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Application of the computed tomography to control parts made on additive manufacturing process

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Abstract

The article presents possibilities of application computed tomography to study elements made with additive methods. 3D printing is currently growing very rapidly and already allows to execute ready-to-use, structurally complex elements consisting of one or more parts. Similarly, computed tomography (CT), as the youngest measurement technique and methods to control the geometrical size of the parts, allows to control through any element and evaluate both the quality of each individual components and their assembly.
This technique is especially valuable for the evaluation of additive methods. What is more, the evaluation of porosity on the individual sections of the parts might be conducted. It is also possible to obtain information about the location and thickness of each of the outer wall and inaccessible by any other techniques of non-destructive quality control of construction elements filling the various parts of the printed parts.

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Keywords: Computed tomography; X-Ray CT; Metrology; Accuracy of measurement; Additive manufacturing

1. Introduction

The world develops permamentally. In recent years, two new fields which change approach to the manufacture and metrology might be observed. In the area of manufacturing, there are additive manufacturing techniques wchich develop fast [1, 2, 3]. A few years ago, these techniques allowed only to execute elements only for spatial visualizations of designed parts. Currently, we can print 3D elements made of different types of plastics or metals. In the area of metrology of geometrical quantities, we observe development of computed tomography. These devices are similar to medical CT scanners in some aspects, however, allow for better accuracy, and their power allow for inspection of large objects made of, among others, metal.

Additive printing technologies allow for production of elements which have hitherto been considered as the non-technological and not possible to made from the point of view of production capacity and cost-effectiveness. 3D printing has enabled production of the moving parts without having to connect the individual elements - for example may be even planetary gears and bearings. Similarly, computed tomography opened new field of measurement. So far, the measurement of geometry took place in a contact or optical mode. Therefore, it was necessary to touch the surface being measured by a measuring tip or “to see” it by the optical system. What is more, computed tomography allows not only for measurement and evaluation of external but also internal geometry without the need to destroy the object being measured [4, 5].

Combining additive manufacturing technology with CT measurement provides a double possibility. On the one hand, to form elements impossible to obtain by any other techniques. On the second hand, to control those elements without destroying.

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2. Additive manufacturing

Rapid Prototyping (RP) is additive technology, in which three-dimensional physical objects are created by overlapping successive layers of material. Executing object is modelled in CAD, and after performing can be put to cleaning and further machining. Wild range of materials are used in rapid prototyping methods, e. g.: plastic, paper, ceramics, metal or specially selected composites [1,6]. RP method allows to produce items with very complex internal and external shapes, which would have been impossible or very expensive to produce using conventional methods [6].

Rapid Prototyping is widely used in all industries where it is necessary to create real models. Typical areas of application of additive manufacturing methods are:

- design and ergonomic research,
- testing and evaluation of design solutions based on real models,
- assessment of manufacturing processes and assembly,
- marketing research and evaluation of new products,
- multifunction models used in foundry and metal forming,
- design and manufacture of medical implants.

Nowadays, there are many kinds and varieties of RP methods. Some of them are similar to each other and differ only in small details [6, 7, 8].

2.1. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) – is now one of the most commonly used methods of rapid prototyping. It is an incremental imposition of semi-solid material by moving the heated nozzle head. The material is supplied in the form of fibers with diameter of about 0.18 mm. When the layer is applicated it is cooled and hardened [7, 9].

The path of the added material may have a width from 0.254 mm to 2.54 mm, and the thickness of the layers is from 0.13 mm to 0.33 mm. In the FDM technology is necessary to use the support legs and parts of the model underlying the construction of the entire model. The primary materials used in the thermoplastic FDM technology is ABS and PC (Fig. 1). The most important advantage of the FDM technology is the possibility of making functional prototypes with very good mechanical properties and a high dimensional accuracy. FDM is also one of the few technologies RP spanning the unit production of finished products. The disadvantages can include poor quality of the obtained surface, quite a long time to build the model, the high wall thickness, cumbersome removal of supports and anisotropy of the mechanical properties of the material, depending on the geometry of construction elements to the direction of applied layers of plastic [10, 11, 12].

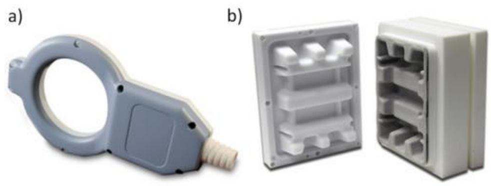

Fig. 1. Examples of models made of ABS plastic (a) PC (b) by FDM methods.

2.2. Stereolithography (SLA)

Stereolithography (SLA) was the first method of rapid prototyping. The first commercial machine was presented in 1987 by 3D Systems Company. Stereolithography process is laminated hardening liquid resin using laser light of low power. There can be separated following stages during the process of creating a model layers [13]:

- Hardening layer by the so-called cross-hatching. Thereby creating a stiff mesh used to reinforce the border and to retain the shape of the model.
- Hardening of the layer contour.
- Filling of the layer contour.

After curing resin layer followed by application of another layer of liquid resin. Layer alignment, and giving the adequate thickness is carried out with the scraper. The model is separated from the platform by supports and therefore processing of the model is necessary. The supports are in the form of thin vertical rods, which are tapered in contact with the model, which facilitates their subsequent removal [1, 14] (Fig. 2). The laser beam hardened polymer only in 96%, so it is necessary to complete the process of curing the material by the UV light. The materials used in the stereolithography process are photo-curable resin: acrylic and epoxy. Significant advantages sterolitografii high accuracy and surface quality made model. It is worth mentioning the high resolution, which allows to do a model holding a lot of details. The condition method is sterolitografii photo curability by a variety of materials are limited, and the process lengthy [15].

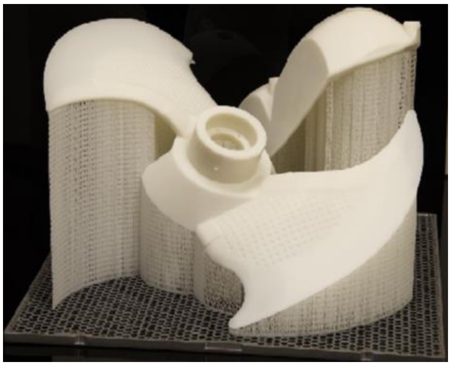

Fig. 2. Example of model made by SLA methods before removal the supports [16].

2.3. Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) is one of the simplest methods of additive manufacturing. The process involves creating a model with a combination of layers consisted of paper and the polyester laminate. Contours are cut by a laser, knife or milling tool in a special paper which is coated with a thin layer of adhesive (Fig. 3). The finished model has properties similar for models made of wood. The geometry of the model can be complicated keeping the dimensional accuracy of 0.1 mm [15, 17].

The advantages of the LOM technology should be a very low cost and non-toxic material that is paper. Another advantage is the simplicity of the process concept, and the low cost of implementation and relatively high operating speed. A significant disadvantage of this rapid prototyping method is a large amount of waste, which, depending on the geometry of the model, can be as high as 90%. A negative trend is also significant anisotropy of mechanical properties made elements and the lack of feasibility model with a very thin wall (minimum thickness is about 1mm) [6, 11].

