

New possibilities for *in situ* CT analysis of additive manufactured samples

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Abstract

Industrial Computed Tomography (CT) is a broadly used measurement method allowing for quality control of objects produced using additive manufacturing methods. The combination of tensile tests and simultaneous 3D imaging of the behavior of an object under a particular force (i.e. *in situ* examination – during the process) significantly broadens the possibilities of analyzing objects with a complex internal geometry. The purpose of this paper is to present the author's project of a mini testing machine, to verify its functioning with regards to a static testing machine, and to present the initial *in situ* examination results for polymer samples.

Keywords: industrial computed tomography, mechanical properties, polymers, additive manufacturing

1. Introduction

Industrial Computed Tomography (CT) is a broadly used measurement method allowing for the quality control of objects produced with additive manufacturing methods (Thompson, Maskery, Leach, 2016). The undoubted advantage of the method described in the paper is the possibility of carrying out non-destructive analysis of the internal and external geometry of examined objects with a resolution from a few to dozens of micrometers (Gapinski, Janicki, Marciniak-Podsadna, Jakubowicz, 2016). Apart from porosity analysis (Ziótkowski, Chlebus, Szymczyk, Kurzac, 2014), the detection of cracks, inclusions or discontinuity, and the dimensional control of manufactured geometry (Barciewicz, Ryniewicz, 2018), computed tomography is increasingly used in combination with tensile tests (Koruba, Karoluk, Ziótkowski, Chlebus, 2018; Mertens et al., 2017) or compression tests (Jansson, Pejryd, 2019; Dhillon, Schneider, Kuhn, 2011). Conducting such tests is possible with the use of mini testing machines that are specifically adjusted to work in CT measurement conditions (Hufenbach et al., 2012; De Chiffre et al., 2014). The combination of tensile tests and simultaneous 3D imaging of the behavior of an object under a particular force (i.e. *in situ* examination – during the process) significantly broadens the possibilities of analyzing objects with a complex internal geometry (i.e. scaffolds) (Pawlak et al., 2015; Szymczyk, Ziótkowski, Junka, Chlebus, 2018). Such a solution allows the development of individualized implants with a unique internal geometry. The implants can be adjusted to both a specific anatomical and physiological structure and to real loads caused by daily functioning. The purpose of this paper is to present the author's project of a mini testing machine, to verify its functioning with regards to a static testing machine, and to present the initial *in situ* examination results for polymer samples with a complex geometry which were manufactured using the FFF method (Fused Filament Fabrication).

2. Mini testing machine

The mini testing machine was designed in a way that allows it to be placed in the measuring chamber of a CT system, and for a full 3D reconstruction, including the 360° rotation of the object (Fig. 1a), to be conducted. The construction of the mini testing machine is characterized by its compact structure, low weight (up to 10 kg together with the examined object), and its module design that allows for measurements to be conducted with a high resolution.

The machine body in which the tested sample is placed and reconstructed is the main element that is exposed to the highest loads. Therefore, this part was made of a fiberglass composite – a material with good tensile features and relatively low X-ray absorption. Two rims made with stainless steel were joined to the tube using the molder-glued joint. The modular system which transfers compressive and tensile loads is developed in a way that it can be freely modified. Such modification depends on the size of the examined sample or the required CT resolution for the reconstruction.

The main element of the drive unit is the servomotor *S-1 FL6* (produced by *Siemens Company*) with the *SINAMICS V90* controller. This solution allows for precise regulation of the engine's rotational speed during variable load. Two worm gears were used in the drive unit, which allowed for the engine's axis orientation to be changed relative to the load screw of the lift. As a result, a firm and compact structure of the device was achieved, while at the same time maintaining the required working parameters. The mechanism used to generate tensile and compressive force is based on a screw mechanism with a movable cap, which is driven by an integrated worm gear. The testing machine allows for the conducting of examinations for samples with a diameter of 35 mm and a height determined by the resolution of the CT measurement. The range of loads is up to 5 kN, and the speed of force can increase from 0.01 mm/min to 30 mm/min.

