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The Place of 3D Printing in the Manufacturing and Operational Process Based on the Industry 4.0 Structure

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Abstract: The article presents the place of 3D printing in the manufacturing and operational process. It analyzes selected incremental technologies in the product life cycle. It describes selected processes for testing the properties of materials used in 3D printing, including accelerated aging tests and simulation of operating conditions. Areas of application of 3D printing were defined, starting from design and prototype development through manufacturing of technological tools and finally finished products. Design criteria of additivelymanufactured elements in relation to the exploitation process are discussed. A methodology for the development of 3D-CAD models of manufactured elements, software processing of data and data storage format for manufacturing products and spare parts is presented. The assumptions of repair procedures based on the production of spare parts by means of 3D printing in relation to data circulation compatible with the idea of Industry 4.0 structure have been adopted.

Keywords: additive manufacturing; Industry 4.0; manufacturing process; operational process; 3D printing

1 INTRODUCTION

Additive manufacturing can occupy different places in the production process and the design of additive manufactured products should also take into account their operational process. The life cycle analysis of additive manufacturing products can be a collection of relevant information allowing the development of criteria for manufacturing products dedicated to different types of 3D printing technology [1]. These criteria should include incremental processes, tests of the properties of materials used in additive technologies, including accelerated durability tests using simulated operating conditions [2, 3]. The analysis of the research results allows to define the areas of 3D printing applications, starting from the design and prototype development, through the production of technological tools and finally finished products [4]. From the point of view of the additive process itself, the method of 3D-CAD numerical modeling of manufactured elements, program processing of data and data storage in formats intended for the production of products and spare parts using 3D printing methods is particularly important. Additive technologies are now an important element of the production system, they allow the production of functional products, components and spare parts based on data transfer in accordance with the idea of the Industry 4.0 structure [5].

2 PLACE OF 3D PRINTING IN THE INDUSTRY 4.0 STRUCTURE

3D printing technologies allow for flexible adaptation of production to the needs of the recipient using solutions of production systems based on network structures in accordance with the INDUSTRY 4.0 scheme. In this case, the integration of network tools, typical technological processes and 3D printing technology is used. In this structure, various software tools are used, starting with the design and processing of numerical models intended for the manufacturing process and quality control. This type of data is often stored in distributed systems and saved on servers in the form of a cloud. The data includes, among others source files of 3D-CAD models, construction documentation, technological documentation, documentation of the manufacturing process, e.g. 3D-STL or 3D-CAM files, layer files, measurement files and results of geometric analyzes related not only to incremental but also conventional technologies. In this structure, due to the network organization of work, data security is very important. The distributed data structure allows for parallel work in different locations of the same company as well as cooperating entities [8, 10]. Thanks to this, it is possible to remotely work or monitor the process from any place with network connections. The use of automated procedures, virtual reality industrial robots or artificial intelligence in the structure additionally increases its possibilities in terms of product quality and production speed. In such a structure, in relation to additive technologies, it is necessary to equip production devices with appropriate interfaces enabling their communication with the entire system in the Industry 4.0 structure [11].

System integration begins when the customer defines the product assumptions as product custumization (Fig. 1). At this stage, it is necessary to define the technological capabilities of the enterprise and the related process of purchasing and supplying raw materials for production. The use of 3D printing allows, in many cases, a flexible approach to the modeling and manufacturing process, and real-time data exchange enables the acceleration of processes such as ordering raw materials, product modeling, data preparation for production and quality control, which can be implemented in a parallel system. The production and finishing process as well as quality control depends on the design of the product itself, it also determines the place of 3D printing in the production system and the individual stages of sub-process and finishing.