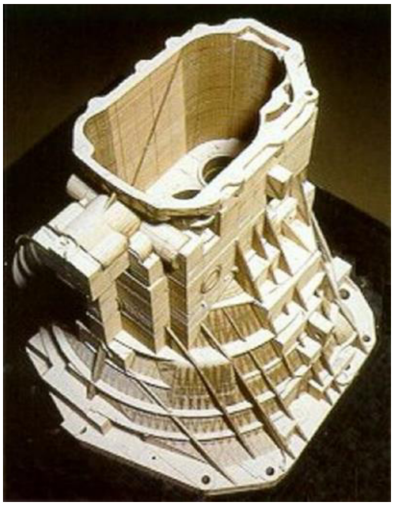

Fig. 3. Example of model made by LOM methods [19].

2.4. Selective laser sintering (SLS)

Selective laser sintering (SLS) is the local sintering of layers of material in powder form. The powder is a grain size of 50µm to 100µm. The laser selectively binds the powdered material by melting the powder to form the required cross-section. In machines adapted to SLS technology has two chambers: chamber with the material and the working chamber (Fig. 4). The powder is distributed by roller material from the chamber into the working chamber. The working space of the machine is heated to a temperature of about 4 ° C below the melting point of the material. Processing takes place in a protective atmosphere of nitrogen to avoid oxidation phenomena of the material. The temperature in the working chamber must be steady and constant, it will allow to obtain a good surface quality and high dimensional accuracy of the model. Even the difference of a few Celsius degrees can cause the model is flawed and its structure will not be uniform. A model are porous with a density of 60% to 85% solid material. Improve the surface quality can be achieved by sanding or polishing. The advantage of SLS is possible to use many different kinds of materials, in particular metals. The advantages include no need to use props to support the construction of the model and option execution model as a finished product unit. Unfortunately, the method SLS also has drawbacks, the biggest of them is the long duration of the process. Already during the design model you have to remember that, especially metal materials under high temperature is accompanied by the phenomenon of contraction. This may be crucial for the proper performance of the model.

Fig. 4. Examples of parts made by SLS method [20].

2.5. Selective laser melting and Direct metal laser sintering

SLM - selective laser melting and DMLS - Direct metal laser sintering according to the company's patent is based on sintering and melting of a laser metal powders. Usually they use ytterbium fiber laser that work in infrared. The model is constructed by applying a thin layer of metal powder with a thickness of 0.01 – 0.80 mm. The process of applying the material most commonly takes place with the help of the blade, which aims to cut disparities caused by remelting the previous layer. After distributing the powder begins the process of laser exposure. Path contouring and filling are melted on the surface of the powder bonding model into a unified whole [9, 15] In oposite to SLS technology, not sinterded powder is not used to support a "hanging" geometry but generates a stable support structures. The use of props is necessary due to the much faster contraction of the metal melted, due to a large temperature difference between the atmosphere of the working chamber, and the liquid metal. High amplitude is related to the fact that the working chamber machines is not heated. After the process of building the object it is necessary to cut off the part of home plate and remove the supports. In practice, the SLM technologies and DMLS are used as substitutes for the casting [9, 15, 18]. Products obtained SLM and DMLS methods are highly durable equaling their properties components made by casting or forging (Fig. 5). You can also be obtained resistant thin walls with a thickness of 0.1 mm. Due to the formation of thin films obtained relatively good surface quality. Adversely affected by the difficulties in building a large surfaces area and the need for support which limits the geometries created model [21, 22].

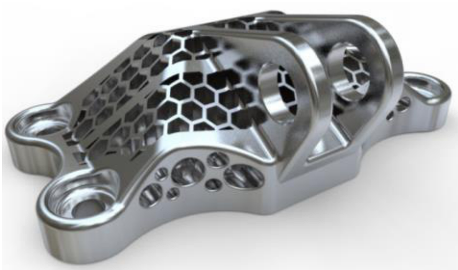

Fig. 5. Examples of parts made by DMLS methods [24].

2.6. PolyJet

PolyJet technology is young (2001) in the field of Rapid Prototyping. Stereolithography is a combination of methods and inkret printing. A special feature of this technology is to spray a liquid photopolymer. With printheads the holes in the material is at a frequency of several thousand droplets per second [18]. The sides of the printing units are equipped with two UV to cure the photopolymer immediately after application. The method PolyJet is necessary to use supporting material. It is also applied to the base material. Supporting material is used as a basis for the construction of model elements having no support and also to surround the entire model to stiffen and fill the void space. The thickness of the layers in the PolyJet technology is about 0.016 mm, which allows for the accuracy of the order of 0.1 – 0.2 mm (Fig. 6). Thinnest achievable wall is about 0.5 mm [18, 26]. The advantages of PolyJet is a very high accuracy and performance modelling. The disadvantage of this method is the low temperature resistance and a reduced tensile strength of the materials used. This is due to the maintenance of a compromise between the increase in strength of materials while maintaining low viscosity of the resin in such a way that it can be applied under pressure by means of piezocrystalline heads [26].

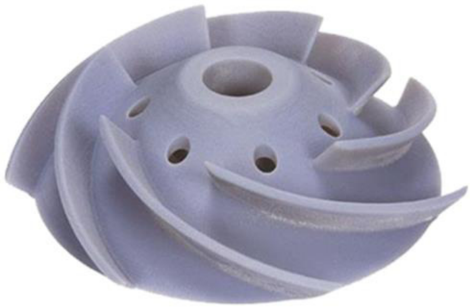

Fig. 6. Examples of parts made by PolyJet methods [26].

2.7. Three Dimensional Printing (3DP)

Three Dimensional Printing (3DP) is a laminated combining the particulate material with the assistance of the adhesive that is applied by the printhead (Fig. 7). This technology remains a classic print, but as happens in the inkjet ink is not used, but powder. 3DP printing starts with the application of a layer of powder which is drawn from the tank complementary. The specific amount of the powder is conducted through the system moving a piston in a cylinder machines and subsequently distributed using a roller on the surface of the working platform. Then, the applied layer of powder is placed adhesive binding - the powdered material. The powder which has not been fixed with an adhesive for supporting the model. Successive layers are applied and bonded so as to form a model designed. The layers which are deposited to a thickness of about 0.1 mm, and the model can be reinforced by soaking substance which enhances the mechanical and elastic properties. Currently, there are several different varieties of 3DP technology, where manufacturers use various materials such as eg. Ceramics, plastics, or metal powders [27]. This is the fastest method of rapid prototyping technology. Unfortunately due to the rapid development of models and lack of variety of materials is observed limits the functionality of the models, their high fragility and low accuracy [11].

