



# On the Use of X-ray Computed Tomography in Assessment of 3D-Printed Components

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## Abstract

Technical advantages of additive manufacturing (AM) have drawn great attention over the past few years. This cost-effective manufacturing process proved its potential applications in a wide range of fields. Although AM techniques (known as 3D printing) are able to fabricate geometrically complex components, it is necessary to evaluate internal and external dimensions of the printed parts. In this context, x-ray computed tomography (CT) as a nondestructive evaluation technique has been utilized. Indeed, CT can be used for geometric analysis, defects detection, quantitative comparison, structural quantification and porosity analysis. In the current study, we present a brief review of 3D printing processes and evolution of CT technology. Moreover, applications of CT in assessment of 3D-printed components are explained in detail. Although CT has been used in academic and industrial researches, abilities of this inspection method are not yet fully documented for precision engineering applications. In this work, usage of this technique in study of printed components are categorized in four subdomains and discussed. The documented data proved that CT is an appropriate non-contact technique for technical evaluation of various printed parts. As usage of CT in assessment of printed parts is still evolving, the limitations, challenges and future perspective are outlined.

**Keywords** 3D printing · X-ray computed tomography · Manufacturing process · Geometric analysis

## 1 Introduction

Additive manufacturing (AM) is a manufacturing process with new capabilities that can solve design problem and optimize the fabrication process. AM (more colloquially: 3D printing) is a popular rapid prototyping process that has been significantly used in several applications area [1–5]. Although various manufacturing processes have been developed over the years [6–10], 3D printing technology proved its unique and favorable abilities in fabrication of geometrically complex components. 3D printing technology has progressed significantly in the recent years, but there are several production aspects which needed further investigations. For instance, invalid printing conditions and wrong processing parameters can lead to unwanted porosity. Moreover, mechanical properties can be changed, and residual stresses can leads to deformation. These issues are important

and complicated in 3D printing of the geometrically complex workpieces. Therefore, qualification of printing process and evaluation of 3D-printed components are necessary.

In evaluation of the manufacturing processes and fabricated parts, various techniques have been developed over the years [11–19]. In this context, destructive and nondestructive tests have been used to evaluate materials and components. Both destructive and non-destructive techniques can be utilized for assessment of 3D-printed parts [20–22]. Visual inspection, ultrasonic testing, eddy current testing and radiography are examples of nondestructive analysis techniques. Due to the simplicity, visual inspection is most widely used nondestructive technique which can be conducted quickly. Although human eye proved its capabilities in visual inspection [23], advanced techniques and equipment are required for a more accurate visual inspection. In this regard, x-ray computed tomography (x-ray CT or simply CT) has been utilized as a nondestructive technique in different fields. For instance, CT was used in medicine [24], fracture of rock-like material [25], bubble detection [26], geometrical verification [27], quantification of damage [28], material science [29] and wear measurement [30]. Different engineering aspects

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have been studied in the field of 3D printing technology over the years [31–37], and technical evaluation of the printed parts is a crucial issue. Currently, there are several methods for assessment of the fabricated components, but 3D-printed complex parts can be examined with a few techniques. In this context, CT presented some benefits compared to traditional techniques. In detail, CT provides three dimensional evaluation of defects inside of the structure at one process [38]. CT as a nondestructive technique, has important application in finite element method (FEM). In [39] experimental tests were performed and finite element simulation was conducted to evaluate defects in 3D-printed parts. In fact, CT is beneficial and can be used to validate the results obtained by FEM. Additionally, CT as an image-based evaluation method is favorable in determining data about internal defects which is beneficial in study of cracks and cavities. More in deep, CT can be used for porosity evaluation, dimensional analysis, characterization of the structure and investigations on the surface roughness. In experimental evaluation, the specimen is subjected to x-ray from many angles by rotating through many small angular increments. Reconstruction of algorithm yield a sequence of 2D gray level image. These images can be computationally stacked to yield a 3D view of specimen which has typical size of  $1000 \times 1000 \times 1000$  voxels. The voxel size is equal to the pixel size by the slice thickness. If each voxel is a 2-byte integer, it gives a 2 Gbyte data size for the image stack. Prior to the scanning, background normalization is required which can be obtained by removing the sample and utilizing the x-ray beam at the selected settings to correct all intensity variations across the detector.

As CT is a powerful technique, a comprehensive information about its capabilities and performed researches, can shed light on the current challenges. An extant study [40] presented an overview of industrial applications of CT. Previous studies have proved that applications of CT in 3D printing technology is accepted. For instance, in [41] development of CT and its applications in 3D printing were explained. In this respect, quality control via dimensional measurement and porosity inspection by means of CT was discussed. Later, in [42] applications of micro CT in 3D printing was presented. In this context, several examples are shown and described utilized micro CT in evaluation of 3D-printed components. Additionally, the researchers suggested some scan strategies for different analyses. In work [43] usage of micro CT in biomimetic research was reviewed. Based on the reviewed studies, it was concluded that the use of micro CT in biomaterials research has a large potential. More recently, in [44] role of CT in detection of defects in 3D-printed metal was investigated. To this aim, applications of CT were discussed and effect of defect in casting and fatigue properties were explained. Moreover, role of CT in property prediction was outlined.

The evaluation of 3D-printed parts is not without its own challenges. At first, a suitable method for this evaluation must be selected. Secondly, several parameters such as cost, time and expertise should be considered. Although CT has been used for assessment of the printed parts, a profound knowledge of its capabilities is needed for further development. However, based on the performed studies it is concluded that there is a significant interest and growth in use of CT for examining 3D-printed components.

This work presents details of utilizing CT in evaluation of 3D-printed parts. Indeed, it was aimed to discuss different applications of CT in assessment of the printed components. In this context, we categorized these applications into four subdomains: (a) defect analysis, (b) dimensional evaluation, (c) density measurement, and (d) surface roughness analysis. These applications are explained in detail. Following this introduction, an overview of AM techniques is presented. In Sect. 3 basics of CT are explained. Applications of CT in assessment of 3D-printed components is discussed in Sect. 4. In Sect. 5 challenges and limitations of CT in AM are outlined. Lastly, Sect. 6 presents the conclusions.

## 2 Overview of 3D printing techniques

Owing to the various demands, different manufacturing processes have been developed over the years. 3D printing is a technology that was developed in the 1980s and has been considered as the third industrial revolution [45]. American Society for Testing Materials (ASTM) classified 3D printing techniques into seven categories [46]: binder jetting, material extrusion, directed energy deposition, material jetting, sheet lamination, powder bed fusion, and vat photopolymerization. In Fig. 1 these techniques are schematically shown. Most of the 3D printing techniques, are based on the layer upon layer process, from 3D model data. The novel engineering fabrication process in AM, confirmed some advantages of this manufacturing processes, such as reduction in environmental impacts, and savings in costs and time compared to traditional processes [47].