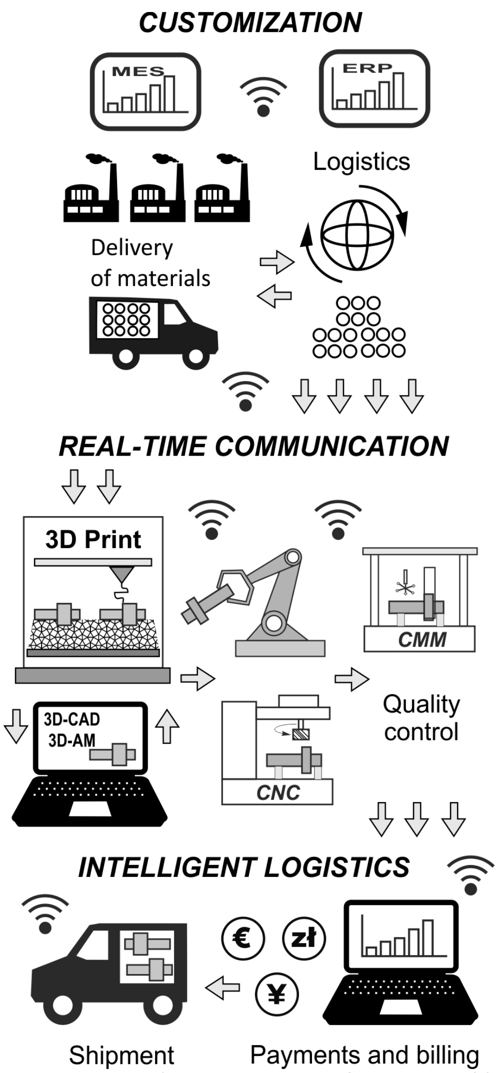

Figure 1 Diagram of processes in the INDUSTRY structure 4.0

The diagram shown in Figure 1 also lists the element of intelligent logistics, which on the one hand can be linked to the system of a given company using MES and ERP software, on the other hand. Intelligent logistics can be an element of internet portals for ordering additive manufacturing products, where it is possible for the orderer to automatically load the numerical 3D model of the product, determine its valuation for a given number of items made of a given material with the selected 3D printing technology. Systems of this type can be equipped with expert advisory modules that suggest to the client the possibilities of using given materials or additive technology.

In the process of additive manufacturing, two basic groups of factors influencing the accuracy of models can be distinguished: factors resulting from numerical processing of data and factors resulting directly from the incremental process. These factors, depending on the technology used, are directly or indirectly related to each other, they are also often related to the technological capabilities of the 3D printer and the course of the additive process itself, or the materials used. The analysis of these factors is important from the point of view of selecting a measurement method to analyze the accuracy of incrementally manufactured products. When analyzing the structure of Industry 4.0, however, it should be remembered that it is based on the efficient operation of IT systems and the supply chain with a specific scope. In this case, it is a very good tool to implement production in a planned manner, tailored to the recipient, with the possibility of saving time and minimizing the costs of production processes. The structure of Industry 4.0, however, is sensitive to disruptions in supply chains, especially in crisis situations related, for example, to a pandemic or economic sanctions. In this case, 3D printing technologies can be an important element of production support in relation to the production of products, spare parts that may be unavailable at a given moment.

3 TESTING THE PROPERTIES OF PRODUCTS MANUFACTURED BY 3D PRINTING METHODS

3.1 Strength Tests

Designing incrementally manufactured products allows for an individual approach to both the customers needs and the possibly flexible approach of the designer. Defining the essential criteria for designing and manufacturing products with the use of incremental methods, however, requires knowledge of 3D printing technology by both the designer and the recipient. This knowledge does not have to include the details of the incremental processes themselves, it may be limited to the knowledge of the basic technological parameters as well as the types and properties of materials used in 3D printing Technologies [9]. Modern computer tools allowing the use of expert systems in the selection of additive technology, and systems of this type can be included in the structure of Industry 4.0 as a tool for the initial verification of the criteria for selecting a manufacturing metod [12, 14].

Detailed guidelines for the production procedures of products manufactured with additive methods require the determination of design assumptions based on the operational requirements of the product assumed at the beginning. This entails the need to carry out strength tests of samples as well as product elements, which can be carried out on the basis of appropriate standards or on the basis of individually dedicated research plans. Additively manufactured products often have different mechanical strengths depending on the layered structure and path distribution within each layer. Taking this into account, it seems advisable to carry out strength tests both in the field of traditional static tensile strength tests as well as in the field of additional loads, e.g. torsional moment. Research of this type may also be the basis for determining the boundary conditions for computations and computer simulations using the finite element method (FEM) for samples and incrementally manufactured elements for which we do not have computational parameters in the available software databases. In addition, carrying out systematized tests may constitute the basis for the development of databases of strength parameters of products manufactured additively with the use of a specific 3D printing method and specific construction materials [13].