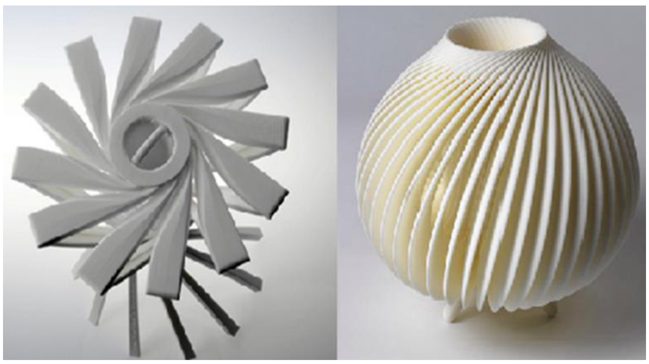

Fig. 7. Examples of complex shapes made by the method 3DP [28]

3. Non medical computed tomography

3.1. Physical basis of x-ray techniques

The X-ray tomography is a class of radiology technic, for which common attribute is the movement of the X-ray [29, 30]. This movement allows for obtaining a clear picture of the test objects inside structures. The device performing the test is called the computed tomograph (CT) while the resulting image the tomogram. The word ‘tomography’ comes from the Greek tomos (layer) and graphia (describe). This name was adopted in 1962 by the International Commission on Radiologic Units and Measurements for all radiography techniques which snap layer view of the workpiece [31]. Computer tomography CT is a type of X-ray tomography, a method enabling to obtain tomographic images (sections) of the object [32, 33]. It applies submission of the object projections from different directions to create a cross-sectional images (2D) and spatial (3D). CT is based on the theorem of Austrian mathematician Johann Radon, who in 1917 proved that the image of two-and three-dimensional object can be reproduced totally from an infinite number of the workpiece projections [34, 35].

The discovery of X-rays owes to W.C. Röntgen, who did it in Würzbburg in 1895. The first X-ray devices is presented on photograph (Fig. 8).

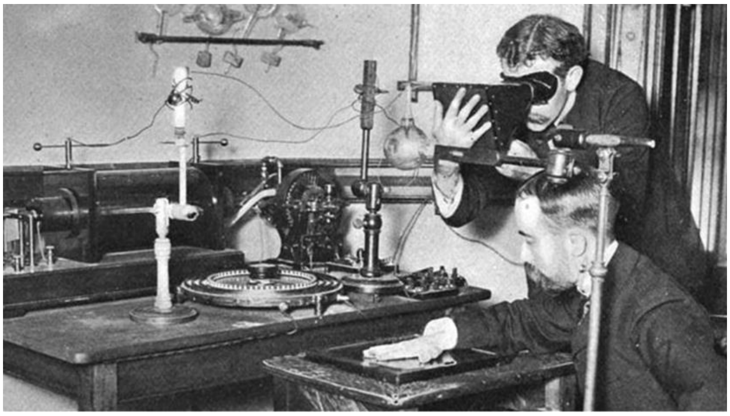

Fig. 8. One of the first X-ray devices [36]

X-rays are – similarly to light – electromagnetic waves. The wavelength is in the range of 0.001 to 10 nm, as shown in Fig. 9.

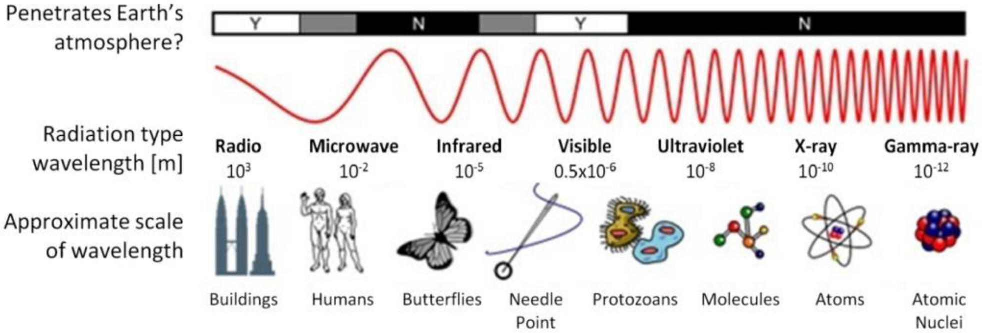

Fig. 9. WaveleBngth of X – rays [37]

X-rays are generated by the inhibition of fast electrons in solids. This effect is dominant. An additional effect is the sputtering of electrons, on which position empty places arise. In those places electrons from higher levels jump through, resulting in a cascading effect. The emitted radiation characteristic appears in the spectrum in the form of discrete lines.

X-rays are absorbed in varying degrees by different materials. Absorption increases with the density of the material, which increases with the atomic number. Thus, for example, lead with the atomic number 82 is applied to the screens against X-rays, and objects of steel (Fe 26) are harder to X-rays from aluminium (Al 13).

3.2. Design and function of CT

The first tomograph was constructed in the years 1969 - 1972 by Hounsfield and Cormack. The production was in 1973. Its appearance is shown in Figure 10.

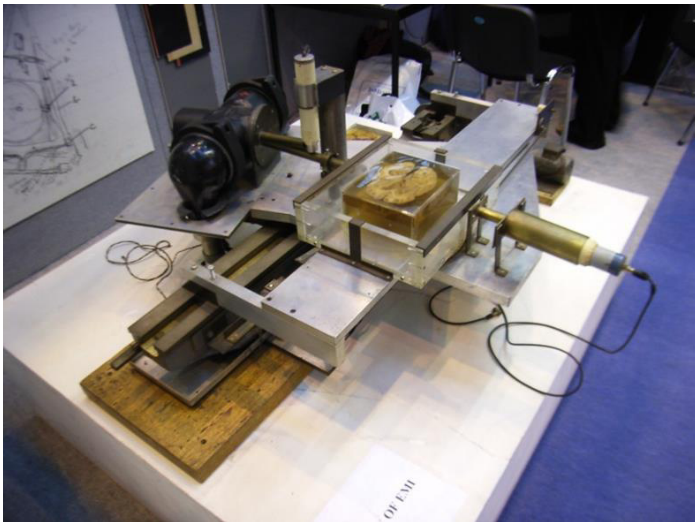

Fig. 10. The first tomograph – Hounsfield's prototype CT scanner [38].

The first commercial X-ray tube was developed by WD Coolidge from General Electric in 1913. He used heated tungsten filament to form an electron beam in a glass tube with a vacuum. Nowadays, in metrological CTs two basic types of lamp are used: transmissional and directional. Transmission tube allows for greater magnification while directional one for greater power. The pattern shown in Figure 11.

