3D-additive manufacturing non-destructive characterization with terahertz waves

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ABSTRACT

Additive manufacturing (AM) is an essential tool to make 3D objects having very complex shapes and geometries, unachievable with standard manufacturing approaches. Meanwhile, quality controls of such objects become challenging for both industrials and applications in laboratories due to both their complexity and the materials they are made of. Consequently, we demonstrate that terahertz (THz) imaging and THz tomography can be considered as efficient methods for such object inspection in routine applications. Thus, this paper proposes an experimental study of 3D polymer objects obtained by AM techniques. This approach allows us to characterize defects and to control dimensions by volumetric measurements on 3D data reconstructed by tomography.

Keywords: terahertz spectroscopy, data analysis, non-destructive testing, tomography

1. INTRODUCTION

Additive manufacturing (AM) methods provide very sophisticated and complex geometries objects without almost material waste. Moreover, these techniques are now appropriate to numbers of materials, including numerous plastics, ceramics, and even metals. However, new defects may occur in the final device with these new techniques so that material quality has to be assessed. Chiefly, physical phenomena related to additive manufacturing processes are complex, including melting, solidification and vaporization, heat and mass transfer. However, every time a new technology emerges, it creates a need for control tools. For example, it is necessary to verify that high-tech components have no defects in order to ensure that they will not become weaker with use. Dimensional measurements of inner structures can also be of paramount importance. Since the position taken by AM in several critical industry sectors (such as aeronautics, aerospace and medical) to produce high-tech parts, it is obvious that both quality control and certification of these parts have to be considered. For example, this principle of fabrication can introduce more defects caused by the bad fusion of a layer and perceived as porosity. The only way to probe and measure complex and/or inner structures manufactured by AM without any damage is to use volumetric Non-Destructive Testing (NDT) techniques. Among these techniques, the only one which both enables defect detection and provides a 3D visualisation of inner structures (allowing dimensional measurements) is tomography. In this paper, we demonstrate that TeraHertz (THz) tomography could be an efficient alternative to X-Ray for NDT of AM objects.

2. MATERIAL AND METHODS

In this section, we first introduce the experimental setups, in two distinct but complementary analysis tools: experimental setups for achieving 3D tomography (section 2.1) and spectro-imaging setup (section 2.2). Complementary of the techniques will be discussed in the result section 3. Then in section 2.3, we define some additive manufactured objects used in this study for illustrations.

2.1 Experimental tomography setups:

Continuous wave (CW) THz imaging can be used to obtain 3D reconstruction of an object [1]. Tomography algorithm requires that the object under investigation is measured at different viewing angles for obtaining a set of 2D radiographs. In this study, we experiment two setups for measuring such an object acquisition. Both consist of an electronical emitter and receiver equipped with polytetrafluoroethylene (PTFE) lenses to focus the THz radiation on one spot-point of the sample. The object is mounted on a rotational stage to rotate the object which is itself mounted on a pair of horizontal / vertical translation stages. Basically, translating the object relatively to the THz focused beam aims at measuring a 2D radiograph by raster-scanning while iterating this process by moving the rotational stage leads to the acquisition of different angle radiograph views. In all our experiments, the raster-scanning is performed according to the sample dimensions such that it is always included in the radiograph field of view, and 36 radiographs, from angle 0 to 175° with a 5° step, are measured. The first scanner (cf. figure 1) consists of a Gunn Diode emitting 12 mW at 287 GHz and a Schottky diode as receiver. The THz beam is modulated at 1 kHz by a mechanical chopper. The signal is rectified by the ultrafast Schottky diode, and measured by a lock-in amplifier. The lenses used to focus the THz beam have a focal length of 50 mm and a diameter of 50.8 mm, which leads to a waist of approx. 2 mm at Full-Width Half-Maximum (FWHM). The second scanner is based on a chirped signal centered at a certain frequency, which is generated by up-converting a fixed frequency signal. Via a ramp generator and a voltage controlled oscillator, a signal with swept frequency is generated at approximately 13-18 GHz with a sweep period of 240 µs. A Schottky mixer is employed as heterodyne detector. The lenses used to focus the THz beam have a 200 mm focal length and a diameter of 50.8 mm. 3D tomographic reconstructions from acquired THz radiographs are performed using the Ordered Subsets Convex algorithm (OSC) [3] adapted to THz radiation. We chose this algorithm for its very good results in reconstruction quality with terahertz waves.

