THE STANDARDIZATION PROCESS IN ADDITIVE MANUFACTURING – CASE STUDIES

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The paper presents an analysis of the standardization process in the area of Additive Manufacturing (3D printing) technology in terms of both the technological process, qualifications of employees operating 3D printers and the safety of their operation. In addition, the article pays special attention to issues related to currently existing standards in the area of both research and typically industrial issues, i.e. related to ordering 3D printing by customers and implementing additive production on customer request. In addition, issues related to currently developed standards and those indicated for development in the future were described. The analysis was carried out based on the currently existing international standards ISO and ASTM, as well as using the Web of Science database. As shown by the review of current literature and analysis of activities in the area of standardization, 3D printing, despite over 40 years of existence, is still a technology that is developing and requires the creation of appropriate conditions through the standardization process, both national and international.

KEYWORDS

Standardization, Metrology, 3D Printing, Additive manufacturing

1 INTRODUCTION

From the point of view of time, Additive Manufacturing also known as 3D printing technologies have been known for over 40 years. From one point of view, this period can be considered very long, but from another very short. It is difficult to clearly indicate the year in which the first 3D printing technology was created. It is estimated that the first attempts at layered production of models date back to the 1950s-1970s, but it was not until the mid-1980s that the first commercial 3D printing systems were developed and implemented into production. The undoubted advantages of Additive Manufacturing include, short production time of products, the possibility of manufactured models with complex shapes (free-form) [Gogolewski 2023] taking into account the LEAN Manufacturing process, low cost of prototype production and high flexibility of the production process. However, the technological process of layered production is not without its drawbacks. The biggest problem in Additive Manufacturing process is the anisotropy of the properties of the models produced, which mainly depends on the 3D printing direction (orientation on the building platform). The problem of anisotropy does not only concern mechanical properties but also, for example, the technological quality of the surface layer, shape deviations, dimensional accuracy, tribological properties, etc. Another problem is unprofitable mass production and, in many cases, too small working area of currently available 3D printers on the market. The necessity of additional finishing processing in order to produce a product with a "high" technological quality of the surface layer is also significant. One of the negative phenomena in this area is primarily the problem of the so-called "stair-step effect". Additive technologies have entered mass use in the work environment only over the last few years, therefore the process related to adapting working conditions to the specifics of 3D printing is not fully known and is only at the development/implementation stage.

Taking into account the above disadvantages and limitations resulting from this in the use of Additive Manufacturing technology, attention should be paid to the issues of the standardization process. It is at the stage of establishing a research procedure, taking into account anisotropy and the working conditions of people operating 3D printers, that the standardization process has huge implementation possibilities. The standardization process certainly supports the relationship between the customer ordering the object produced by 3D printing and provides a simpler way of complaint. In addition, standardization ensures uniform quality of manufactured products regardless of the company and supports issues related to the safe use of 3D printing, which is especially important in everyday life. The presented article describes the current standardization process that allows for increasing the quality of models produced by Additive Manufacturing, metrological process associated with it, work condition, safety and risks and recycling/ecology.

1.1 History of progress in Additive Manufacturing Technologies

Analyzing over 40 years of commercial Additive Manufacturing systems, we can say that this period has been well spent, and Additive Technologies have made a huge development. The first Additive Manufacturing technologies involved material extrusion and polymerization. Around the mid-1980s, a patent was obtained for both Fused Deposition Modeling (FDM) [Crump 1989] and stereolithography (SLA) [Hull 1986]. In the following years, there was a huge development of new Additive Manufacturing technologies, which include, among others, 3D printing using the SLS - selective laser sintering or SLM - selective laser melting, powder bonding with binder, gluing layers LOM - laminated object manufacturing, photo-curing of liquid polymer resins and many others based on the same layered/additive nature of the process.

Over these 40 years, there was also a huge development of materials used in Additive Manufacturing, where the greatest development occurred in the last decade. In the early years, the most popular material in Additive Manufacturing was PLA (polylactic acid), a plastic used in FDM technology and occurring in the form of filament wound on a spool. Over time, however, in the case of this technology, new materials began to be used, such as ABS, composite materials with additives such as copper, carbon fibers, glass fibers, natural components, etc., which allowed both the increase in the strength of the models produced and the use of Additive Manufacturing in new industrial areas. A huge development of materials also occurred in the area of selective laser melting and currently we have at our disposal materials based on titanium, stainless steel, tool steels, aluminum, based on copper, etc. Currently, a very large development of materials is also taking place in the area of technologies related to photo-curing of liquid polymer resins, which include, among others, the PolyJet Matrix technology. In this technology, materials with a high degree of biocompatibility for the dental industry are constantly being developed, which must always be confirmed by an appropriate standard. The medical aspect of 3D printing has one of the largest number of standards available. The development of 3D printing materials also includes technologies based on the so-called bioprinting, i.e. technology using living cells most often connected by a gel. Due to the dynamic development of new technologies and material chemistry, the standardization process often does not keep up with the needs of the technique. Such a large number of materials with a different method of connecting layers makes the process of designing manufactured models and further research extremely difficult, which requires an appropriately adapted standardization process. It is also particularly important in the future to define standards related to the safe recycling of model and support materials, which very often change their properties after the production process