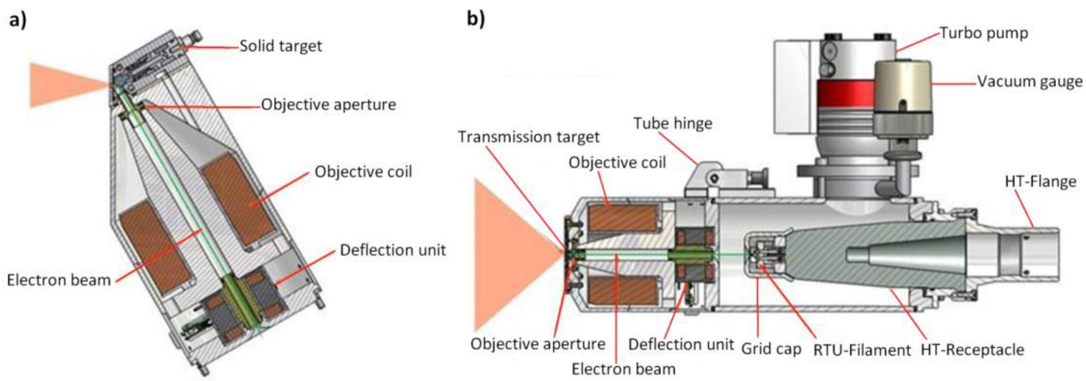

Fig. 11. Lamps applied in tomographs a) transmissional, b) directional [39]

In order to obtain better resolution of the CT a microfocus and nanofocus tubes are applied. Especially in the latter one, additionally equipped with a shutter allows for a very small spot size, even less than 1 micron, with an additional stabilization of tension. The CT can be constructed in 2D and 3D version. 2D CT is known as a flat beam CT (Fig. 12a), while 3D ones as cone beam CT (Fig. 12b).

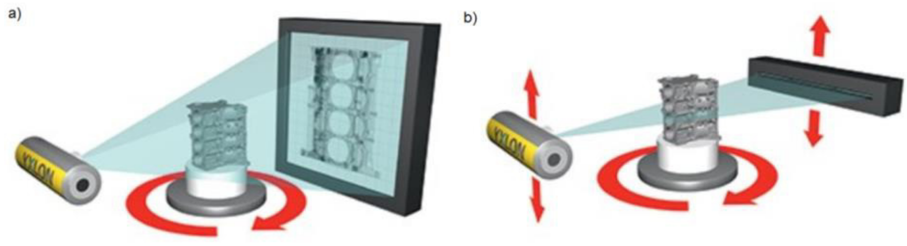

Fig. 12. Tomograph: a) with cone beam, b) with fan beam [40].

Another important element of CT is the detector, which is the system that presents the resulting image. Firstly, X-rays are converted to visible light by a film or scintillation crystal. Then this visible light is received by photodiodes, making possible presentation of the image. Schematic layout of the detector is shown in Figure 13.

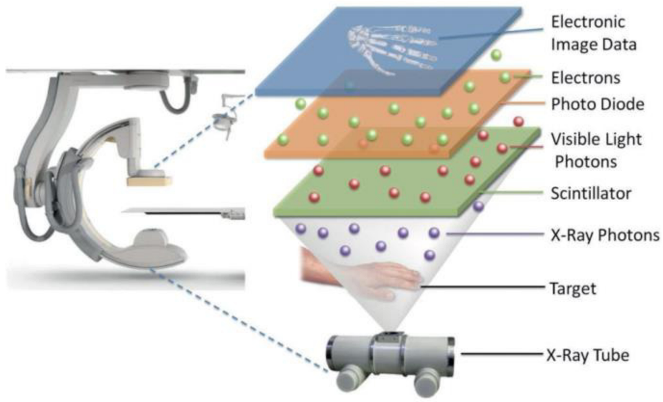

Fig. 13. Detector in CT [41].

3.3. Image analysis

The next step after collecting the images is reconstruction of the whole element [42, 43]. It takes place in space, considered as a three-dimensional array of voxels. By definition voxel (called volumetric element - similar to the pixel) is the smallest element of the 3D space, the equivalent of a pixel in 2D (Fig. 14).

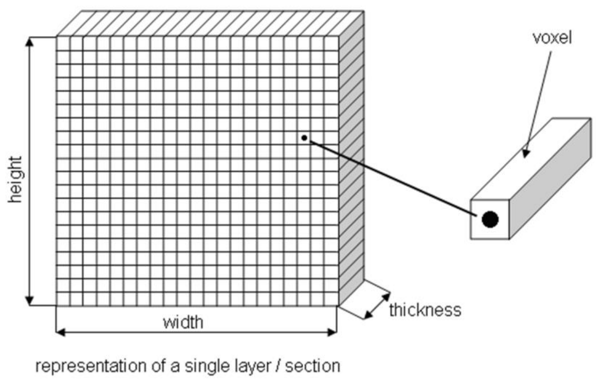

Fig. 14. – Graphical presentation of voxel.

The accuracy of the reconstruction is affected substantially by the size of the voxel V and the spot size at the focal point F (Fig. 15a), which is the limit of resolution [44]. In addition, there are relations between: V = P / M, M = FDD / FOD, where P – pixel, M – zoom. ROI is the area of observation (Fig. 15b).

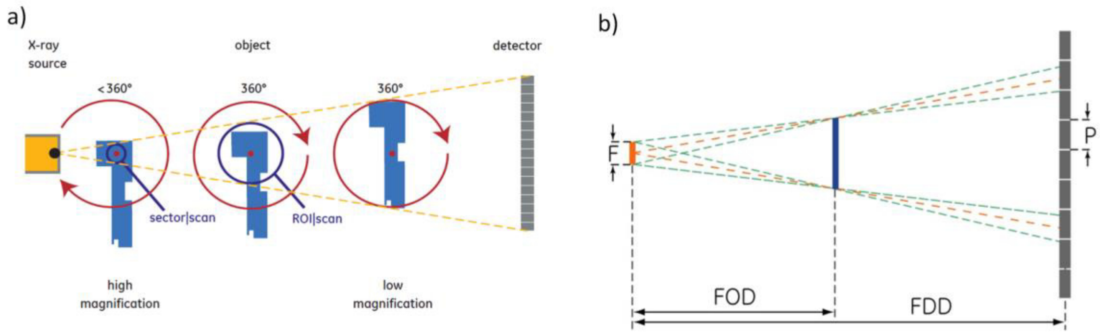

Fig. 15. Image analysis: a) area of observation, b) size of the spot and zoom.

Geometric zoom is therefore dependent on the distance between the lamp and the object, as shown in Figure 16.