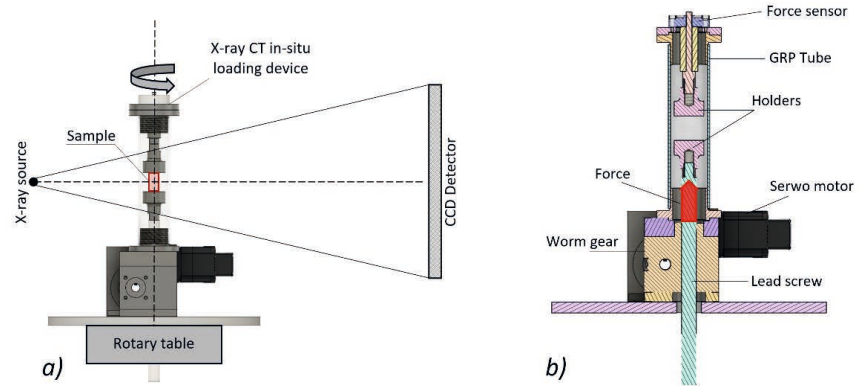


Fig. 1. Diagram of the measuring system
a) in situ loading device in the measuring
chamber of the CT system, b) cross-section
through an in situ loading device (by authors)

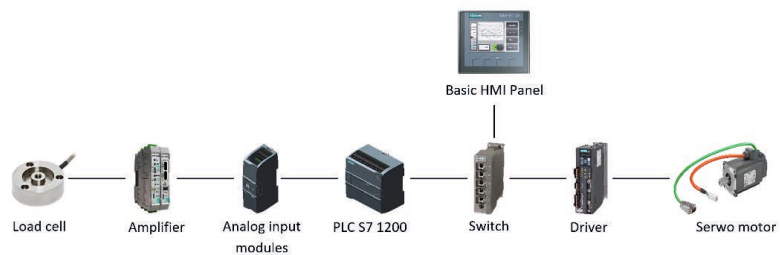


Fig. 2. Diagram of the mini testing machine's
control system (Alitech, 2019; Mall.industry.
siemens, 2019)

A force sensor produced by *Burster Company* (model 8524-6010 with a range of up to 10 kN) was used as the measurement element. This device is characterized by a non-linearity coefficient in the range below 0.25%. The strengthening and conversion of a signal's reading from the force sensor to the voltage (or current) standard was gained by using the *Burster model 9250 amplifier*.

As the control unit, a Siemens S7-1200 PLC controller expanded with a 13-bit analog I/O module was used. The mini testing machine is controlled by the operator's panel HMI (Fig. 2). All the elements described above are a part of the control unit and are connected according to the industrial standard *PROFINET*. Such a solution makes the communication of every device possible in an internal network.

3. Test samples

In order to evaluate the test results obtained with the use of the mini testing machine, verification tests were carried out on samples in the form of cylinders with a diameter of 15 mm and a height of 30 mm. The samples had linear filling (with 45° angle) on the level of 25% of the material's volume. Every sample had an external frame with a thickness of 0.4 mm, made as one contour of the printing head (Fig. 3).

