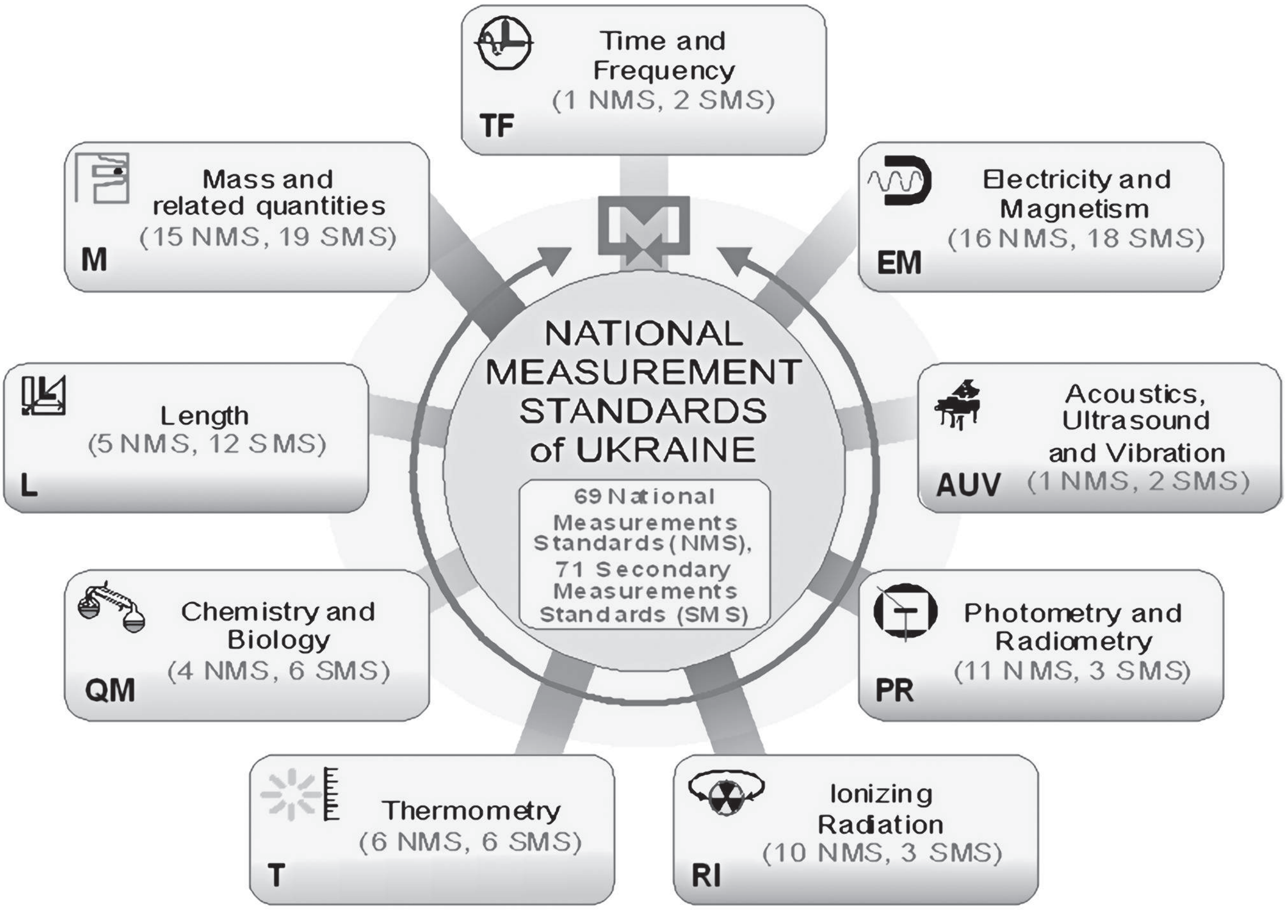

Fig. 2. The national measurement standards of Ukraine

the laser should have the sufficient thermal energy to cut the layer of solid material through, or the powder from which the object is printed should melt. For powder processes, the key is to control the melting of the material in the necessary way, without creating too large thermal field, so that when the laser turns off, the molten material will quickly solidify again. Previously, gas-discharge lasers were used to provide the necessary energy, but many manufacturers have recently switched to solid-state technology, which provides greater efficiency, service life and reliability. The power of laser radiation ranges from 70 W to 500 W for the polishing and bonding of the object and up to 15 kW for cutting, welding and building up of the object. According to the features of the technology, the wavelength of laser radiation is in the range from 360 nm to 560 nm and 1064 nm (Nd: YAG — neodymium-doped yttrium aluminum garnet laser) with a laser beam travel speed from 0.2 m/min to 60 m/min and the effect time from 2 ms to 6 ms [11, 12]. The ranges of values of AM characteristics for additive manufacturing are given in Table 1 [9].

3. The national measurement standards of Ukraine for aditive manufacturing

The national measurement standards are the integral part of the national metrological system and provide the reproduction of measurement units and the transfer of their sizes by means of the secondary measurement standards to working measuring instruments (MIs) [13], which are exploited in the manufacturing and non-manufacturing spheres (Fig. 2).

As of December 1, 2017, there are 69 national measurement standards and 71 secondary measurement standards in Ukraine that provide reproduction, maintenance and transfer of the units of physical quantities. In accordance with the Law of Ukraine “On Metrology and Metrological Activity” [13] and the Program for the Development of the Measurement Standards for 2018—2022 [14], scientific and design work on the creation of the new national measurement standards and secondary measurement standards as well as improving the existing ones in Ukraine is ongoing.

4. The national measurement standards in the field of length