- **Binder jetting (BJ):** in this process, a binder is deposited onto the powder bed, and bonded layers of material make the desired part. Bonding at room temperature is one of the advantages of binder jetting compared to other 3D printing techniques.
- **Material extrusion (ME):** thermoplastic materials are used in material extrusion to print the components. In this technique, the raw material is heated and molten material coming out of the nozzle. The part can be created layer by layer via movements of the nozzle. Fused deposition modeling (FDM) is an example of this 3D printing process.

- **Directed energy deposition (DED):** in this technique, a focused energy source melting the raw material. After deposition of the first layer, the nozzle and the energy source are moved and continue the process by making the next layer. This method is one of the most common techniques for metal additive manufacturing.
- **Material jetting (MJ):** in this accurate 3D printing technology, firstly the raw material should be heated to reach the desired viscosity. Then, print heads moves and begin printing. The ultraviolet light source can cure the sprayed photopolymer resin. This process should be repeated until last layer of the part.
- **Sheet lamination (SL):** in this method, layers of metal laminate, plastic, or paper are bonded via adhesive or utilizing ultrasonic welding. The precision of the printed part depends to the thickness of layer. The sheet lamination can be utilized to produce colored components in a high resolution.
- **Powder bed fusion (PBF):** in this class of 3D printing process, fusion between powder particles is made via a thermal source. Similar to other 3D printing techniques, the desired part is fabricated layer by layer in powder bed fusion method. The selective laser melting (SLM) and selective laser sintering (SLS) are placed in this 3D printing process.
- **Vat photopolymerization (VP):** in this technique, a liquid photopolymer resin is utilized which can change to solid once it presented to a light. In this context, ultraviolet light is commonly used to harden the utilized resin. The parts fabricated by this method have high level of accuracy. Stereolithography (SLA) is a subdomain of vat photopolymerization technique. In Table 1 different materials used in 3D printing techniques and common layer heights in different processes are summarized.

Although 3D printing techniques have been used for fabrication of different components, there are several limitations and challenges which need further research in this field. In Table 2 main advantages and disadvantages of 3D printing process are briefly presented. However, there is still lack of standards and suitable metrics for mechanical characterization and quality control of the 3D printed parts.

### 3 Basics of x-ray computed tomography

Different destructive and nondestructive techniques have been developed over the past decades to examine structural components and parts [48]. Optical investigations, real time radiography, ultrasonic techniques, eddy current testing, and x-ray computed tomography are examples of the developed techniques. In Fig. 2 the nondestructive tests are classified according to the detectable defect location and geometrical

complexity. These methods are currently used in investigation of various materials such as plastics and metals based on their relevant protocol and standard.

Classical tomography was introduced in the last century, and later CT was developed due to the appearance of modern computers and advances in electronics. Indeed, medical applications of CT back to the early 1970s, but it was utilized as nondestructive technique in the early 1980s. The full history of CT development is presented in [49].

CT is defined as method of 3D representation of a component which indicates internal details of the parts. In CT, the representation of the component is performed via many x-ray images. These images were taken form around an axis of rotation. In Fig. 3 the process of CT is schematically shown. This schematic illustrates the most typical industrial CT setup, with x-ray source, a rotating test stand, a specimen, a detector, and capturing software. In practice, after the scanning, the data must be processed and analyzed via an appropriate software. It should be noted that, the spatial resolution can be changed by differences in distance of the specimen between the detector and the source. There differences between industrial and medical CT. For example, in medical CT the detector and x-ray source moved around the sample, while in industrial CT they are fixed around a rotating specimen. Moreover, industrial CT is more flexible and can be modified to use for various materials.

There are three main methods of CT which have been developed over the years: (a) pencil, (b) fan, and (c) cone beam methods [50]. In detail, the first CT method uses a pencil beam of x-rays translated linearly opposite an x-ray detector in order to capture density data along each beam. In the second method, a two-dimensional fan of x-ray has been used with a one-dimensional detector array that corresponds to the outer edges of the fan beam. The last techniques, uses a full 3D cone of x-rays with a two-dimensional detector. In utilizing CT technique, contrast of the image and the resolution are the primary subjects. Industrial CT systems are basically classified into macro, micro, and nano CT. This classification is based on the focal spot size. For instance, a micro CT system uses x-ray tubes with focal spots in the range of micrometer. Indeed, for a high quality micro CT, parts should be in the range of 10–100 mm (voxel sizes 10–100  $\mu\text{m}$ ). In a nano CT, system have x-ray tubes with focal spots less than 1 nm that is appropriate for scanning small objects. Use of CT scan indicated several advantages. Examination of inner and outer geometry at one process and short scanning time, are examples of these advantages. However, problem can occur on scanning multiple materials within one component.

Data processing is an important step in utilizing CT scan. The modern computers equipped with data analysis software are needed for visualization and analysis of large image data sets. Although there are some open source software for image analysis, advanced features of high-tech software showed

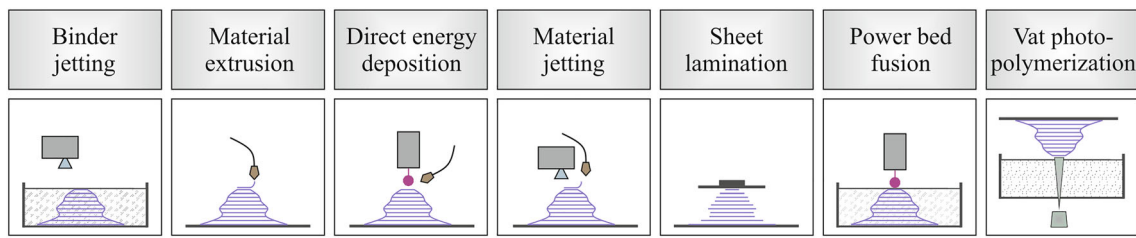


Fig. 1 Classification of 3D printing technology

Table 1 Additive manufacturing processes and relevant specifications

Parameters	BJ	ME	DED	MJ	SL	PBF	VP
Materials	Metals Plastics Ceramics	Glass Ceramics Thermoplastic	Metal Tool steels Super alloys	Waxes Polymers	Paper Plastics	Steel Titanium Aluminum	Resins Plastics Polymers
Layer thickness (mm)	0.1	0.05–0.5	0.2–1	0.016–0.03	0.05–1	0.01–0.1	0.05–0.15

Table 2 Advantages and disadvantages in different 3D printing techniques

Theme	BJ	ME	DED	MJ	SL	PBF	VP
Advantages	Low cost Colorful printing	Low cost Multi material	High speed High durability	Low waste High speed	Low cost Multi material	Low cost Multi material	High speed High resolution
Disadvantages	Low strength Post-processing	Rough surface Low resolution	Post-processing—Poor surface	Post-processing—Design limits	Post-processing Support structure	Low speed Size limitation	Fragility of parts Support structure