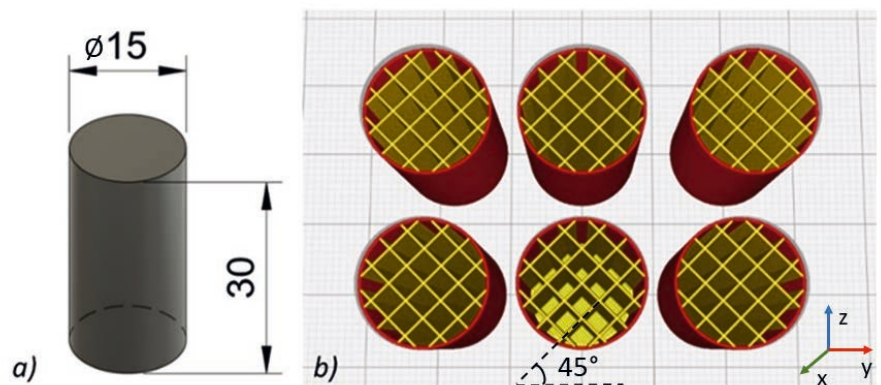


Fig. 3. a) Designed specimens for research,
b) Designed internal geometry with linear filling
at a 45° angle; external frame is marked in red,
linear filling is marked in yellow (by authors)

The shape and dimensions of the manufactured samples were developed according to the PN-EN ISO 604:2004 standard (Polski Komitet Normalizacyjny, 2006). The CAD models of the test samples were prepared using *Autodesk Fusion 360* software and then saved to STL format. Such a format enabled them to be loaded into the software, which in turn allowed executive files to be generated for the *Ultimaker 2+* device that works using FFF additive technology. To create the executive files, *Cura v. 4.00* software was used. All the samples were manufactured from thermoplastic material PLA (Pro 3D), in the form of filament, using the same parameters as for the manufacturing process (Tab. 1).

Table 1. Parameters used in the FFF process of the PLA samples

Working head temperature [°C]	Work platform temperature [°C]	Nozzle diameter [mm]	Layer height [mm]	Filament diameter [mm]
210	60	0.4	0.06	2.85

For the research described in this paper, 13 identical samples were produced. Twelve samples were used for the examination, which included a static compression test. For the CT reconstruction during the *in situ* static compression test using variable load values, one randomly chosen sample was taken.

4. Verification of the mini testing machine

To evaluate the examination results obtained with the use of the mini testing machine and to verify the correctness of the device, it was decided to conduct a comparative test in order to confirm that the measurement method is appropriate for the defined usage. The referential tests were carried out using the INSTRON 3384 testing machine. A measurement head, weighing 150 kN and with 0.5% of accuracy, and compression testing discs were used. During the tests, regardless of the device used, the samples were initially loaded with 100 N and the measurement was made at a speed of 0.5 mm/min. To compare the results given with the described methods and to determine the precision of the measurements, a variation coefficient RSD (relative standard deviation %) was used. The results of testing are presented as graphs that show the increasing force in relation to the displacement. Figure 4 shows an example of a compression curve given for each described device.

It can be seen that the shape and flow of both curves are similar. In addition, based on the conducted tests, it was revealed that the results from the mini testing machine correspond to the results from the commercial testing machine. The average value of the noticed load, which causes permanent deformation

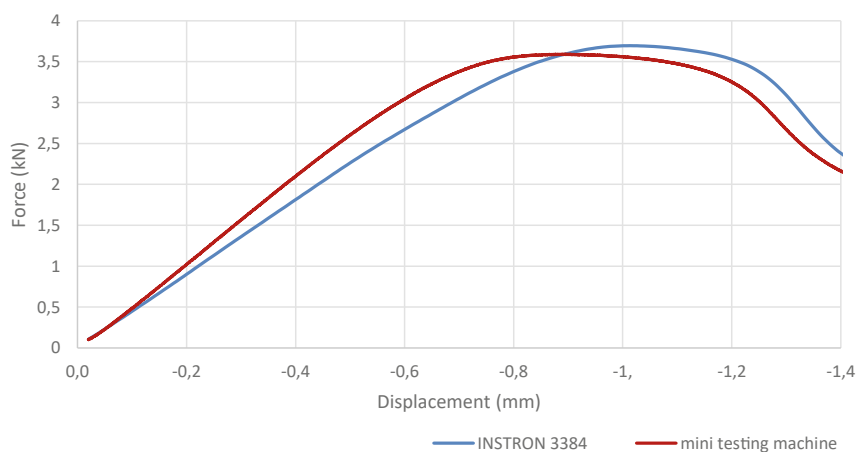


Fig. 4. Comparison of results obtained for loading samples from a) INSTRON 3384 testing machine, b) mini testing machine (by authors)

of the sample, is on the level of 3580 ± 141 N for the mini testing machine and 3645 ± 193 N for the INSTRON 3384. The repeatability of the method, which is presented by the RSD coefficient, is at the level of 3.9% for the mini testing machine and 5.3% for the commercial testing machine. The value gained for the author's device shows the high repeatability level of the test results.