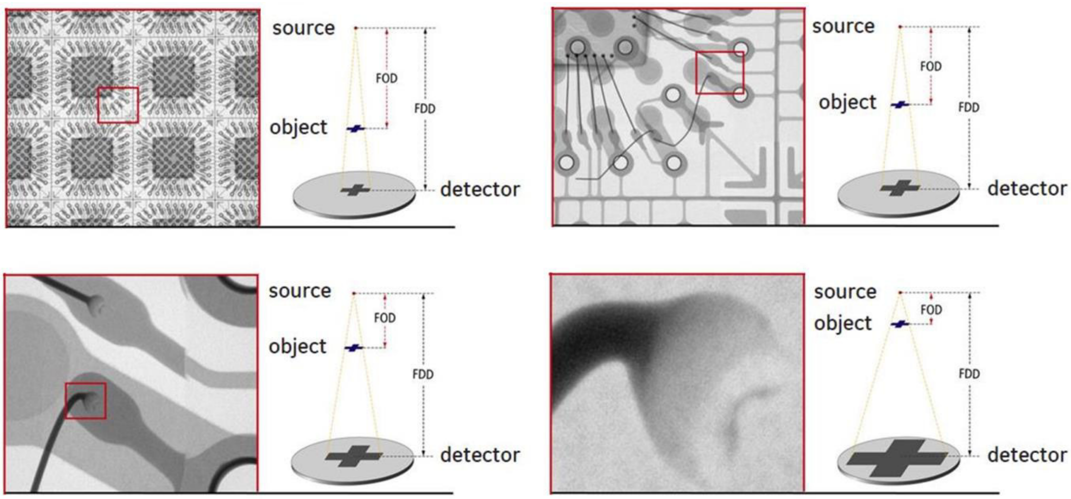

Fig. 16. Following steps of the image zoom.

4. Control of the 3D printed parts

4.1. Design of the parts and measuring devices

The study developed three research models. The first - the element halves of the circles having a diameter Ø8mm; Ø16mm; Ø24mm; Ø32mm; Ø40mm; Ø48mm; Ø56mm and Ø64mm. Each stage has a height of 8 mm (Fig. 17a). The second element was the model stepped on the degrees of different width and height. Grades are designed with a width of 0.8 mm; 1.6mm; 2.4mm; 3.2mm; 4,0mm; 4.8mm; 5,6mm; 6.4mm and 7,2mm and height of 0.8 mm; 1.6mm; 2.4mm; 3.2mm; 4,0mm; 4.8mm; 5,6mm; 6.4mm; 7,2mm and 8,0mm (Fig. 17b). The third element is a square plate with a side of 32mm and 8mm thick with through holes in the shape of a circle, rectangle and triangle (Fig. 17c).

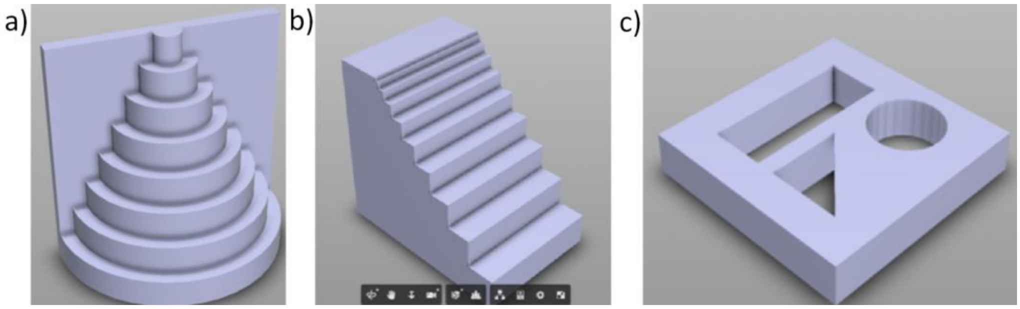

Fig. 17. Model with arches (a); Stepped model (b); Model with holes (c).

Designed models were made by FDM printer's UP! 3D ABS. View research after printing elements shown in Figure 18.

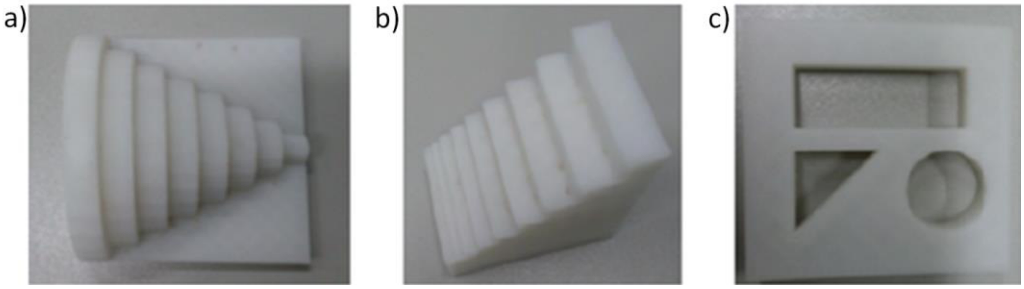

Fig. 18. Printed research models.

Research of the parts dimensional accuracy was performed on a computer tomography (Fig. 19b) and comparatively on the coordinate measuring machine (Fig. 19a). CMM DEA Global Image has a MPE_E = ± (1.5 + L/333) um, measuring range 700x700x500 mm and is equipped with a scanning head SP25M. CT measurement v|tome|x s 240 General Electric is equipped with a lamp microfocus allowing to obtain as the maximum 320W and magnification up to 100x.

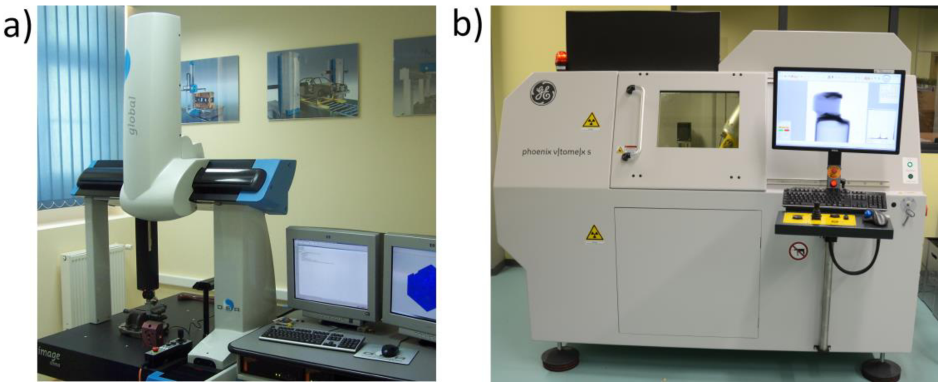

Fig. 19. a) CMM DEA Global Image; b) CT GE v|tome|x s240.

4.2. Results of model with arches measurement

Research for CT allow observation of the entire measuring object in the outer as well as any cross-section of its internal structure. This is particularly important in the case of components made of 3D printing technology, as it allows control of the wall thickness and interior architecture. 3D printing allows not only to produce part of the designed shape, but at the same time to determine parameters of the filling material's internal structure. CT enables us to control the implementation of the inner ribs, their thickness and location. These values depend on the algorithms of the printer and the strategy chosen application layers. Watching the images from the CT you can see uneven print wall in the passage of the vertical wall in the landscape. Additional material can permanently connected to the horizontal and vertical walls, it is being applied from the inside, which in no way interfere with the geometry of the outer surface (Fig. 20).