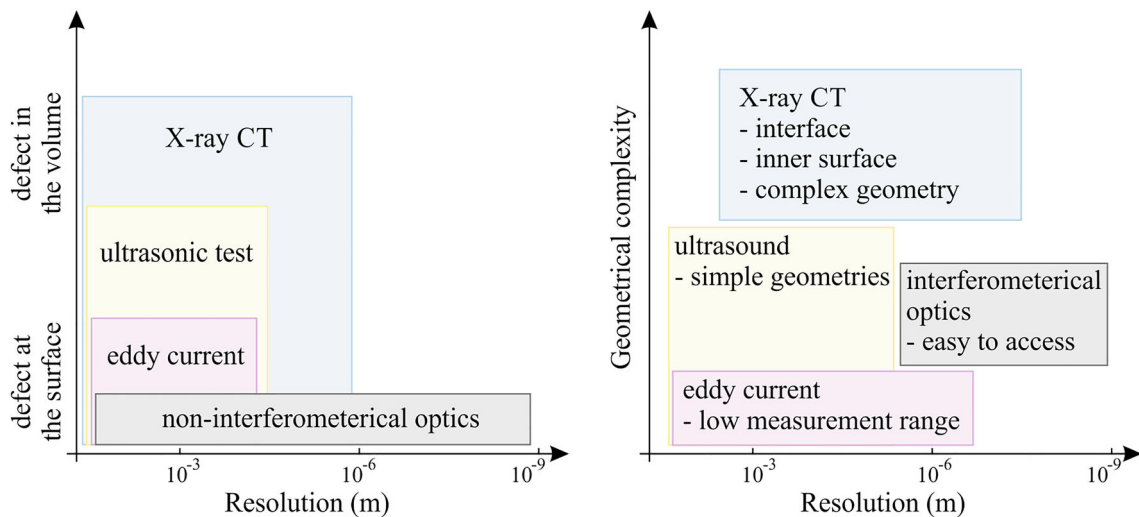


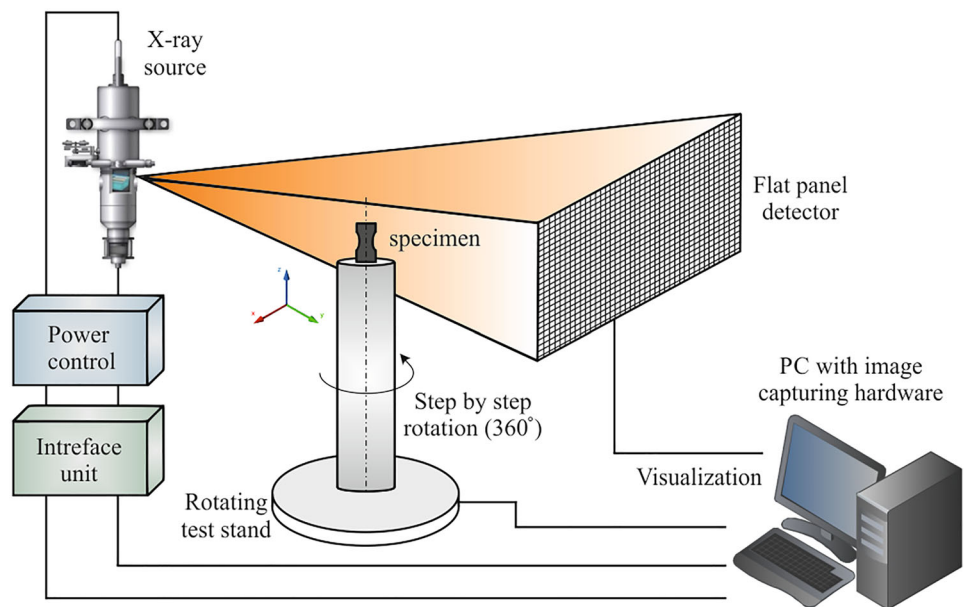
Fig. 2 Classification of nondestructive techniques according to: defect location (left), and geometrical complexity (right)

some advantages. It should be noted that a profound knowledge and guidelines are required for a high quality scanning.

As CT is a robust nondestructive tool, it has been employed for various academic and industrial projects. Its academic applications cover several sub-domains of engineering and medical sciences. These applications are summarized in [51].

In the following section, applications of CT in investigations of 3D printed parts are discussed in detail.

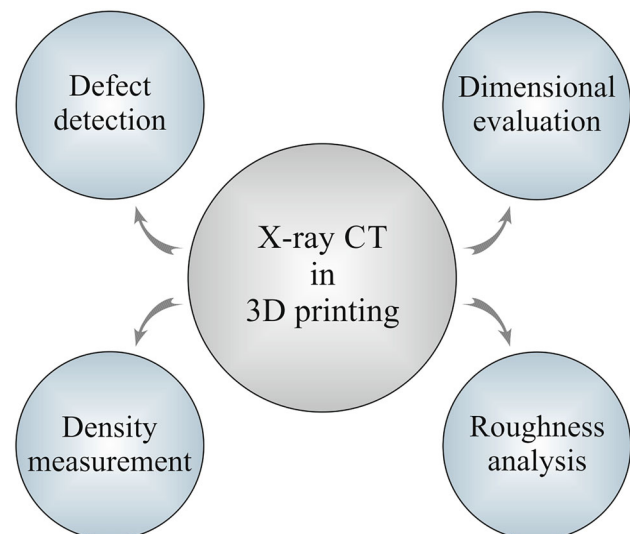
**Fig. 3** A schematic set-up of a x-ray computed tomography in industrial application



#### 4 X-ray computed tomography in 3D printing

Various measurement technologies and instruments have been developed over the years [52–58]. As 3D printing technology has attracted a lot of attention recently, demands on evaluation and control of the printed parts are continuously increased. In [59] 3D printing technology and CT were used together for a reverse engineering to fabricate a model of cranial bony anatomy. After this first usage of CT in 3D printing, it has been used for various purposes in this process. However, the early use of CT in 3D printing was for a medical modeling [60]. In 1999, the first industrial application of CT was reported in the automotive industry [61]. Figure 4 shows the main industrial applications of CT in 3D printing which are considered for review here.