3.2 Static Strength Tests of Incrementally Produced Samples

Tensile strength is the basic parameter used in the calculation and design of machine elements. Strength tests for products manufactured additively should be carried out on the basis of appropriate standards for the shapes of samples with a standardized shape. The most commonly used for testing polymer materials are samples of the shape shown in Fig. 2 with the use of appropriate testing machines. Thanks to this, it is possible to determine the strength parameters for products manufactured additively with a heterogeneous internal structure (Fig. 3).

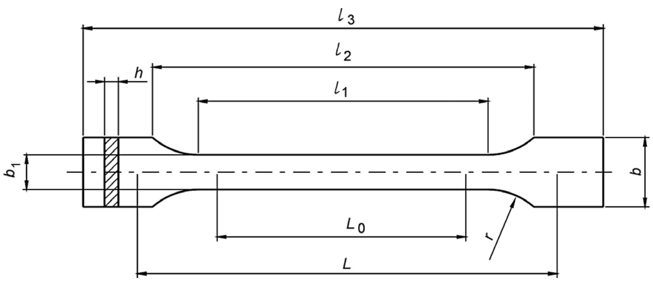

Figure 2 Sample model for strength tests (l_1 - length of the part delimited by parallel lines, l_2 - distance between wide parts, l_3 - total length, b - the width of the gripping part, b_1 - width of the measuring section, h - sample thickness, L_0 - measuring length, L - initial distance between the handles)

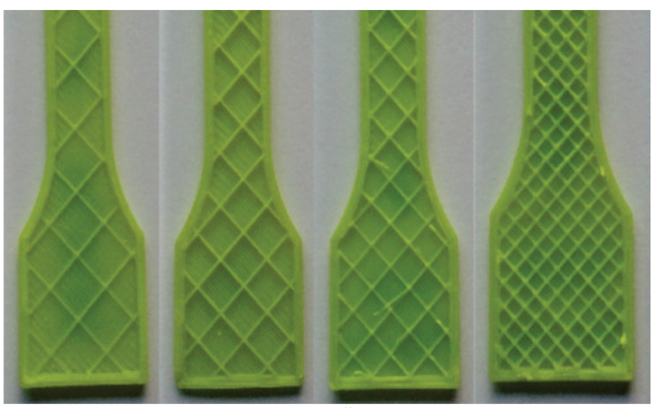

Figure 3 Test samples with different internal structures

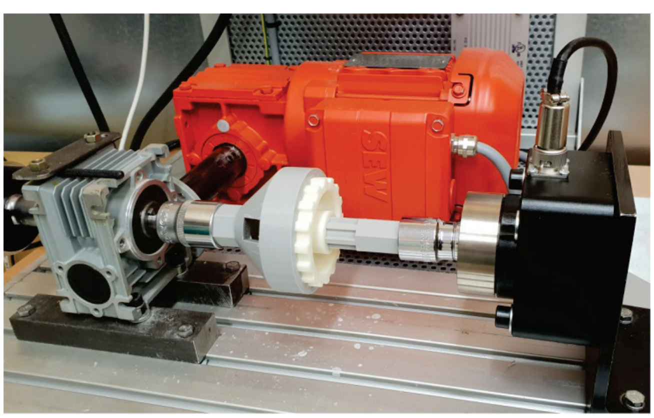

Figure 4 Elements made incrementally during torsional strength tests

The analysis of mechanical strength based on basic tests, which also includes bending strength tests and compressive strength tests, allow to determine the basic parameters of samples produced with various incremental methods in relation to their industrial applications.

The strength of additive manufacturing products can also be subjected to static torsional strength tests, which can be particularly useful for machine components used in drive transmission systems. Fig. 4 shows the stand for testing the torsional strength of incrementally produced samples. The results of this type of research can be important information in the product design process, they can also be used as data for strength calculations used in the simulation process based on the finite element method.

3.3 Durability Tests of Incrementally Produced Samples

The exploitation of products, including those manufactured additively, requires durability tests under conditions of accelerated wear. Construction of product durability test stands should take into account the possibility of load changes and simulate working conditions similar to real ones. One of the examples of such a test may be the durability tests of gear pairs carried out with the use of a special stand developed at the Department of Machine Design, Rzeszów University of Technology (Fig. 5). The stand is universal and allows for the implementation of durability tests of gears of various geometries, produced by injection and incremental methods from polymeric materials. The stand consists of the test gear, the driving system of the loading system equipped with the rotational speed and torque measurement system, which values are recorded continuously. The control system allows you to program test cycles dedicated to specific pairs of gears, allowing you to simulate various working conditions at a given load.