5. *In situ* CT reconstructions

The mini testing machine was integrated with the tomographic system *METROTOM 1500* (Fig. 5a), which has an X-ray tube with a tungsten target, a maximum accelerating voltage of 225 kV and flat panel detector 1024 x 1024 pixels. The parameters used during the CT reconstruction are shown in Table 2. Five CT reconstructions were made for the load levels of 100 N, 2,500 N, 2,750 N, 3,000 N, and 2,900 N. Every reconstruction was done in the conditions of constant interaction of the determined force, without unloading the sample.

Table 2. CT measurement parameters used in the in situ reconstruction

Voltage [kV]	Current [μ A]	Int. Time [s]	Voxel size [μ m]	Projections	Filters Cu [mm]
220	120	2	39.68	900	0.5

Fig. 5. a) The in situ loading device integrated in the measuring system *METROTOM 1500*, b) the X-ray image obtained for a load of 100 N, c) the x-ray image obtained for a load of 2,900 N (by authors)

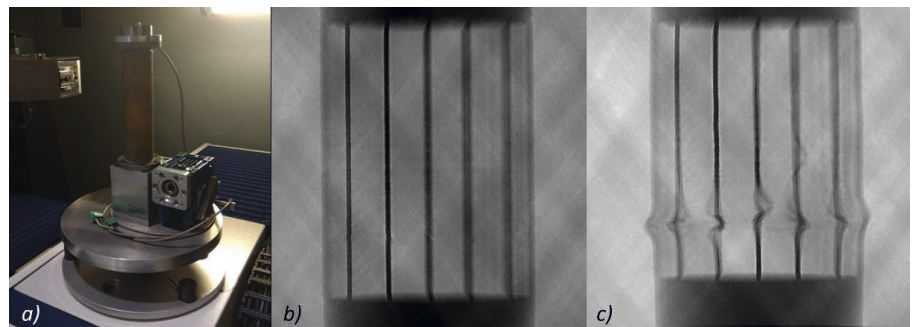
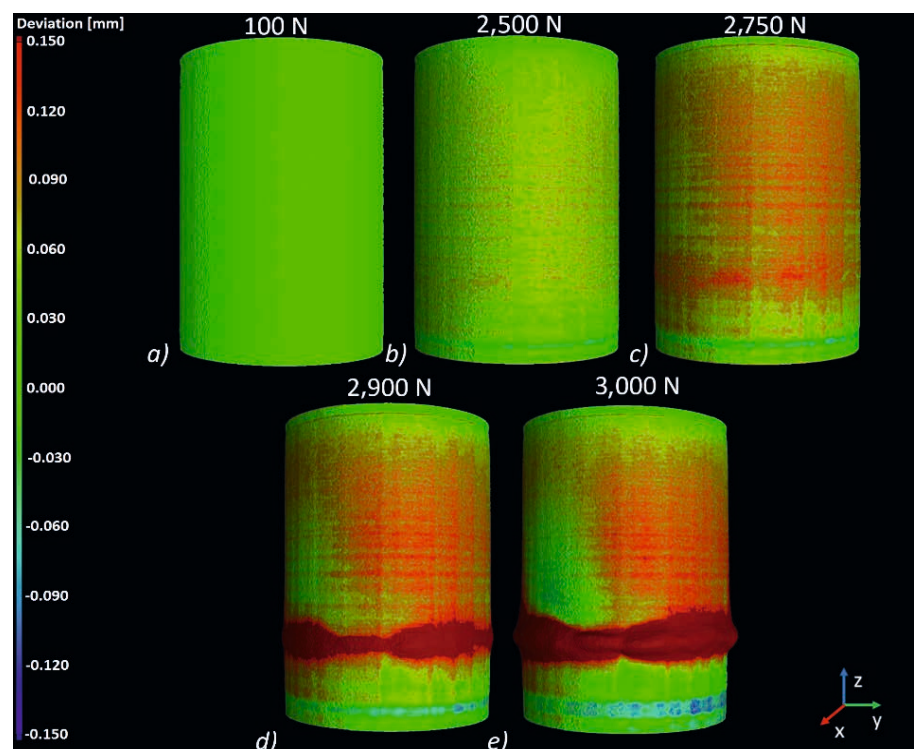