1.2 Web of Science Analysis

Additive Manufacturing and the aspect of standardization are the subject of research and analysis, and this area is growing year by year. Figure 1 shows a graphic illustrating the search result for the phrase “additive manufacturing standard” in the Web of Science search tool in the “title”. The total number of publications is 46. As can be seen, there has only been a dynamic increase in the number of search for about 8 years. It is worth emphasizing that the first publications appeared in 2000, but their actual development can be determined for the years 2017-2025. By making a minor change, i.e. replacing the word “standard” with the word “ISO”, the total number of publications decreased to 17, and in the case of changing to the word “ASTM” it is only 10.

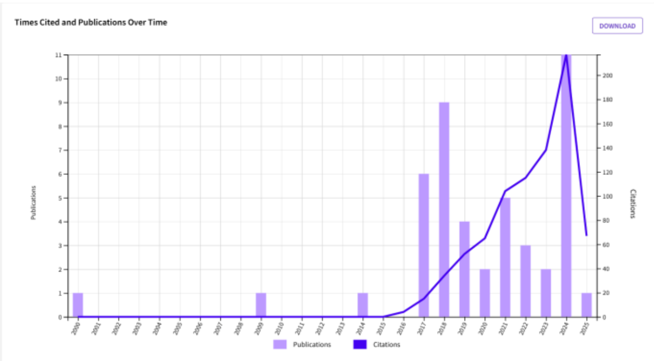

Figure 1. Web of Science analysis for the topic “additive manufacturing standard”

Another analysis was also carried out in the Web of Science database. Figure 2 shows a graphic illustrating the search result for the phrase “3D printing standard” in the Web of Science search in the “title”. The total number of publications in this case is 60. It is worth emphasizing that the first publications appeared only in 2015. By making a minor change, i.e. replacing the word “standard” with the word “ISO”, the total number of publications decreased to 8, and in the case of changing this word to “ASTM” it is only 2.

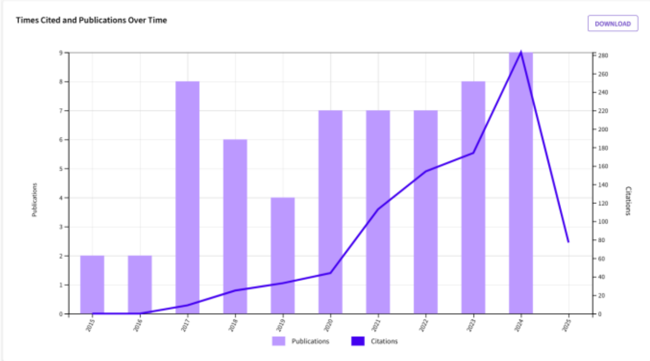

Fig. 2. Web of Science analysis for the topic “3D printing standard”.

Performing the next three searches for the phrase “machining standard” and then changing the word “standard” to “ISO” and then to “ASTM” we get: 787; 130 and 15 publications, respectively. Analyzing the Web of Science database, it is clear that additive technologies are starting to enter the standardization process and the number of publications is incomparably smaller than for other known manufacturing methods, such as machining. This is understandable due to the relatively short period of operation of 3D printing on a mass scale. It seems that as part of the ongoing industrial revolution 4.0, the upward trend in Standardization should continue to cover many new areas resulting from the nature of the process and its high degree of digitalization