The calibration and measurement capabilities (CMCs) of Ukraine in the field of geometric measurements are provided by 5 national measurement standards and 12 secondary measurement standards. Metrological characteristics of 4 national measurement standards of geometric parameters responsible for AM are given in Table 2.

Table 2

Name of the measurement standard	Range of values of metrological characteristics	Expanded uncertainty
The national primary measurement standard of length unit for the parameters of evolvement surfaces and tilt angle of tooth trace	circle radius — 37 mm to 150 mm tilt angle of tooth trace on its width 10 mm to 160 mm	0,5 μm 0,7 μm
The national primary measurement standard of length unit for deflections from linearity and planarity	0 μm to 10 μm	$2\cdot10^{-1}$μm
The national primary measurement standard of length unit	$1\cdot10^{-6}$ m to 1 m	$6\cdot10^{-11}$m
The national primary measurement standard of the length unit for measurements of the parameters of roughness R_{max}, R_z and R_a	0,025 μm to 1,0 μm 1,0 μm to 1600 μm	0,007 μm 0,006 μm

Table 3

Name of the measurement standard	Range of values of metrological characteristics	Expanded uncertainty
The national primary measurement standard of temperature unit on radiation in the range from 1357,7 K to 2800 K	1357,7 K to 2800 K	3,9 K
The national primary measurement standard of Kelvin temperature unit in the range from 273,16 K to 1357,77 K	273,16 K to 1357,77 K	$2{,}3\cdot10^{-4}$ K to $5{,}5\cdot10^{-3}$ K
The national primary measurement standard of Kelvin temperature unit in the range from 13,80 K to 273,16 K	13,80 K to 273,16 K	$2\cdot10^{-3}$ K to $6\cdot10^{-3}$ K
The national primary measurement standard of temperature unit on IR-radiation in the range from 692,67 K to 1234,93 K	692,67 K to 1234,93 K	1,7 K

The traceability of geometric measurement results is provided via the results of international comparisons and the availability of CMCs in KCDB (Key Comparisons Date Base — https://kcdb.bipm.org/). As of December 2017, 13 international comparisons were performed with national standards of COOMET and EURAMET member countries and 27 CMCs were published. This particular group of measurement standards provides the most important parameters of AM — the geometric and spatial dimensions of the object.