Fig. 6. Geometry deviations of the tested sample obtained for subsequent load levels (by authors)



Exemplary X-ray photos for the samples loaded with 100 N and 2,900 N are shown in Figure 5b and 5c.

The X-ray pictures show the condition of the sample and the deformation of its internal structure in a 2D cross-section, which enables the impact of the given force on the sample's internal geometry to be assessed. The quantitative evaluation may be done based on the comparison of the 3D volumetric models given in the CT reconstruction to different states of loading. Figure 6 shows, in the form of a color map, deviations in the geometry, which result from the sample being loaded with a force of 100 N (Fig 6a), and successively with a force ranging from 2,500 N to 3,000 N (Fig. 6b-e).

The force of 2,750 N caused the formation of geometric variables located in the bottom part of the sample. Further loading caused the enlargement of the deformation space and permanent deformation of the sample. The loaded sample had a lower level of durability than the samples described in point 4.

This phenomenon may be explained by the existence of heterogeneities in the material layer (red arrow no. 2) that was laid during the FFF manufacturing process. The material discontinuities that can be seen in Figure 7a reduce the mechanical properties of the analyzed structure, and are also the place where the largest deformations of the internal and external structure are concentrated. This can be seen in the following figures that show the 3D view of the internal geometry of the sample under the initial load (Fig. 7b) and during the maximal deformation (Fig. 7c). The geometry variables are shown as a map of colors. The changes for further levels of loading in the planes marked with red arrows in Figure 7 are shown as cross-sections in Figure 8.

The changes in the internal geometry of the analyzed sample, exposed during the *in situ* tests, allow for evaluation of the influence of the used loading

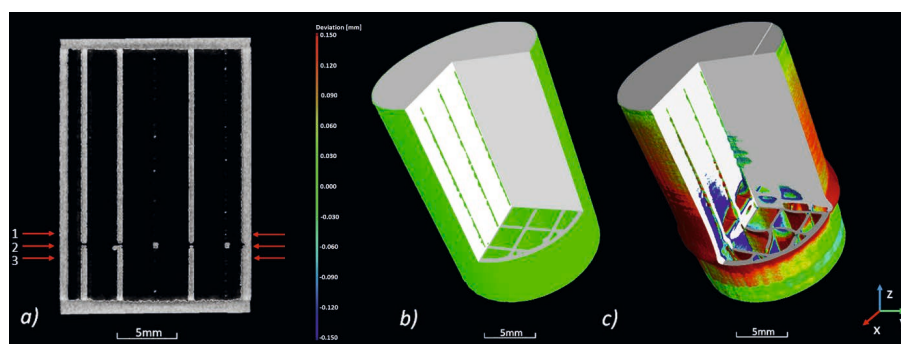


Fig. 7. a) Cross-section through the tested sample (defects appearing on one of the layers of the sample are marked with the red arrow no. 2, b) volumetric model obtained for a load of 100 N, c) volumetric model obtained for a load of 2,900 N (by authors)