2 STANDARDIZATION

The standardization process plays an extremely important role in the aspect of scientific research. Carrying out all types of measurements based on the standard allows for the comparison of research results both for scientific purposes and in the case of model verification by a client ordering a model produced by Additive Manufacturing in an company. The standardization process does not only concern the research procedure and the technological process of production, but also in many cases determines the shape of the sample. In the case of Additive Manufacturing, we also talk about the appropriate nomenclature related to the technological process, materials, digital files, the process of cleaning models, etc. Due to its specificity, 3D printing requires the use of separate standards in many measurement areas, although there are already standards covering the research procedure for the same materials produced using conventional methods. An example of metrological problems related to 3D printing is the measurement of the surface layer using various optical measuring devices. The research results published in [Zmarzly 2023, Malara 2025] indicate that depending on the applied measurement method, different results of roughness and waviness parameters are obtained, and very often other measurement problems arise, related, for example, to a large number of non-measured points or the process of their completion (approximation). It seems reasonable to develop a separate standard for measuring surfaces of models obtained by various Additive Manufacturing technologies, specifying the entire measurement procedure. Additive Manufacturing is constantly developing and is becoming an increasingly perfect production tool, but in terms of the standardization process, there is still a lot to be done. Below is an example of standards from the area of Additive Manufacturing, which have been implemented over the last few years and mainly concern ISO and ASTM. It is worth noting that the implementation of

standards into the national standardization process is usually carried out with a slight delay.
In European countries, the interpretation of ISO standards is key but ASTM - American Society for Testing and Materials, with which ISO cooperates, has extensive experience in the standardization process in the aspect of Additive Manufacturing. The International Organization for Standardization in the area of additive technologies has established a special Technical Committee - ISO/TC 261 Additive manufacturing. The International Technical Committee has national Technical Committees in the associated countries, which carry out tasks in the area of standardization, development of new standards and implementation of existing ones. In Additive Manufacturing in Poland, the relevant national Technical Committee is KT 207 (PKN). Below is a description of several key currently applicable standards from the point of view of their practical use both in the area of conducted scientific research and commercial orders for the production of models using additive technologies. The activities of ISO/TC 261 in the area of Additive Manufacturing are still progressing and they are working on current draft standards and plans to develop new ones. A good example of this is the short communication [Pei 2023] in which current activities in the area of Additive Manufacturing are presented. Most of presented in this work standards was prepared by ISO/TC 261 - Additive manufacturing, in cooperation with ASTM Committee F42 - Additive Manufacturing Technologies and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438 - Additive manufacturing.

ISO/ASTM 52900:2021 Additive manufacturing — General principles — Fundamentals and vocabulary [ISO/ASTM 52900:2021]

The presented standard contains key information covering the nomenclature of Additive Manufacturing. This is an extremely important standard from the point of view of international cooperation and this applies to both research and industrial and didactic applications at the level of vocational and academic education. Additive Manufacturing is increasingly used as a simple prototyping tool within the ongoing industrial revolution 4.0, where in many cases engineering knowledge is not required, and the standardization process thus supports people without this education. The standard classifies Additive Manufacturing systems, where the novelty is the introduction of the name MEX (material extrusion) as a process covering Additive Manufacturing using materials dispensed through a nozzle or orifice. The undoubted advantage of the standard is the unification of the nomenclature related to digital files and terms related to the technological process of production, layer connection, etc. This standard is the second edition of the standard with the same number, but from 2015. It seems that the implementation of this standard is a kind of obligation in terms of using a unified Additive Manufacturing language. The development of new technologies will certainly contribute to the creation of further standards in this area replacing the old ones.

ISO/ASTM 52901:2017 Additive manufacturing — General principles — Requirements for purchased AM parts [ISO/ASTM 52900:2021]

Another standard worth noting is ISO/ASTM 52901, which concerns an extremely practical part of the production process, i.e. the requirements for models produced using Additive Manufacturing. The standard specifies the information that should be agreed between the person ordering the model and the company that manufacture it using Additive Manufacturing. The most important information includes: production time, characteristics of the model made based on the ordered documentation and the agreed method of assessing the agreed requirements. In the case of Additive Manufacturing, it is these agreements between the customer ordering model and the supplier who makes the model that are most often the source of problems. Without agreement on specific quality features, it is difficult to blame the manufacturer or designer. It is worth noting that 3D printing, for example, in the case of metal powders is extremely complicated, and the person ordering the prototype may not be aware of how, for example, the direction of manufacturing will affect the quality of the models - thanks to the implementation of this standard in the company that manufacture, these issues should be agreed in advance. Currently, when ordering models, you can refer to the development of a protocol prepared on the basis of the abovementioned standard, which will enable an increase in the quality of the service, contact between the customer and the person performing the manufacturing and will allow for easy settlement of disputes. It is extremely important to include in this standard the assessment of the measurement method, which in the case of 3D printing, which belongs to layered methods, generates many problems, for example related to the assessment of the quality of the surface texture, which was described above. The production of models with high/established strength properties for industries such as aerospace, automotive, medicine requires the definition of a Additive Manufacturing strategy, which, according to the standard, should be agreed before the order started. This situation means that before making a decision on the selection of a supplier of models produced by Additive Manufacturing, it is worth obtaining information on whether a given company has implemented the ISO/ASTM 52901 standard, which is certainly beneficial for the customer.