5. The national measurement standards in the field of thermometry

The CMCs of Ukraine in the field of temperature and thermophysical measurements are provided by 6 national measurement standards and 6 secondary measurement standards. The metrological characteristics of 4 national measurement standards of temperature parameters responsible for AM are given in Table 3.

The traceability of measurement results for temperature and thermophysical quantities is provided via the results of international comparisons and the availability of CMCs in KCDB. As of December 2017, 6 international comparisons were performed with national standards of COOMET and EURAMET member countries and 63 CMCs were published.

6. The national measurement standards in the field of photometry and radiometry

The CMCs of Ukraine in the field of optical and optical-physical measurements are provided by 11 national measurement standards and 3 secondary measurement standards. The metrological characteristics of 2 national measurement standards of the power of laser equipment responsible for AM are given in Table 4.

The traceability of measurement results for optical and optical-physical quantities is provided by the results of international comparisons and the availability of CMCs in KCDB. As of December 2017, 9 international comparisons were performed with national standards of COOMET and EURAMET member countries and 6 CMCs were published.

Table 4

Name of the measurement standard	Range of values of metrological characteristics	Expanded uncertainty
The national primary measurement standard of the units of mean power and laser radiation	$1\cdot10^{-4}$ W to 3 W $1\cdot10^{-4}$ J to 3 J	$1{,}2\cdot10^{-3}$ to $3{,}5\cdot10^{-3}$ $1{,}2\cdot10^{-3}$ to $3{,}5\cdot10^{-3}$
The national primary measurement standard of the units of mean power and high-class laser radiation energy (wavelength — 10,6 μm)	10 W to 1000 W 10 J to 1000 J	$1{,}5\cdot10^{-2}$

Table 5

Name of the measurement standard	Range of values of metrological characteristics	Expanded uncertainty
The national primary measurement standard of the units of time and frequency	Time intervals from $1{\cdot}10^{-10}$ s to $1{\cdot}10^{8}$ s	$1{\cdot}10^{-13}$
	Frequency intervals from 1 Hz to $7{\cdot}10^{10}$ Hz, ns	2
	Relative instability of frequency over the time intervals from 1000 s to 1 day	$2{\cdot}10^{-14}$
	Difference between the national coordinated time scale of Ukraine UTC (UA) and the International coordinated time scale UTC, ms	± 1

Table 6

Name of the measurement standard	Range of values of metrological characteristics	Expanded uncertainty
The national primary measurement standard of the absolute pressure unit	$1{\cdot}10^{-3}$ Pa to $1{\cdot}10^{3}$ Pa	$7{\cdot}10^{-3}$
The national primary measurement standard of the pressure unit for absolute pressures	$2{,}7{\cdot}10^{2}$ Pa to $1{,}3{\cdot}10^{5}$ Pa	2,4 Pa
The national primary measurement standard of the pressure unit for overpressure	0,05 MPa to 10 MPa	$1{\cdot}10^{-5}$

7. The national measurement standards in the field of time and frequency

The CMCs of Ukraine in the field of time and frequency measurement are provided by 1 national measurement standard and 1 secondary measurement standard. Metrological characteristics of the national measurement standard of time and frequency responsible for AM are given in Table 5.

The use of autoregression model for maintaining the national time scale of Ukraine have been developed in [15].

8. The national measurement standards in the field of mass and related quantities

The CMCs of Ukraine in the field of measurement of mass and related quantities are provided by 15 national measurement standards and 19 secondary measurement standards. Metrological characteristics of the national measurement standards in the field of pressure measurements responsible for AM are given in Table 6.

At present, international comparisons are carried out in the range of from 1 MPa to 10 MPa.