In several research studies [62–65] CT is considered as an invention which has been continuously developed. CT is a suitable method to achieve detailed information about the components in 3D. It is noteworthy that using CT for in-situ x-ray imaging of 3D printing process is an ongoing research topic. For instance, in [66] in-situ x-ray imaging in laser additive manufacturing has been presented. At the same time, design and implementation of a laboratory scale instrumented is documented which can optimize in situ x-ray experiments in laser powder bed fusion [67]. Later, in [68] in-situ high-speed imaging of the powder-blown AM process is reported. The documented data can be used to understand physical phenomena during interaction of laser beam and powder-blown deposition. Additionally, data obtained from in-situ high-speed x-ray imaging is beneficial to determine effect of process parameters on powder flow. In the cur-

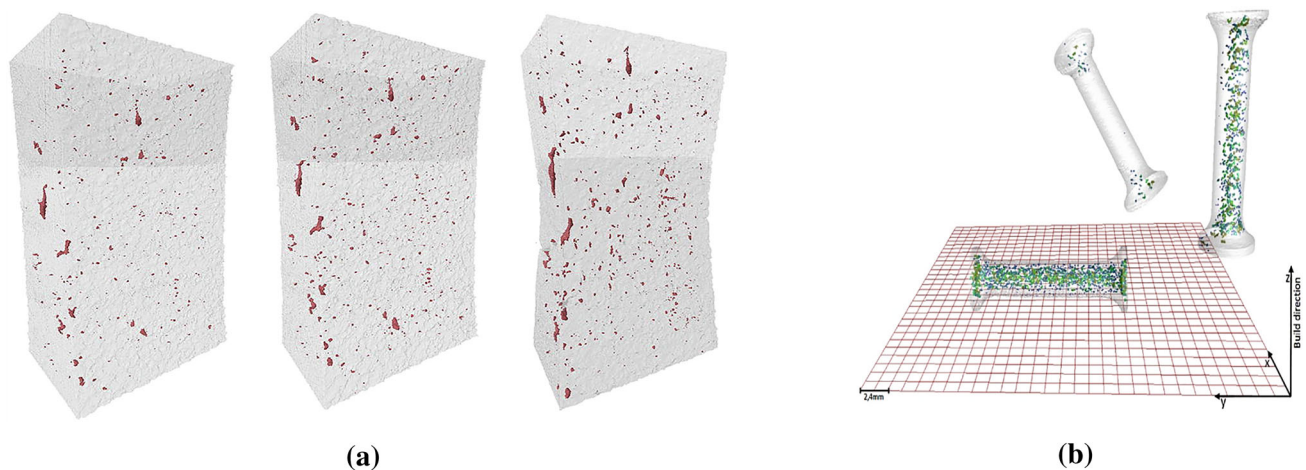


**Fig. 4** Applications of CT in 3D printing technology

rent study, we classified the technical data obtained from CT into four groups and review applications of the CT in these domains.

##### 4.1 Defect detection

Although attempts have been done to fabricate the components without defect, different types of defects have been characterized during manufacturing process and service life [69–73]. For instance, in [73] CT analysis was performed to investigate evolution of pores during deformation of aluminum alloy produced by SLM. In Fig. 5a CT models of the specimen before deformation at three different strain



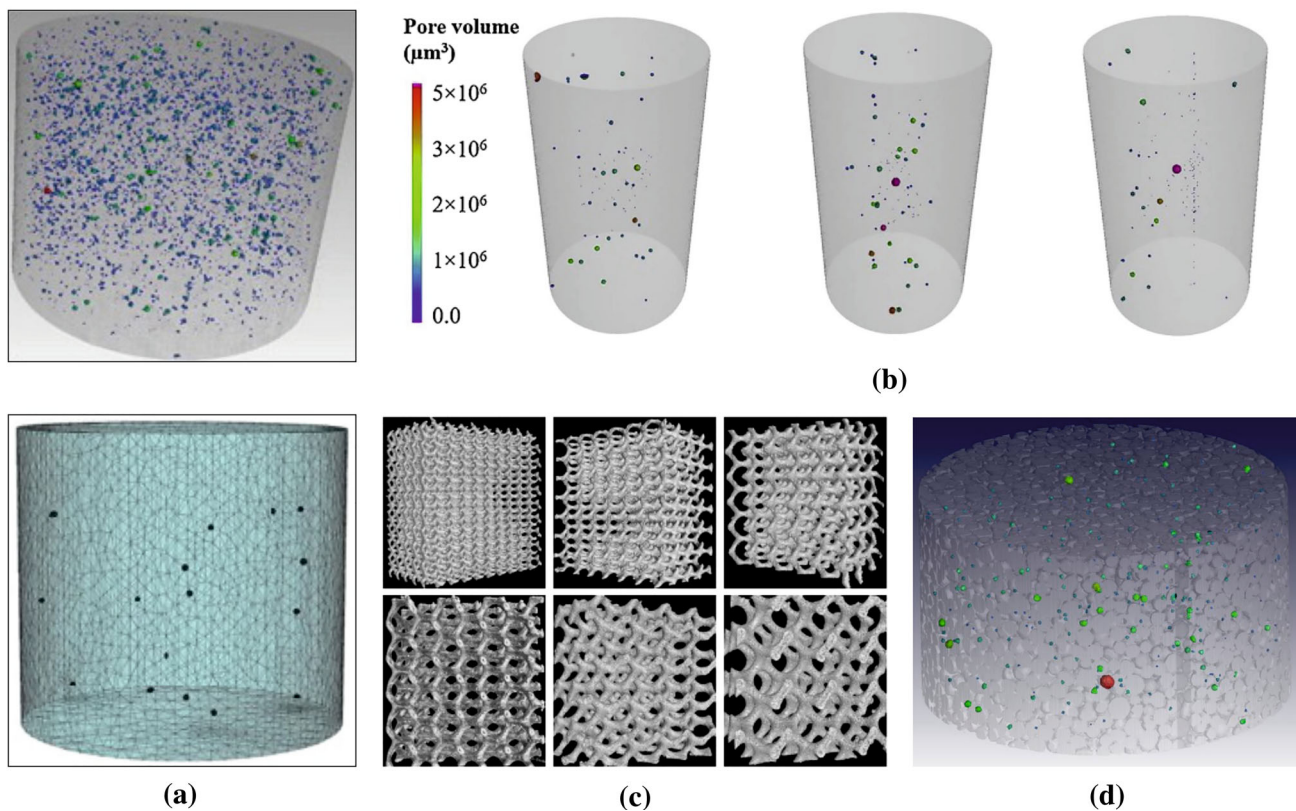
**Fig. 5** **a** CT models of specimens at different steps of strain [73], and **b** porosity of the printed specimens in XYZ coordinate system [85]

levels are illustrated. Despite several advantages and technological improvements of 3D printing technology, different defects are reported in the printed parts which can change the mechanical behavior of the parts [74–78]. Investigation on defect layer and quality assessment of a 3D-printed component are important issues, because the achieved data can be used in failure simulation to improve the future fabrications. In this context, CT scans play an important role in study of the defects and pores. However, pores can be made by several not optimized process parameters [79]. In powder-based 3D printing processes, several types of defects are related to the powder properties. For instance, the particle size distribution and humidity have effect on homogeneity and performance of the printed part. Here, we considered pore as an internal defect which brings local stress concentration and it can be detected by CT. The CT number of each point or pixel is a function of the average density and composition of the material in a given volume or voxel. In measurement of pores, CT can be utilized at voxel size down to tens of nanometers. If voxel sizes of the order of micrometers are required, this limits the size of the sample which can be used. As high quality images are required for inclusion analysis in 3D-printed parts, a long scan time is required. The optimal resolution is a factor of 1000 smaller than the width of the sample. The pore size limit for CT detection can be set before characterization based on the scanning resolution. Indeed, pore size has been limited by CT resolution and the pores with a diameter of the order of one voxel or less cannot be detected.