ISO/ASTM 52902:2023 Additive manufacturing — Test artefacts — Geometric capability assessment of additive manufacturing systems [ISO/ASTM 52902:2023]

Another one of the newest standards in the field of 3D printing is ISO/ASTM 52902, which contains information on the geometry of test elements for comparison purposes, as well as information on quantitative and qualitative measurements that should be performed in order to assess the accuracy of 3D printing systems. This standard is important because cyclically conducted tests based on the existing standard allow for the production of models with predictable dimensional and shape accuracy, which allows for the presentation of a reliable offer to a customer interested in performing 3D printing. This standard allows for the comparison of systems with each other and how well they can produce models with specific shapes/geometric features. In addition, the standard allows for the presentation of such data by 3D printer manufacturers as an element of a transparent sales/manufacturing policy.

ISO/ASTM 52903-1:2020 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials [ISO/ASTM 52903-1:2020]

An extremely interesting standard is ISO/ASTM 52903, which concerns the requirements for materials used in Additive Manufacturing technology - MEX, and therefore also the most popular Additive Manufacturing technology - FDM/FFF. The standard also covers input materials for 3D printing realized by, for example, large-scale 3D printing systems based on industrial robots. The creation of the standard is a good step towards increasing the quality of input materials in the form of filament and pellet. In this area, there are currently large quality differences, which can certainly be reduced by implementing the standard.

ISO/ASTM 52911-1:2019 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals [ISO/ASTM 52911-1:2019]

The 52911-1 standard mainly concerns Additive Manufacturing technology using metal powders, which is a process with one of the highest levels of complexity. In such processes, the number of technological parameters affecting the quality of the models produced reaches up to several dozen. The standard covers the process called laser-based powder bed fusion of metals (PBF-LB/M) and contains design guidelines for the process. The use of this standard will certainly contribute to the unification of the quality of the models produced and will allow for minimizing losses resulting from printing incorrectly made/damaged models.

ISO/ASTM 52931:2023 Additive manufacturing of metals — Environment, health and safety — General principles for use of metallic materials [ISO/ASTM 52931:2023]

Safety related to the 3D printing process is an extremely important topic taken up by the ISO and ASTM Technical Committee. This standard provides guidelines and requirements for risk assessment and implementation of preventive and protective measures related to printing on the basis of metal powders, where full melting occurs and harmful chemical compounds are produced. Issues related to waste management and all stages of the production process have been applied in the standard, which is important in connection with the implementation of industry 4.0 tools in the area of recycling/ecology.

ISO/ASTM TR 52906:2022 Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts [ISO/ASTM TR 52906:2022]

A very good example of a research and industrial standard is the 52906 standard, which presents guidelines related to non-destructive testing mainly for metal materials manufactured using 3D printing technologies. Due to the layered nature of the process, full melting during production and the need to use heat treatment, providing a standard in the area of non-destructive testing seems reasonable and necessary. The standard broadly addresses defects arising in the manufacturing process and provides guidelines for good measurement (metrological) practices in this area.

ISO/ASTM TR 52916:2022 Additive manufacturing for medical — Data — Optimized medical image data [ISO/ASTM TR 52916:2022]

An example of a standard from the area of 3D printing and medicine is 52916 from 2022. This standard pays special attention to the process of digitizing 3D files from the area of medical imaging. Key problems related to 2D imaging and 3D file generation are presented. It seems that progress in the area of digitization of medical devices and methods of reducing errors arising in imaging may allow the development of a much more accurate file for Medical Additive Manufacturing (MAM).

ISO/ASTM 52933:2024 Additive manufacturing — Environment, health and safety — Test method for the hazardous substances emitted from material extrusion type 3D printers in the non-industrial places [ISO/ASTM 52933:2024]

Another example of a standard that strictly concerns the safe use of 3D printers is 52933 from 2024. This standard presents guidelines related to the measurement of hazardous substances emitted during the operation of machines from the MEX group, i.e. the most popular FDM and FFF printers, which very often work in offices, private apartments, schools, universities, etc. The key issue of the standard is the presentation of the main hazardous substances for known materials and information on their reduction. The document contains methods for measuring hazardous substances. ISO/ASTM document does not cover all gas phase chemical emissions but a range of Volatile Organic Compounds (VOCs) from n-hexane to n-hexadecane, including aldehydes.