Thus, given the existing potential of the national measurement standards of Ukraine and the present need for AM, it can be concluded that these requirements are partially met (Table 7). Further improvement is needed in order to expand the range of the measurement standard in the field of high-temperature measurements and to establish a measurement standard for the high power laser radiation.

9. Conclusions and future scope

As it can be seen from Table 7, the national measurement standards of Ukraine partially satisfy the existing requirements on ensuring the traceability of measurement results for the above-discussed types of AM.

The expansion of the temperature range to the melting point of titanium and more refractory materials is a promising area for further improvement of the national measurement standards of Ukraine. The development of contactless thermometry and the use of eutectic points will provide measurement and metrological traceability of measurements of high-temperature parameters of additive manufacturing.

Table 7

Metrological characteristics	The range of values of metrological characteristics	The range of metrological characteristics provided by the national measurement standards of Ukraine	Expanded uncertainty
Minimum permissible height of the printing layer, μm	5 to 20	1 to 10	$6{\cdot}10^{-6}$
Minimum surface roughness of the object, μm	2 to 5	0,025 to 1,0	0,007
Temperature, K	473,15 to 3423,15	13,80 to 2800	$2{\cdot}10^{-3}$ to 3,9
Laser radiation power, W	70 to 15000	$1{\cdot}10^{-4}$ to 1000	$3{\cdot}10^{-3}$ to $1{,}5{\cdot}10^{2}$
Time of effect of laser radiation, s	$2{\cdot}10^{-3}$ to $6{\cdot}10^{-3}$	$1{\cdot}10^{-10}$ to $1{\cdot}10^{8}$	$1{\cdot}10^{-13}$
Pressure, MPa	10 to 20	10 to 60	$1{\cdot}10^{-5}$

Another promising area is the creation of a standard for measurement of high-power laser radiation.

To ensure reliable manufacturing in AM, the use of test methods and non-destructive testing means as well as application of certified reference materials of comparison of the composition of which the object is being constructed (printed) is necessary.

The other promising area of research is the improvement and harmonization of the existing regulatory and legislative, regulatory and technical framework for additive manufacturing. Modeling of the processes of applying the existing national measurement standards of Ukraine will allow to determine the ways and areas of improvement of certain components of the measurement standard, especially the primary transducers. The use of CAD/CAE/CAM systems allows modeling the behavior of composite materials for AM process. Taking into account the fact that it is necessary to ensure the traceability of results of AM measurement processes, it is advisable to create a technical committee on standardization and metrology of AM in Ukraine.

Аналіз можливостей національних еталонів України щодо забезпечення простежуваності вимірювань у галузі адитивного виробництва

П.І. Неєжмаков, В.В. Скляров, О.В. Прокопов

Національний науковий центр "Інститут метрології", вул. Мироносицька, 42, 61002, Харків, Україна
vladimir.skliarov@gmail.com

Анотація

Розглянуто національні еталони з точки зору простежуваності результатів вимірювань при адитивному виробництві в Україні. Наведено метрологічні характеристики національних первинних еталонів у галузі геометричних, температурних, оптико-фізичних та часо-частотних вимірювань, вимірювань маси та пов'язаних із нею величин, що брали (або беруть) участь у міжнародних звіреннях за проектами КООМЕТ. Точні вимірювання геометричних, температурних, оптико-фізичних величин та часо-частотні вимірювання є ключовими для контролю якості адитивного виробництва. Проблема з методами класифікації полягає у тому, що деякі процеси мають комплексну (гібридну) технологію виробництва, наприклад, спікання, пов'язане з АМ, а застосування лазерного зварювання — із подальшою обробкою на фрезерному або токарному верстатах. Відповідно до напрямків технології адитивного виробництва розглянуто шляхи вдосконалення національних еталонів України для зростаючих потреб метрології адитивного виробництва.

Ключові слова: адитивне виробництво, метрологічне забезпечення, простежуваність, національний еталон.