In [80] CT was used for pore measurement to determine the differences between the designed and printed structure. At the same time, in [81] pore size in cellular titanium was determined via CT at a resolution of 10  $\mu\text{m}$ . It was documented that the pore size can be affected by scaling of the computer-aided design (CAD) model. Later, in [82] and [83] the same researchers employed CT to determine porosity

of 3D printed scaffolds. In the subsequent year, porosity of 3D printed titanium alloy was reported [84]. In detail, the researchers printed the specimens based on SLM process, and used CT at a resolution of 22  $\mu\text{m}$ . Consequently, it was reported that pores within the specimens have a significant role on the fatigue behavior of printed specimens. Moreover, it was claimed that reduction of the porosity can improve fatigue strength. Next experiments were performed to detect orientation, size and shape of pores in 3D printed steel parts [85]. In Fig. 5b three-dimensional porosity of the printed specimens based on their position on the SLM machine is illustrated.

Since investigation can be performed from raw material to the finished part, CT can be used for evaluation of raw material [86]. In [87] defects and detection methods in powder-based additive manufacturing were reviewed. In several studies [88–91] researchers used CT for pore measurement in polymeric parts printed via SLS technique. The results indicated that the findings are different compared to examined metallic printed parts. For instance, in [88] porosity of sintered parts was measured by different methods (Archimedes, gas pycnometer and CT). Consequently, it was documented that higher closed porosity was obtained by Archimedes method. Later, in [92] and [93] the researchers used CT to investigate porosity and determine fatigue performance of SLM printed parts. In more recent work on this topic, CT was used to determine porosity distribution on 3D printed titanium alloys before and after fatigue tests [94]. In Fig. 6 three-dimensional reconstructed models for porosity measurement in different studies are presented. It is noteworthy that large components suffer from x-ray penetration problem, which has effect on the image quality. For large-size parts, penetration of x-ray is a crucial issue and high scan voltage is required. It is especially true for the parts larger than 100 mm. Increase in the size of the part has influence on



**Fig. 6** Applications of CT in porosity measurement: **a** image from CT (top) and meshed model (bottom) [87], **b** CT images which show porosity size and distribution in 3D printed titanium alloys before fatigue test [94], **c** reconstruction of lattice structures [95], and **d** porosity analysis of metal powders [96]

resolution of the image. Moreover, high density materials are more difficult to evaluate compared to low density materials due to the lower x-ray penetration (Fig. 7).

In 3D printing of a component, homogeneity of the layer can be affected by irregularity in the previous printed layer, which can form a void in the final product. Indeed, high porosity in a specimen can be observed in in-homogeneous powder layer. In order to recognize metallurgical pores and voids smaller than  $100\ \mu\text{m}$  in the printed parts based on laser powder bed fusion process, a high laser power and a low scanning speed are needed [97]. However, porosity testing via CT is accepted as an evaluation method for quality assessment of 3D printed parts [98–100].

In several studies, researchers used CT for defect analysis in 3D printed parts [101–105]. In [101] defects in printed titanium parts were detected and effect of build direction on the defects was discussed. At the same time in [102] and [103] the researchers utilized CT for investigations on 3D printed titanium components. More in deep, in [102] pore distribution was examined and crack formation as a result of pores was investigated.

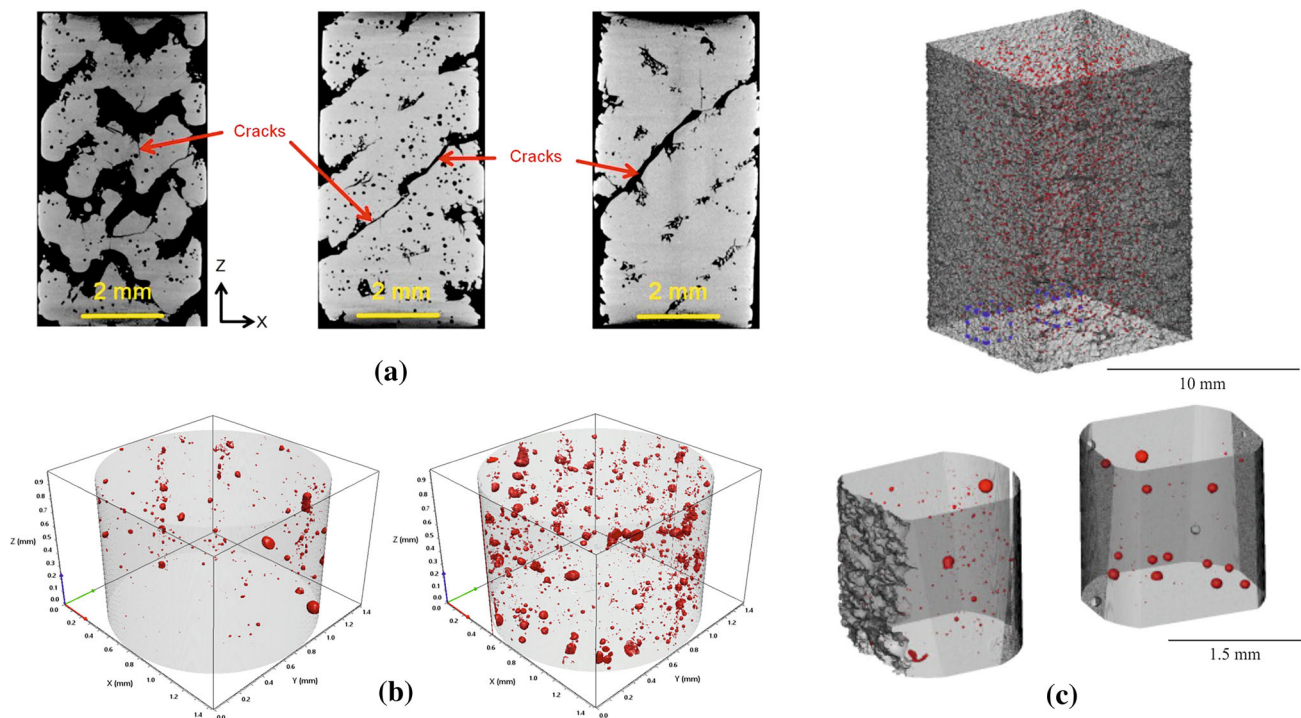
In [103] the effect of porosity on the processes parameter was discussed, and optimization process was presented. The

documented results in different studies proved benefits of CT compared to other methods. Capability of CT in providing information about the internal geometry of complex parts at one process is one of the advantages. Moreover, visualization of different defects and unexpected porosity within the components is another ability of.