Figure 5 Stand for durability tests of gear pairs

4 DETERMINING THE PLACE OF 3D PRINTING IN THE PROCESS OF DESIGNING AND MANUFACTURING PRODUCTS

4.1 Place of 3D Printing in the Design Process

Additive technologies, especially in the first years of their development, were mainly used in the process of designing and prototyping products for the production of conceptual and visual prototypes. Currently, 3D printing continues to perform these functions at the design and prototyping stage, however, it allows for the production of functional prototypes and finished products at the same time. In the case of additive technologies, an independent process approach can be distinguished, regardless of whether it is the stage of design or primary production, or the stage of preparing numerical data for the 3D printing process. These stages include the basic processes of numerical processing of the model, starting from the 3D-CAD model, through the transformation of the 3D-CAD model as a file that can be read by the software controlling the 3D printer, to transforming the model into a layered structure as numerical data readable directly by the printer's executive system. 3D. The first stage of CAD modeling is particularly important and has a fundamental impact on the geometrical parameters of the product and enables its conversion to an intermediate format suitable for 3D printing. 3D-CAD modeling programs are equipped with modules for exporting the solid model to a readable form in the subsequent stages of the incremental manufacturing process. The numerical processing of data has a significant impact on the accuracy of the product representation in relation to the 3D-CAD nominal model, therefore this process should be carried out while maintaining appropriate procedures.

4.2 The Use of 3D Printing in the Production Process of the Product

Manufacturing products using 3D printing has many advantages, including belong:

- relatively quick production of the product without the use of specialized tools typical for mass production,
- production of personalized products, production of products with complex shapes that are difficult or impossible to produce using conventional methods,
- manufacturing of products with a controllable structure and directional mechanical strength, designed with the use of topological optimization algorithms.

The mentioned advantages cause that 3D printing is more and more often used for the production of final products or for the production of semi-finished products intended for further finishing processing. At the same time, there are new challenges regarding the life cycle of such a product, the processes of supplying or manufacturing spare parts for machines and devices, and waste management. Among the trends in the exploitation area, it can be noted that manufacturers using 3D printers to produce machine components are moving away from supplying spare parts in the traditional workflow used classically. This place is taken by the delivery of additively produced spare parts documentation along with the device in the form of files with 3D-CAD models or models in intermediate formats prepared for production with the use of a 3D printer. This causes a change in the approach to the planning of operational processes in relation to both wear processes, but especially to renovation processes. It should be remembered that the documentation of the model alone is insufficient to produce a spare part that meets the assumptions of the operational process. In this case, the data should also indicate what 3D printing technology was used to produce a given element, what material was used and what were the parameters of the 3D printing process itself. This type of information is often overlooked by manufacturers of this type of product, which may cause some problems when manufacturing spare parts using additive methods. By using the elements of the Industry 4.0 structure, it is possible in the production process of products to assume what data will be provided to the recipient of the product and thus eliminate the possibility of subsequent service or post-warranty complaints.

5 METHODOLOGY FOR DESIGNING ELEMENTS MANUFACTURED BY 3D PRINTING METHODS

The methodology of designing mass-produced products is based on the traditional scheme of conduct presented in Fig. 6, which includes the following stages:

- Determining the functional and operational assumptions of the product and making preliminary design calculations,
- Preparation of designs and CAD models of the product as well as numerical simulations,
- Development and execution of research prototypes and conducting tests at research stands,
- Introducing design changes based on the performed tests,
- Preparation of technological processes and tools as well as production launch,
- Distribution, sale and exploitation of products.