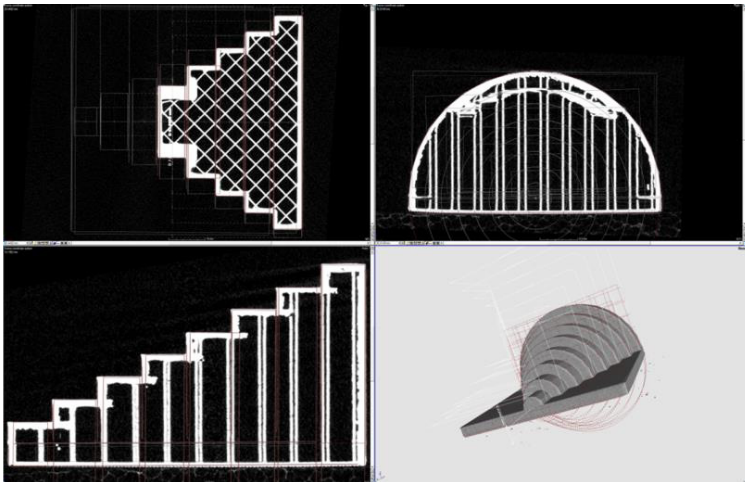

Fig. 20. Crossections of an arc model made on CT.

Analyzing the image of being a result of the imposition of the model and the measured part it can be observed that during the printed cylinder is approximated by many planes, which makes it resemble a polygon (Fig. 21).

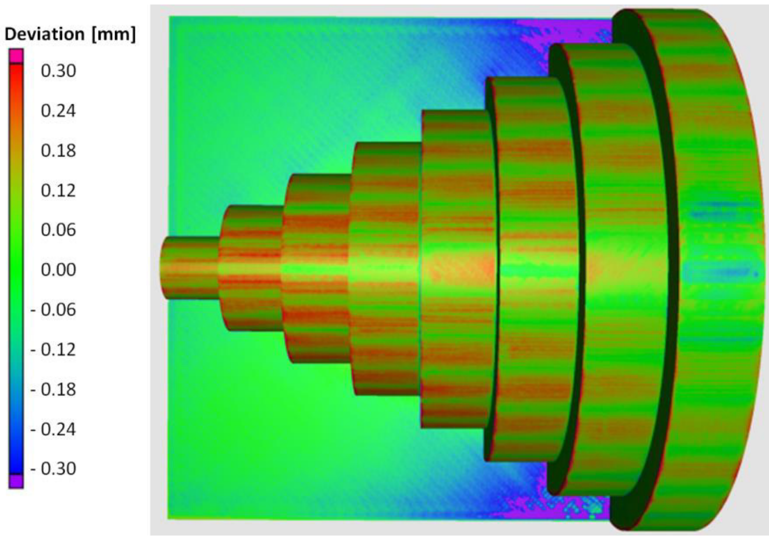

Fig. 21. View of the model after the comparison with the CAD model.

Analysis of the measurement results for particular degrees and diameters leads to the conclusion that the differences in results between CT and CMM does not exceed 0.1 mm while assumed value of dimensional deviations for the element not exceed 0.2 mm (Fig. 22 and Fig. 23).

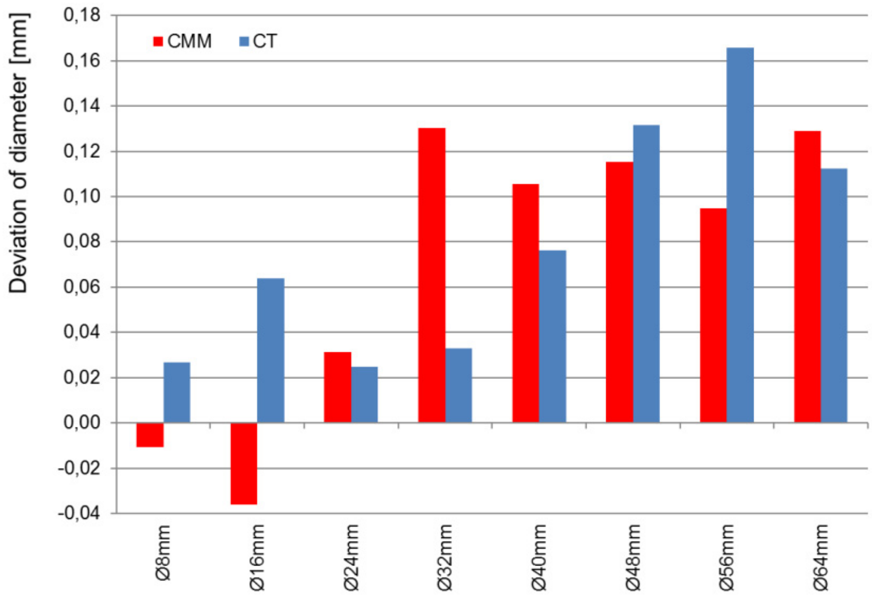

Fig. 22. Deviation of the diameters of the arced steps measured by CMM and CT.

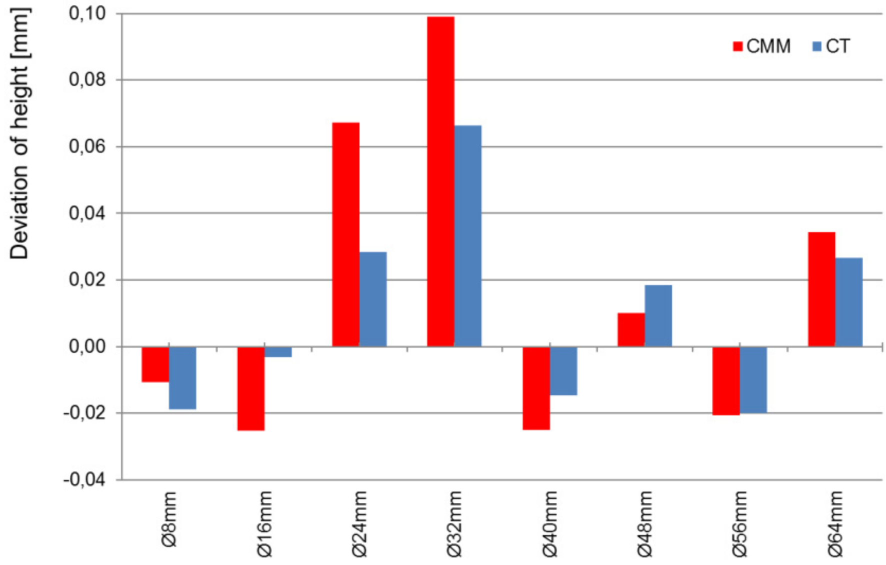

Fig. 23. Deviation of the height of the arced steps measured by CMM and CT.

4.3. Results of stepped model measurement

In the case of a stepped model, CT allows the observation of the internal structure which results from printing. Also, as in the previous case it can be observed that the surface of each step is elongated and penetrates deep into the element. It is a suitable base for printing the vertical walls (Fig. 24).