CT in evaluation of 3D printed parts. This defect detection can be used in optimization of processing parameters.

## 4.2 Dimensional evaluation

Initially, 3D printing technology was utilized for prototyping, but currently it is being used in rapid manufacturing of final products [106]. Hence, dimensions and applicable tolerances of the produced parts must be checked. Literature investigation showed that use of CT as a tool for dimensional measurement was increased in the last decade. Dimensional measurements can be divided to several major categories: (a) linear measurements, (b) analysis of wall thickness, and (c) comparison of CAD model and printed part. However, several parameters can cause difference in geometrical characterization between the desired model and the real dimensions in the finished product. As an example,



**Fig. 7** Applications of CT in defect analysis: **a** CT images of the printed parts based on SLM method after compression test [102], **b** printed cylinder under different laser power during printing process [105], and

**c** CT images of titanium alloys with different voxel sizes [103]. The defects are illustrated with red ellipsoids

we mention here that single scan and rescan present unequal dimensions.

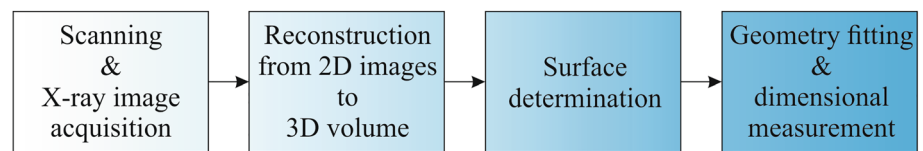
As performance of the 3D printed structures can be influenced by dimensional errors, dimensional evaluation via CT found an important role in this aspect. In the paper by Fukuda et al. [107] CT was utilized in measuring of the channel dimensions for study of bone ingrowth. Similarly in [108] the evaluation of lattice structure was performed via CT as a dimensional measurement equipment. At the same time, in [109] the researchers used CT to evaluate implant and the titanium bone scaffolds. As lattice structures are used in lightweight design, they are extensively used in 3D printed components. Abilities of CT in dimensional measurements of this type of structure is a crucial issue which leads to optimization. In [110] applications of CT in dimensional measurement of bone structures was reported. After this successful study, applications of CT in dimensional evaluation of lattice structure was started. An extant study [111] presents usage of CT in measurement of 3D printed lattice structure. At the same time, in [112–114] different printing processes have been used to fabricate metallic lattice structures. As there are thin struts in the lattice structures, problems with unmelted material can be occurred. In this regard, color coding in CT can represent thickness at each point and provide a better assessment.

In utilizing CT for dimensional evaluation, a 3D images of interior and exterior of the component are generated. Also, a precise surface determination algorithm can be used to extract the component's surfaces from the reconstructed volume. Finally, CT presents dimensional results. In Fig. 8 dimensional measurement in a flowchart of CT analysis is shown. In dimensional evaluation of 3D printed parts, a high quality scan and a calibrated system are needed. This issue is reviewed and discussed in [115]. Based on the demands, temperature stabilized CT systems have been presented. These devices are equipped with a high-tech calibration system which is used before each scan to reach a high accuracy. In a paper by Kruth et al. [116] application of CT in dimensional metrology was discussed. In this context, authors reported that measurement uncertainty and traceability are important issues in this field. However, similar to other technical equipment, accuracy of CT is a crucial issue as discussed in [117].

Uncertainty in CT measurements comes from different sources. Therefore, calculating the total uncertainty of CT measurement is difficult, as CT systems are multi-purposes devices. Regarding to the particular usage of CT, x-ray source setting, material, specimen geometry, orientation, detector, measurement strategy, and evaluation algorithms play crucial roles. Although CT is able to obtain internal dimensions of the printed parts which are not achievable by coordinate



**Fig. 8** A flowchart of CT process containing dimensional measurement, adopted from [121]



measuring machines, in dimensional measurement optimization of parameters is needed. It requires more than one hour for scan of a part and the similar time is needed for analysis of each part. It allows a part-to-part and also part-to-CAD comparison and shows dimensional deviations. Additionally, this high quality dimensional measurement can be used for in reverse engineering. In this context, the reconstructed model must be converted to an STL file that can be used in 3D printing technology. In [118] and [119] CT and 3D printing were used to perform reverse engineering. In detail, in [118] data from CT were transferred to a 3D printer to produce a historical wind instruments. To this aim, different parameters were optimized to reach a higher quality in fabrication of a copy of antique model. This application of CT in reverse engineering proved high accuracy of this technique in fabrication of musical instrument. Later, in [120] comparison of CT dimensional measurement was discussed. In this context, a good repeatability was reported.

### 4.3 Density measurement

Measurement of density is necessary in both raw materials and final products. In this context, different techniques have been developed over the years. In evaluation of 3D printed components, density is considered as a quality parameter that should be measured. There are several methods of density measurement which used Archimedes' principle. Although density measurement of 3D printed parts via Archimedes test is not technically complicated, it has some disadvantages. For instance, air voids can attach to the printed surface. This leads to a larger volume measurement and lower density measurement. Moreover, water penetration to the channels and cracks on the surface of the printed parts leads to a smaller volume measurement and higher density.

In [122] there different methods for density measurement of 3D printed metallic parts, were compared: (a) Archimedes method, (b) micrograph of a cross-section, and (c) x-ray scanning. Consequently, it was reported that three dimensional arrangement of pores can be illustrated via x-ray scanning which leads to an accurate density measurement and it is an advantage of this technique. There is a possibility to use CT for accurate measurement of the entire part volume, and it can be combined with the mass to determine the volumetric density. The above-mentioned problems with air voids can be solved by measurement of volume via CT. In this context, the scan resolution has an important role in the accuracy of

the volumetric evaluation. It should be noted that a low resolution scanning can be performed in density measurement, if there is an access to the calibrated density specimens. In this case, the same material with different densities (containing expected density of the unknown specimen) is needed which. In this regard, we refer to [123] where CT and calibrated polymeric specimen were utilized for density measurement.

An extant study [124] presents details of experimental tests on the printed stainless steel was described. In this regard, CT and scanning electron microscope were used. Based on the reported results, fracture mechanisms is highly affected by the porosity, compared to the bulk density. Later, in [125] presents different scan strategies in density measurement of 3D-printed parts. In this context, single scan and double scan strategies were proposed and tested. Consequently, it was reported that the double scan strategy provides improvement in the density measurement of the printed parts. Since the bulk density of material is often known, by the measured density we can determine the porosity. As density of the metal is usually well known, it is possible to translate the achieved density into a porosity. In the case of polymer components, their densities commonly dependent on the polymer microstructure. Indeed, the bulk density of 3D printing polymers is often not well known, because processing of the component has a crucial impact on the microstructure.

Considering benefits of CT, more applications of this technique in density measurement of various 3D printed structural elements is expected. This density measurement significantly helps the designers to optimize the parts and provide denser components. In [126], medical and industrial CT are compared. It has been reported that utilizing CT for measurement in lower density components such as glass fibers, wood products, and light metal alloys showed improved quality of the results compared to the medical scans.