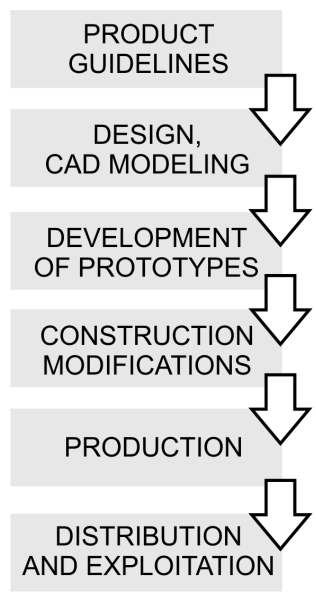

Figure 6 Classic diagram of the main stages of the production process

The presented diagram can be extended using rapid prototyping methods and 3D printing at various stages of the production and operation process, including repair and renovation tasks. By analyzing individual stages, it is possible to determine for them the possibility of applying various additive technologies, most often from the third stage. In the second stage, 3D-CAD models, virtual prototypes and data for the 3D printing process are developed, and preliminary visual models using additive technologies can also be implemented. The third stage of the process, concerning the development and implementation of research prototypes, has a very high potential for the use of various 3D printing methods depending on the purpose of the prototype. It is possible to make visual and test prototypes as well as functional and technical prototypes from materials similar to the finished products or the same as the products are manufactured. Not all 3D printing technologies should be used at this stage, due to the purpose of the prototype, costs and time of its implementation. For this reason, 3D printing methods have been selected in the diagram shown in Figure 7 and assigned to the subsequent stages. Abbreviations for determinations of incremental methods were adopted in accordance with the standard ISO: VPP – VAT Photopolymerization, MJT – Material Jetting BJT – Binder Jetting, PBF – Powder Bed Fusion, MEX – Material Extrusion, DED – Directed Energy Deposition [6, 7].

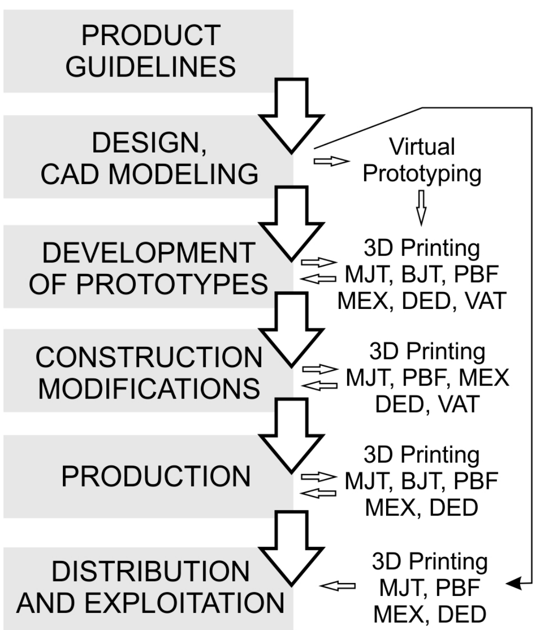

Figure 7 Diagram of the main stages of the production process using various incremental methods

Design changes can also be made with the use of additive technologies, which allow for quick testing of modifications. The production of technological tools is a stage where additive technologies can be used, especially those enabling the production of metal tools (e.g. injection molds) and tools in foundry processes (e.g. casting molds or casting models). In the last of the presented stages of the product life cycle, additive technologies can also be used. This is the case when we base the production process on the production of elements using additive processes, then the spare parts needed for operation are also produced incrementally. The second possibility of using additive technologies at the stage of operation and repair of products is the production of spare parts that are difficult to obtain for various reasons, e.g. a crisis situation or a lack of suppliers. Here, a reverse engineering process should be used, in which not only the geometry of a given element is recreated, but also the material properties are tested in order to make a replacement part, which will allow the functionality of the object to be restored and its failure-free operation within the assumed time.

6 CONCLUSIONS

The production process using incremental methods can be based on various patterns that allow for the inclusion of new technologies. This is possible thanks to the Industry 4.0 structure which, thanks to the use of IT and network tools, allows the exchange of information related to production in real time and quick response to production needs. In the simplest cases, 3D printing is used at the prototyping stage. Taking into account the development of additive technologies, these solutions can be used at most of the production stages. This also applies to the design process, which can be oriented towards the production of products or semi-finished products using 3D printing and the use of modern modeling methods based on topological optimization. This type of products can have completely new properties in relation to traditionally manufactured products. At the same time, the operational aspects that determine the design of the products as well as the renovation and repair processes should be taken into account. Taking this into account, the integration of design, production and operational processes with 3D printing in the industry 4.0 structure and using the TPM method - Total Productive Maintenance can give positive effects, the dimension of which can be an important scientific and application issue.

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