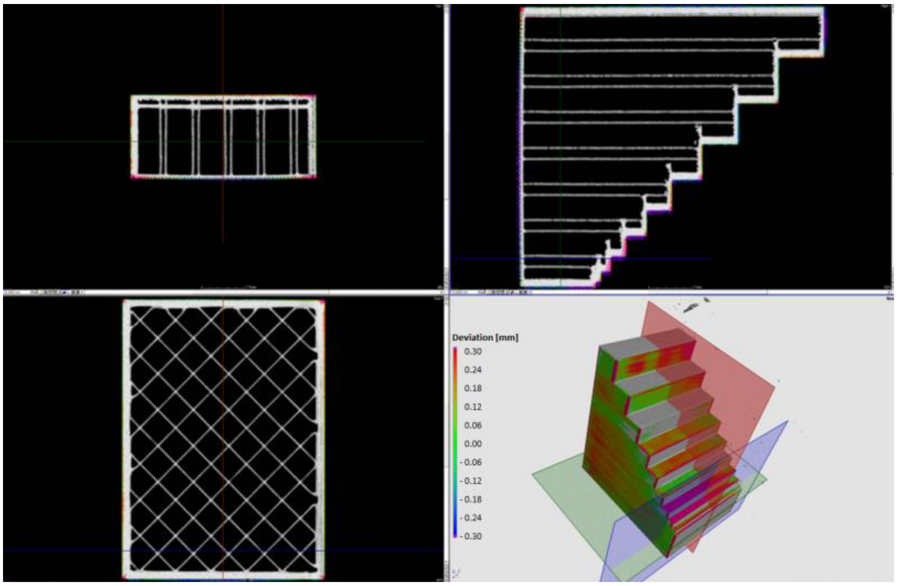

Fig. 24. Crossections of an steps model made on CT.

A comparison with the CAD model leads to present color maps of deviation. It can be seen that the depth of each grade varies from positive to negative values, but the deviation does not exceed 0.15 mm. On the lower surface of the model positive deviation area located along the vertical walls can be observed. This phenomenon is a result of the thermal deformation (Fig. 25). In order to avoid this effect in the future, modififations of the technology process or structures need to be considered with taking into account changes occurring heat.

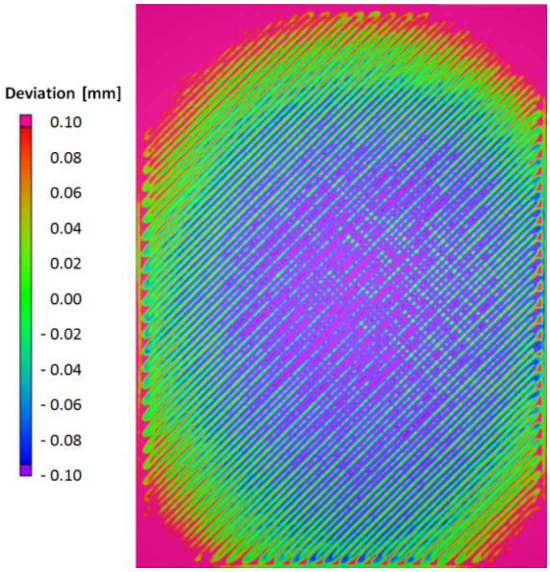

Fig. 25. The deformation of the surface of the cube

Analysis of the results leads to the conclusion that the differences in the depth and height for each grade, do not differ by more than 0,04mm. What is more, of interest there is a change width for each grade varying in the range of plus / minus 0.1 mm (Fig. 26 and Fig. 27).

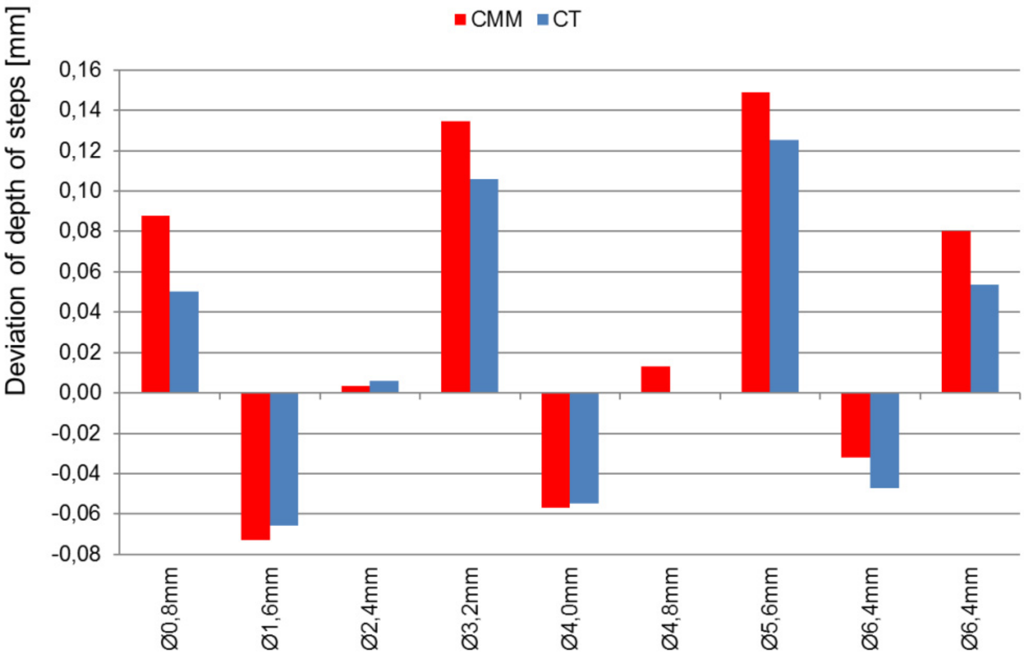

Fig. 26. Deviation of depth of steps measured on CMM i CT.

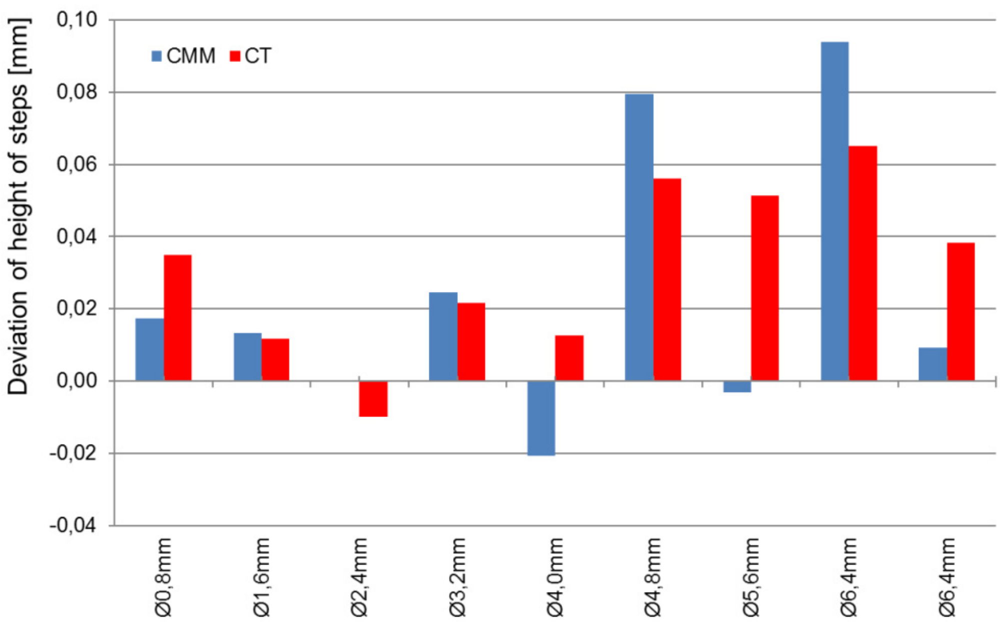

Fig. 27. Deviation of height of steps measured on CMM i CT.