2.2 Experimental spectro-imaging setup:

The test setup for spectroscopy investigation is a "TPS Spectra 3000" from Teraview. Fundamentally, we use a standard THz-Time Domain System (TDS) transmission setup with a femtosecond Ti-Sapphire laser. Normally, the helpful transmission bandwidth of this instrument is between of 0.1 and 4.5 THz, depending upon the examined test under test [2]. The TDS measurements are obtained using coherent photoconductive detection based on a photo-conductive antenna similar to the one used in emission. A signal-to-noise ratio (SNR) of around 4000:1, limited by the thermal noise of the antenna, can be achieved. Thus, we can access to the dielectric property map of the sample. Moreover, THz-TDS setup offers a time-of-flight analysis mode for in-depth (3D) reconstruction without needing different viewing angles such as tomographic setups. This approach is particularly interesting for in-depth analysis of flat and/or large objects that are not acquirable by tomography. In brief, the THz pulse is directed at the sample and the reflected beam is measured in amplitude and phase. The temporal position in time of the reflected pulses directly indicates the presence of interfaces or defects along the propagation direction of the beam. In this way, by using the difference of time-of-flights from pixel to pixel, depth information of the 3D profiles of the target can be deduced.

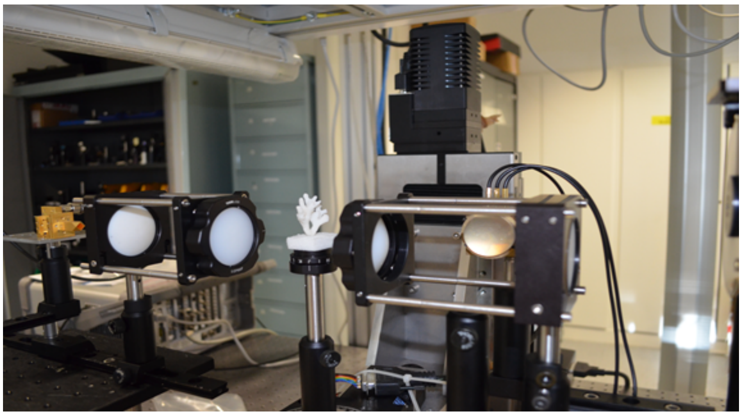

Figure 1: millimeter wave scanner wortking at 287 GHz

2.3 Samples

The materials available for 3D printing are numerous and depend on targeted solicitations. There is now a wide variety of numerous material types that are provided in different states (powder, filament, pellets, granules, resin, etc) for many types of printing procedures. Specific materials are also developed for particular systems performing dedicated applications (examples would be the dental, automotive, medical sectors, etc). For example, Nylon, or any Polyamide in general, are commonly provided in powder form with the sintering process or in filament form with the fused deposition modelling process. It is sufficient strong, flexible and durable plastic material that has proved reliable for 3D printing. Acrylonitrile Butadiene Styrene (ABS) is another common plastic used for 3D printing, and is widely used on the entry-level FDM 3D printers in filament form. It is a particularly strong plastic and used in a wide range of applications. Polyactic acid (PLA) is a bio-degradable plastic material that has gained attention with 3D printing because it is derived from renewable resources, such as cornstarch, sugar cane, or even potato starch. This key point makes PLA the most environmentally friendly in the domain of 3D printing, compared to all the other petrochemical-based plastics. In [4], Busch et al present the THz properties of various polymer materials which can be processed by 3D printers. Besides the absorption which becomes a limiting factor above 1 THz [5], the printability is an important factor for the material selection. To limit an extensive study, we focus on studying three relevant polymers and ceramics samples to establish that THz spectro-imaging and tomography are well adapted for routine controls to detect defects and qualify the materials: “Sample1” is composed of 2 lumbar interbody devices. It is made of Polyether ether ketone (PEEK), which is a semi-crystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures. PEEK is considered as an advanced biomaterial used in medical implants. It is of increasing interest in spinal fusion devices and reinforcing rods. Secondly, “Sample2” is a ceramic object made of alumina.

3. RESULTS

In this section, we provide several thermoplastic materials (composing Sample1 and Sample2) characterisation and properties by THz spectroscopy. This preliminary study helps us to determine the parameters (especially the frequency of the signals) to be used for an efficient tomographic acquisition and 3D reconstruction of the objects (second part of the results). Then third, appart from thermoplastics objects, we deal with 3D printed ceramics samples, especially made of alumina.

3.1 Thermoplastic material characterisation and properties by spectrocopy:

The THz-TDS system used makes possible to determine some material properties and optical characteristics such as the complex optical index, the refractive index and, by deduction, the absorption. First of all, one can measure the temporal profile of the electric field of the THz pulses and therefore recover the complex index of refraction of the studied samples in the range between 0.1 and 3.5 THz by Fourier transform spectrocopy. This characterisation method requires two measurements: i) a reference waveform, Eref(t), without the sample, and, ii) a signal waveform, Es(t), with the sample. The ratio between the Fourier components of the two signals defines the complex transmission function, T(w), of the sample:

$$T(\omega)=\frac{E_s(\omega)}{E_{ref}(\omega)} \qquad (1)$$

In the case of a homogeneous sample, the complex refractive index n* □□n □□i□□□where n is the real part of the optical index and k is the extinction coefficient) is related to the complex transmission function and is easily extracted [6]. Then we are able to estimate the absorption coefficient. The frequency–dependent complex dielectric constant of the sample is obtained by computing the complex ratio of the output amplitude spectrum to the input of the reference spectrum. Indeed, the experiment by itself gives directly the frequency characteristics of the electric field (amplitude and phase). The internal reflections of the sample are taken into account in the analytical expression of the transfer function, which is then numerically solved. This problem constitutes two equations for the real parameters n and □. As a result, one obtains without any ambiguity the complex dielectric function of the sample in the entire transmitted THz spectral range. However, the calculated refractive index may be strongly affected by unavoidable errors in the determination of the thickness and depends on material quality and fabrication. Meanwhile, since the phase of the electric field is measured with a high accuracy, the absolute value of n can be precisely determined. As a consequence, the optical data maximal error is less than 5 % while the film thickness determination deviation is about 10 %.