Анализ возможностей национальных эталонов Украины для обеспечения прослеживаемости измерений в сфере аддитивного производства

П.И. Неежмаков, В.В. Скляров, А.В. Прокопов

Национальный научный центр *"Институт метрологии", ул. Мироносицкая, 42, 61002, Харьков, Украина*
vladimir.skliarov@gmail.com

Аннотация

Рассмотрены национальные эталоны с точки зрения прослеживаемости результатов измерений при аддитивном производстве в Украине. Приведены метрологические характеристики национальных первичных эталонов в области геометрических, температурных, оптико-физических и время-частотных измерений, измерений массы и связанных с ней величин, принимавших (или принимающих) участие в международных сличениях по проектам КООМЕТ. Точные измерения геометрических, температурных, оптико-физических величин и время-частотные измерения являются ключевыми для контроля качества аддитивного производства. Проблема с методами классификации заключается в том, что некоторые процессы имеют комплексную (гибридную) технологию производства, например, спекания объединены вместе с АМ, а применения лазерной сварки — с последующей обработкой на фрезерном или токарном станках. В соответствии с направлениями технологии аддитивного производства рассмотрены пути совершенствования национальных эталонов Украины для растущих потребностей метрологии аддитивного производства.

Ключевые слова: аддитивное производство, метрологическое обеспечение, прослеживаемость, национальный эталон.

References

1. Standardisation Roadmap for Additive Manufacturing, 2017, available for download at https://share.ansi.org/Shared%20Documents/Standards%20Activities/AMSC/AMSC_Roadmap_February_2017.pdf
2. Additive Manufacturing, Strategic Research Agenda, 2013, available for download at http://www.sasam.eu/index.php/press/sasam-in-magazines-english/viewdownload/9/175
3. ASTM F2792–12a. Standard Terminology for Additive Manufacturing Technologies (Withdrawn 2015), ASTM International, West Conshohocken, PA, 2012. Available at: www.astm.org
4. Waller J., Parker B.H., Hodges K.L., Burke E.R., Walker J.L. Nondestructive Evaluation of Additive Manufacturing. State-of-the-Discipline Report, NASA/TM-2014–218560.
5. Angel J., De Chiffre L. Inter-laboratory Comparison of Industrial Computed Tomography. CIA, CT Comparison, 2013.
6. Sikder S., Barari A., Kaji F., Kishawy H. Using Acetone Vapour Treatment to Improve Secondary Finishing Operations in Additive Manufacturing. *Proc. ASPE,* 3898, 2014. 2 p.
7. Alfieri V., Argenio P., Caiazzo F., Sergi V. Reduction of Surface Roughness by Means of Laser Processing over Additive Manufacturing Metal Parts. *Materials*, 2017, 10(1):30, pp. 1–12.
8. Willenborg E. Polishing with Laser Radiation. *Kunststoffe international*, 2007, vol. 97, no. 6, pp. 37–39.
9. Gibson I., Rosen D., Stucker B. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Springer, New York, 2014. 498 p.
10. Available at: http://www.matweb.com
11. Tailored light 2. Laser application technology. doi: https://doi.org/10.1007/978–3–642–01237–2.
12. Huber S., Glasschroeder J., Zaeh M.F. Analysis of the Metal Vapour during Laser Beam Welding. *Physics Procedia*, 2011, vol. 12, pp. 712–719.
13. Law of Ukraine “On Metrology and Metrological Activity”, dated June 5, 2014, no. 1314-VII. Available at: http://zakon2.rada.gov.ua/laws/show/1314–18
14. Program for the Development of the Measurement Standards for 2018–2022, no. 1041 of December 28, 2016. Available at: http://zakon2.rada.gov.ua/laws/show/1041–2016-%D0 %BF
15. Neyezhmakov P., Koretskyi E. The use of autoregression model for maintaining the national time scale of Ukraine. Proc. CIM 1051, 08005 (2017).