### 4.4 Surface roughness analysis

The surface characterization is an important issue, because the contact area depends to the surface properties. Moreover, the solid surface contains different zones which indicate some properties of material and process. Although several traditional methods (e.g., optical profilometers and contact type instruments) have been widely used for surface roughness analysis of different parts, these equipment can be used only for analysis of the exterior surfaces. As 3D printing technology has been utilized for fabrication of geometrically

complex components, internal surfaces of the printed parts must be investigated to ensure safety features. To this aim, CT has been used in different researches. Indeed, surface roughness analysis of 3D printed components is a relatively new ability. Based on the published results in [127] and [128] in the CT images, the line profiles is related to surface roughness of complex printed components. As discussed in different researches, capabilities of CT scans in measurement of surface topography of complex 3D printed parts have been proved [129, 130]. In this respect, the values obtained from CT scans are in a good agreement with evaluation of the same surfaces which are investigated with traditional surface measurement techniques.

In a paper by Townsend et al. [131] CT was used in reconstructions of 3D-printed metal parts. Indeed, the researchers extracted areal surface data and generated surface texture parameters. A good repeatability was reported, and it was claimed that the proposed method can be used for 3D printed medical parts where definable pass-fail limit should be set. Later, in [132] CT was used for quality control of a cubic specimen. In detail, 3D-printed cubic sample was examined and its surface roughness was reported. At the same time, Thompson et al. in [133] and [134] used CT for investigation on 3D printed metal surfaces. More in deep, in [123] influence of resolution and magnification on surface topography were determined (see Fig. 9). Consequently, it was documented that geometric magnification indicated a stronger influence compared to sampling resolution in surface evaluation of the printed parts. In work [134] internal surfaces of powder bed fusion components were investigated by CT and the obtained results were compared to data achieved by other optical surface measurement methods (see Fig. 9). Indeed, the researcher used coherence scanning interferometry measurement and CT for analysis of a surface in a hollow Ti6Al4V component. Documented results showed similarity between the data acquired by the CT systems and the results of other optical systems. Although CT has been used for characterization of flat surfaces, it can be used for analysis of non-flat surfaces.

In a paper by du Plessis and le Roux [135] a series of test were conducted via CT on different 3D printed metal components. Consequently, it was reported that incorrect process parameters can be identified by analysis of the results. Moreover, it is claimed that the performed analysis was a first step in developing technical standards in application of CT in analysis of 3D printed parts. As pores which are close to the surfaces, can lead to stress concentrations, surface analysis via CT has been continued in the researches. As discussed in [136], the proximity of the defect to the surface, is more important than the crack initiation in analysis of 3D printed titanium parts.

An extant study [137] examined surface defects via CT. In this context, influence of surface temperature on pores was

determined. Later, in [138] researchers investigated influence of surface topography on the tensile resistance of the parts fabricated via SLM process. To this aim, the researchers fabricated Ti-6Al-4 V implants which experienced high cycle fatigue test. Surface treatment was performed on some of the printed specimens, and all the specimens were analyzed for surface roughness. Consequently, it was documented that fatigue behavior of treated specimens was improved by reduction in roughness. Moreover, it was reported that this reduction in roughness has no effect on the specimens with porous regions. More recent work on this topic explained usage of CT on surface texture metrology [139]. In this regards, various examples were presented and discussed.

Although here we presented applications of CT in four defined subdomains, it can also be utilized for other purposes. For instance, CT can be used for powder analysis of additively manufactured parts. However, despite of performed projects and research studies, there are limitations and challenges in this field that are explained in the following section.

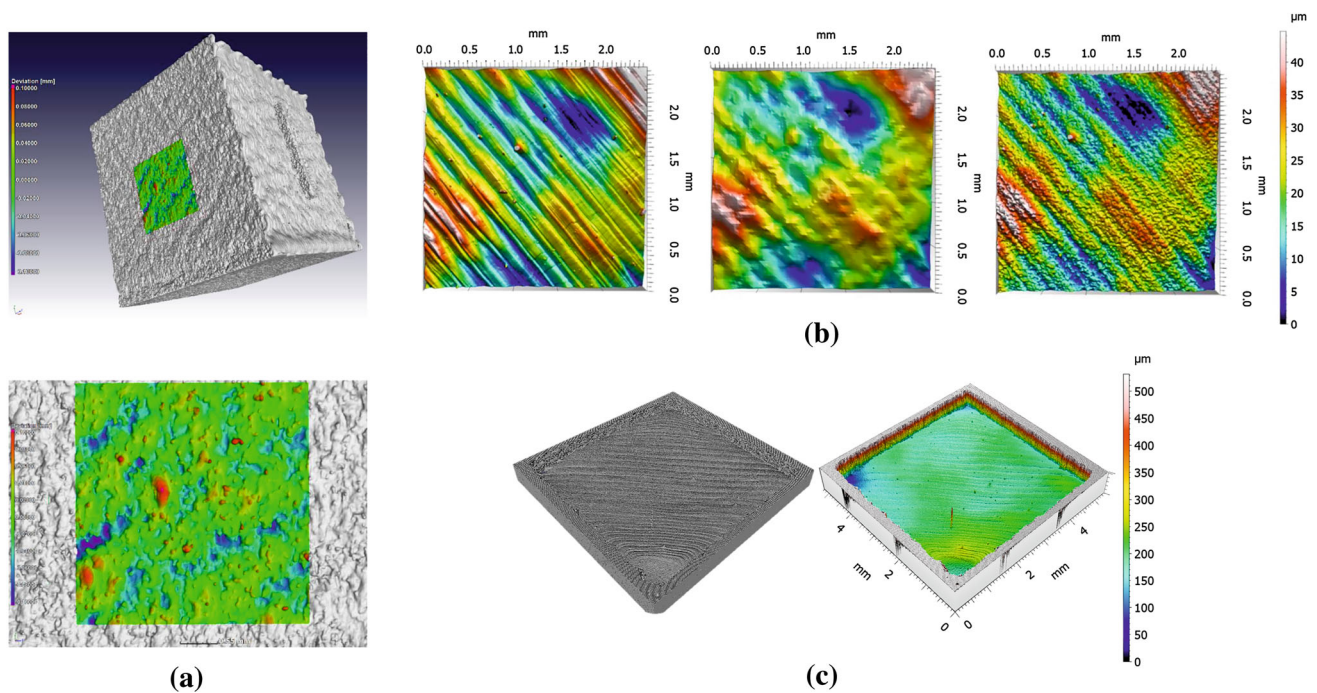
## 5 Challenges and limitations

Since CT proved its abilities in evaluation of components, it has attracted the interest of academic and industrial researches. Evaluation of fabricated components in the assembled state provides tracking the changes after assembly which is not easily achievable with other evaluation methods. Based on capability of CT, it is expected to see more applications of this technique in optimizing processing parameters in different 3D printing processes.