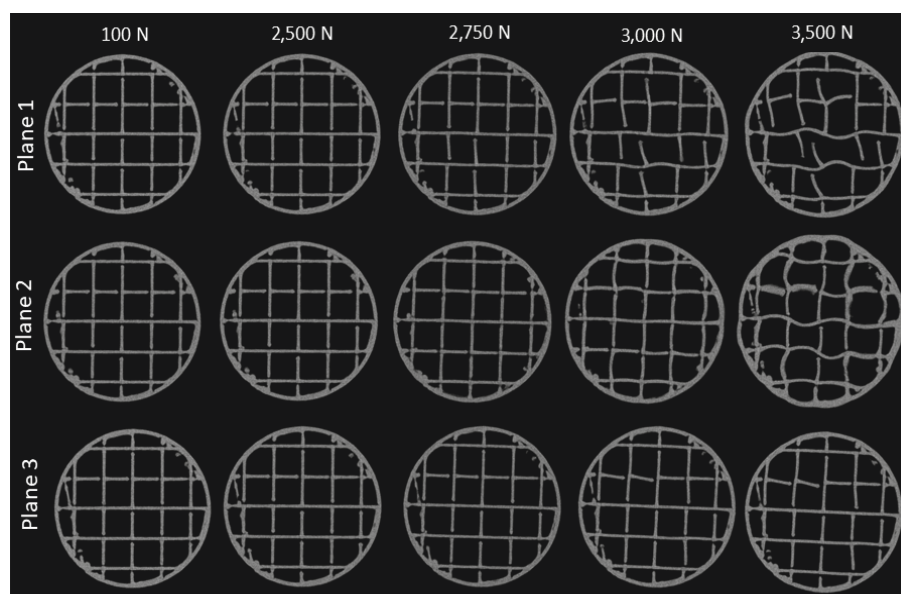


Fig. 8. Cross-sections (marked with red arrows in Fig. 7a) of the tested sample subjected to loads with different levels of forces (by authors)

on the functional features of complex structures. This kind of analysis enables the identification of areas that are particularly vulnerable to the formation of permanent deformations. Moreover, it gives the opportunity to optimize both the manufacturing process and the construction of the final product.

6. Conclusion

The device presented in this paper can be successfully implemented for *in situ* testing examinations when using technical computed tomography. The modular design of the mini testing machine allows the device to be adopted to different sample sizes or to a different types of tomographic systems. The following conclusions can be drawn:

Comparison of the test results obtained using a static compression test with those obtained using a commercial testing machine reveals a high level of convergence. Further development works on the mini testing machine will be connected with the enlargement of examination possibilities of mechanical tests, including a static tensile and bending test.

The preliminary research of the static *in situ* compression test for the sample made of thermoplastic material (PLA) described in this paper allowed the functional properties of spatial structures with a complex internal geometry to be evaluated.

The obtained results enable the behavior of a designed structure during loading to be fully characterized. This in turn may be a basis for optimizing the internal structure's geometry in order to adjust the construction to specific mechanical and functional requirements.

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Nowe możliwości analizy CT *in situ* próbek wytwarzanych metodą przyrostową

Abstrakt

Tomografia komputerowa (CT) jest obecnie powszechnie stosowaną metodą pomiarową pozwalającą na kontrolę jakości obiektów wytwarzanych z wykorzystaniem technologii przyrostowych. Połączenie badań wytrzymałościowych z jednoczesnym trójwymiarowym obrazowaniem zachowania się obiektu pod wpływem działania określonej siły (tzw. badania *in situ* – w procesie) znacznie rozszerza możliwość analizy obiektów o złożonej strukturze przestrzennej. Celem niniejszej pracy jest przedstawienie autorskiego projektu minimaszyny wytrzymałościowej oraz weryfikacja poprawności jej działania w odniesieniu do komercyjnych rozwiązań, a także przedstawienie wstępnych wyników badań *in situ* dla przestrzennych próbek polimerowych.

Słowa kluczowe: techniczna tomografia komputerowa, właściwości mechaniczne, polimery, wytwarzanie przyrostowe