ISO 27548:2024 Additive manufacturing of plastics — Environment, health, and safety — Test method for determination of particle and chemical emission rates from desktop material extrusion 3D printer [ISO 27548:2024]

Another standard in the area of safe use of 3D printers is the ISO 27548:2024 standard, which specifies measurement methods for determining the emission of particles (including ultrafine particles) and certain volatile organic compounds in popular 3D printing - FDM - MEX-TRB/P. The standard can be considered as a supplement to the previously mentioned ISO/ASTM 52933:2024. An important aspect in the area of safety is the knowledge of employees about the hazards associated with Additive Manufacturing, which varies depending not only on the technology, but also on the material used.

ISO/ASTM 52928:2024 Additive manufacturing of metals— Feedstock materials — Powder life cycle management [ISO/ASTM 52928:2024]

An interesting standard from the area of practical industrial application is the 52928. Additive Manufacturing has always been struggling with the problem of recycling and reusing unsintered/unmelted powder. This standard refers to the life cycle of the powder and includes its properties, testing methods, which perfectly fits into the concept of powder quality as a feedstock. The standard is a supplement to another standard regarding the quality of new material - ISO/ASTM 52907.

ISO/ASTM 52909:2024 - Additive manufacturing of metals — Finished part properties — Orientation and location dependence of mechanical properties for metal parts [ISO/ASTM 52909:2024]

The standard presents guidelines for the evaluation of mechanical properties of metal-based models manufactured by Additive Manufacturing, to provide guidance on reporting test results of samples made in the raw state or samples cut from parts. The standard is important for practical applications of Additive Manufacturing, for example in the aerospace or automotive industry, where we expect high level of repeatability and “high” quality in terms of safety, and thus meeting subsequent standards of the aerospace industry.

ISO/ASTM 52926-2:2023 Additive manufacturing of metals — Qualification principles — Part 2: Qualification of operators for PBF-LB [ISO/ASTM 52926-2:2023]

An extremely necessary standard in the area of Additive Manufacturing technology is the 52926-2, which concerns guidelines related to the training of employees involved in the operation of 3D printers in the PBF-LB laser-based powder bed fusion of metals technology. It is also worth noting that identical standards were created for the PBF-ED 52926-3, DED-LB 52926-4, DED-Arc 52926-5 technologies. This is because despite similar materials, the layered nature of the process, there are large differences in the area of quality. The standard presents information that allows for ensuring consistency and repeatability of production through the proper involvement of a properly trained employee in the production process.
The series of four ISO/ASTM 52926 standards describes the activities and responsibilities of operators in the field of Additive Manufacturing technology. The standard specifies qualification tests that should be used in assessing the skills of 3D printer operators. The extremely interesting fact of tests for employees allows to direct the implementation of this standard to improving the competences of employees operating complex Additive Manufacturing systems, which translates into ensuring quality in the production aspect and increasing the use of Additive Manufacturing in new "responsible" industrial areas.

ISO/ASTM 52967:2024 Additive manufacturing for aerospace — General principles — Part classifications for additive manufactured parts used in aviation [ISO/ASTM 52967:2024]

Due to the great interest of the aviation industry in Additive Manufacturing, the ISO/ASTM 52967 standard was created, which covers the production process of parts in a very broad area, but also areas such as operation, testing, determining compliance, addressing the issue of failures and their consequences. This standard refers to all 3D printing systems that can potentially be used to produce elements used in one of the most responsible industrial sectors – aviation.

3 CONCLUSIONS

In summary, Additive Manufacturing technologies known since the 1980s have only been equipped with appropriate standards for the last decade to streamline the manufacturing process, improve the relationship between the customer ordering the model and the company performing 3D printing, and also improve the quality of the models produced. It is worth noting that the latest standards address the issue of safety and certain guidelines related to the materials used and 3D printers used in non-industrial places such as universities, schools and offices. The introduction of a standard specifying the requirements for 3D printer operators, especially for industries in the scientific discipline of Mechanical Engineering and 3D printers producing from metal-based materials, deserves great positive attention. Due to the ongoing industrial transformation 4.0, it is extremely important that the standardization process in the area of 3D printing progresses dynamically, which will certainly contribute to increasing the quality of manufactured models, Additive Manufacturing services and improve working conditions in this area. It seems that the subject of standardization should also go into the areas of new use of Additive Manufacturing in other/new industrial sectors and keep up with changing materials and newly implemented additive technologies. It is also worth noting that most of the presented standards concern Additive Manufacturing or from materials based on metal powders, or MEX technology, which is one of the most commonly used methods in Additive Manufacturing. Standardization issues are clearly less frequently discussed in the area of, for example, photo-curing of liquid polymer resins or methods based on ceramics.

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