4.4. Results of measurement plate with holes

CT measurement on plates with holes and its comparison with nominal data from the CAD file shows that during the manufacturing process the base element has become distorted (Fig. 28).

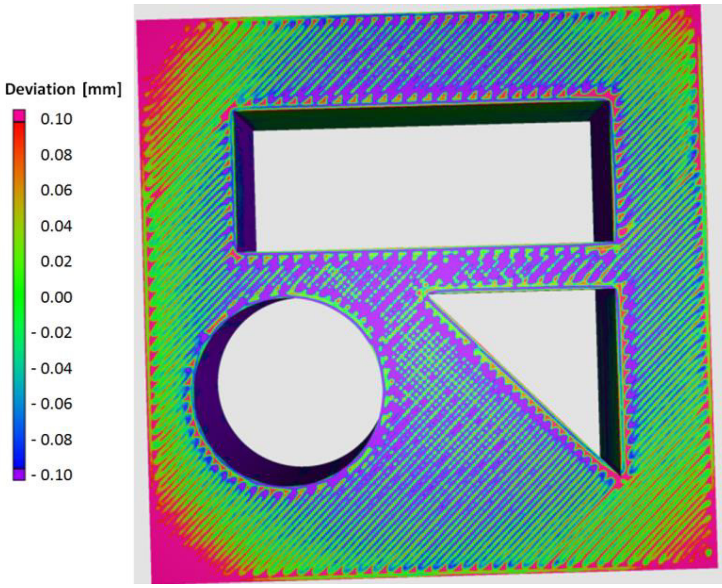

Fig. 28. The deformation of the bottom surface of the part.

This is the effect of thermal deformation resulting from long time cooling element on the edges. Watching the element "from the top" phenomenon is not visible (Fig. 29).

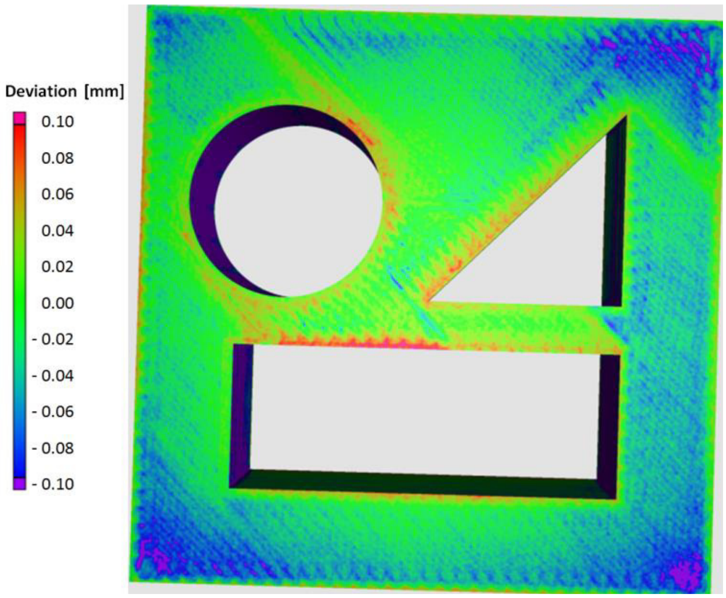

Fig. 29. The deformation of the top surface of the part.

Analysis of the histogram of deviation it can be concluded that the deviation between the actual component and nominal in the CAD does not exceed ± 0.3 mm, and a substantial majority of them in the range of ± 0.1 mm (Fig. 30).

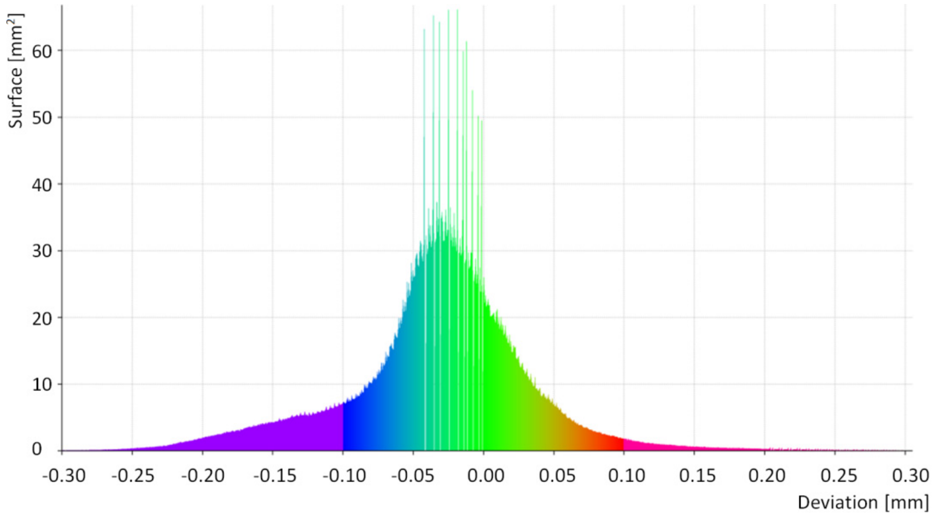

Fig. 30. Histogram of deviations of element with holes relative to the CAD model.

5. Conclusions

Computed tomography is a very useful tool for control and measurement. It allows to observe both the internal structure of the material as well as its individual layers. This is particularly important for applying printed part as functional elements and not only visualization of a model. Assessment of the internal structure of the element is very helpful especially for workpieces obtained with additive technologies, because it allows to evaluate and modify printing parameters in order to improve its properties and develope the process.

Results obtained from coordinate measuring machine and CT scanner show the convergence of measurement with these two methods. Differences arising mostly from the fact that using a CT scanner collected data represent whole element with much greater number of points. Therefore, whole picture of the element is also taken for the evaluation. In this way the system detects all deviations of the surface and its value are presented as positive and negative extremum. In contrast, results from the tactile measurement on coordinate measuring machine are automatically filtered which is implicated from the size of the measuring tip and the number of measurement points. Thus, the chance of catching the extremes is less, and this is the main cause of the differences between results from these two method. The reason for this phenomenon is also roughness of the surface, an effect of 3D printing. Its impact is much smaller in the image obtained from the CT scanner, and as already mentioned, measurement tip of CMM is a mechanical filter.

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