However, there some challenges and limitations in utilizing CT as a nondestructive testing method for evaluation of 3D-printed components.

Scan duration and also image analysis process are considered as challenge which have effects on the cost. Although the scan time is reduced due to recent developments in the hardware, it is remained as matter of concern. By utilizing faster scanning, detection of small defect might be neglected. Hence, this issue is one of the ongoing research topics in this field. Moreover, image quality can be reduced by a noticeable distortion. In this case, modification in scan parameter is needed that leads to increase in cost and time. However, obtaining high quality image is a challenging issue which is affected by several parameters (e.g., sharp material edges and high contrast). Additionally, part size has an important influence on scan parameters, and a different setting is required for large components. All these issues must be considered to obtain a high quality image. Despite of CT application in assessment of 3D-printed parts, there are limitations on type of material and the size of specimens.

Beam hardening should be considered as one of the current challenges in this field. As discussed in [140], beam



**Fig. 9** Surface analysis by CT: **a** surface topography of a cubic specimens [132], **b** various CT measuring setup [133], and **c** internal surface of Ti6Al4V under CT measurement [134]

hardening produces false line integrals, because of the photon-energy dependence of the attenuation coefficient. In order to decrease importance of beam hardening, polyenergetic x-ray beam can be considered. Because of the beam hardening, the effective energy of a spectrum is no longer constant throughout the absorber. In fact, polyenergetic nature of the x-ray source is beneficial in artifact reduction. In detail, Previous studies showed that systematic bias of the cupping artifact from beam-hardening can significantly reduce by incorporating the polyenergetic nature of the x-ray spectrum into the reconstruction. Although attempts are made for medical applications, it is needed to introduce new techniques for beam hardening corrections in assessment of 3D-printed parts. It is noteworthy that pre-harden the beam and post correction are two common strategies, which have been developed to reduce or correct beam hardening. In [141] researchers demonstrated how this problem can be solved and optimized by an expert user in evaluation of a natural material.

Available literature confirmed that CT is a suitable equipment in evaluation of defects and pores. Although accuracy of CT in porosity measurements of metallic parts is less than Archimedes' method, it is recognized as a nondestructive technique for investigation of pores within components. However, in using CT low and high magnifications are depend on detector pixel size and focal spot enlargement, respectively [142]. One of the challenges in CT back to incapability of this method in measurement of small pores.

Indeed, CT has a limit that can not measure defects smaller than the minimum voxel size. Solving this problem to improve performance of CT is one of the interesting research topics.

Although CT has been used for dimensional and density measurements in additively manufactured parts, there are difficulties due to the lack of a suitable protocol. Indeed, lack of documented inspection procedure and shortage of influence of defect studies have been observed. Moreover, undefined critical defect types on the examined components lead to extra time and cost. Therefore, great efforts and attempts are needed to provide appropriate protocols and references.

In utilizing CT for surface roughness, edges of the parts are potential points to make a challenge. In detail, edge detection is a crucial issue and images with pixelated edges can lead to a challenge which significantly influence surface profile reconstruction. Additionally, missing data is a key challenge in surface reconstruction. However, control of several variables such as current, voltage, magnification, and filtering must be performed.

Knowledge of the user has an important role in obtaining reliable and high quality results in evaluation via CT. In fact, a profound knowledge of user in evaluation of the measurement uncertainty is required. This uncertainty must be recognized via a system in the measurement process, but it is limited in the real application. Hence, a further development is necessary. In development of techniques, utilizing reference objects can be considered. In this context, it is needed

to determine the sensitivity of measurements to geometrical parameters.

It is needed to study the link between processing and mechanical behavior of 3D-printed components. This studies should performed be computationally and experimentally to determine role of printing parameters on mechanical properties of the printed parts. More in deep, a main challenge in reported applications of CT in 3D-printed parts is that in most of the cases the processing parameters are not well documented. Based on the discussed issues, here we present suggestions as follows:

- As capabilities of CT in FEM has been investigated in a few studies, this issue should be considered in future research projects. With respect to abilities of CT, its combinations with FEM allows to predict behavior 3D-printed parts precisely. Indeed, CT can detect the defects in the printed part, and considering these defects in FEM is an accurate input data which leads to a reliable prediction.
- Although CT has been used in a wide variety of applications, there is no international standard that presents an extensive guidance for operators. As usage of CT is complicated compared to optical systems, it is needed to establish a comprehensive industrywide standard in usage of CT in 3D printing technology in order to overcome existing problems.
- For future improvements, it is recommended to develop 3D-printed artefact which are specifically designed for CT measurements. Since existing 3D-printed designs are not suitable for this purpose, this development seems to be necessary. Additionally, attempt should be made to produce available artefacts that are utilized in CT calibration.
- Based on the high cost of evaluation by CT, it is suggested to establish and develop researches in order to provide similar information by other techniques. In fact, assessment costs can be significantly decreased, if approximate data could be provided by cheaper evaluation methods.
- Considering existing problems in surface reconstruction of 3D-printed parts, algorithms must be developed for a better edge detection. In this context, it is required to extract boundary surfaces. Indeed, novel methods are required to obtain surface data from CT, and utilize standards for surface reconstruction of additively manufactured components.

- A closed-feedback loop can significantly help to increase quality of 3D-printed parts. In detail, results of CT should be compared to the designed model by an appropriate software to determine discrepancies. These differences must be removed in redesigning process. In this case, it is expected to fabricate high quality components in shorter time.

## 6 Conclusion

Application of additive manufacturing (AM) has been changed from rapid prototyping to the fabrication of final products. In this context, engineering evaluation of produced parts is more needed than ever. To this aim, x-ray computed tomography (CT) has been used as a nondestructive technique. In this review paper, existing data have been compiled to evaluate and summarize applications of CT in assessment of 3D printed components. To this aim, we considered usage of CT in four subdomains: (a) defect detection, (b) dimensional evaluation, (c) density measurement, and (d) surface roughness analysis. In the current study, academic and industrial applications of CT were outlined and discussed in detail. Based on the reviewed research studies, CT has been used for evaluation of both metallic and polymeric 3D-printed parts. Here, we demonstrated all the different ways which CT has been utilized in 3D printing technology. Considering several potential applications of 3D printing, standardized test procedures are required for evaluation of end-use products fabricated by this technique. Although, CT has been used for analysis of 3D-printed components, international standard test methods is required. As applications of CT in assessment of 3D-printed parts is under continuous professional development, we tried to help the general understanding and shed light on potential of this technique. Based on the discussed applications and current challenges, several suggestions are presented. Based on the applications and capabilities of CT, results obtained from this method can be evaluated with experimental tests. Obtaining accurate results can lead to use CT as a routine technique for evaluation of additively manufactured components.

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## Compliance with ethical standards

**Conflict of interest** The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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