As an example, Figure 2 shows the complex optical indexes of PEEK and Polyamide which is a macromolecule with repeating units linked by amide bonds. Polyamides are commonly used in textiles or automotive applications, due to their high durability and strength. These spectroscopic measurements show a quasi flat dispersion curve of the refractive index for the both samples, with: n=1.58 for PEEK, and n=1.78 for Polyamide12 [7]. However, considering that further complementary analysis of these samples will consist of 3D tomography, we mainly have to account for the analysis of the material absorption coefficients. Indeed, the absorption determines the maximal thickness a particular wavelength can penetrate and goes through the sample (transmission) before encountering a complete absorption (no transmitted signal measured on the radiographs makes 3D tomography unachievable efficiently). As an example, Fig 2, the absorption coefficients as a function of the frequency (hatched lines) for the both materials, show that an object with a thickness greater than 1cm can be analyzed with a frequency lesser than 500GHz.

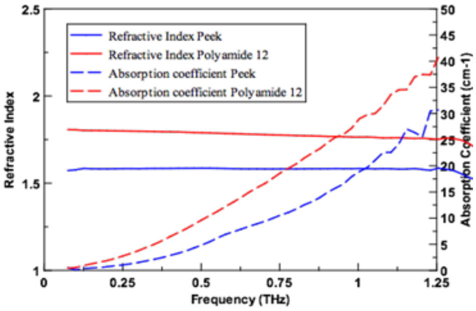

Figure 2: Complex optical index of PEEK and Polyamide.

3.1 NDT of thermoplastic manufactured objects by 3D tomography:

Considering spectroscopic anlaysis, we have imaged in 3D the objects made in thermoplastic materials using the CW-THz scanner with the 287 GHz source. Thanks to an advanced processing sequence [9], going from the 3D tomographic reconstruction to the automated segmentation and meshing of volumes of interest (VOI) we are able to measure the dimensions, analysis the surface, determine the volume morphology and compare the volume with the CAD model developed for 3D printing.

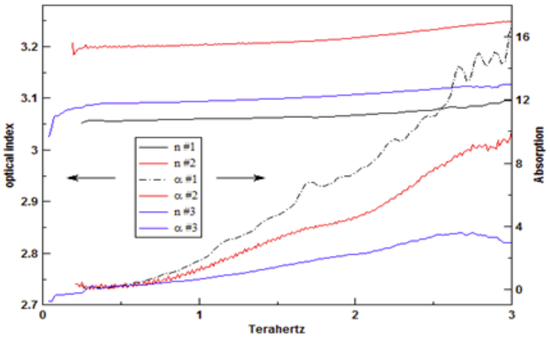

Figure 3: Left: acquisition (set of 36 radiographs) at 287GHz with an angular step of 5°. Center: 3D reconstruction of the object by tomography using the OSC-THz algorithm. Right: Original sample with its dimensions.

For example, Fig.3 shows lumbar interbody 3D reconstruction using the CW scanner equipped with a 287 GHz source. After acquisition of the radiographs of the different samples represented in Fig3. a , tomographic reconstructions are performed in fig3.b . The reconstructed data obtained under different orthoslices reconstructed from the different projections. This rendering allows one to visualize, analyse and measure the sample on surface and in depth. Then visualisation and dimensional measurements can be achieved separately for each Volume Of Interest (VOI), which is particularly useful to analyse correctly the inner structure of an object. We accomplish this analysis by showing how 3D segmentation and 3D rendering [8] can be used as a qualitative and quantitative analysis for inspection.

3.3 THz analysis of ceramic samples :

A spectral analysis similar to the one made for thermoplastics manufactured objects (secion 3.1) is now conducted over different ceramics. Fig.4 presents the dielectric measurements extracted from THz-TDS acquisition of different alumina provided by AM manufacturers.

Figure 4: Optical index and absorption coefficients (cm-1) of different alumina samples

Once again, it shows again a quasi flat dispersion curve of the refractive index, with n ranging from 3 to 3.2 whatever the sample. Absorption is less than 10 cm-1 for frequencies smaller than 2 THz. The flat shape of the object making 3D tomography difficult to achieve, the 3D imaging of this sample has been performed using the time-of-flight mode of the THz-TDS setup.

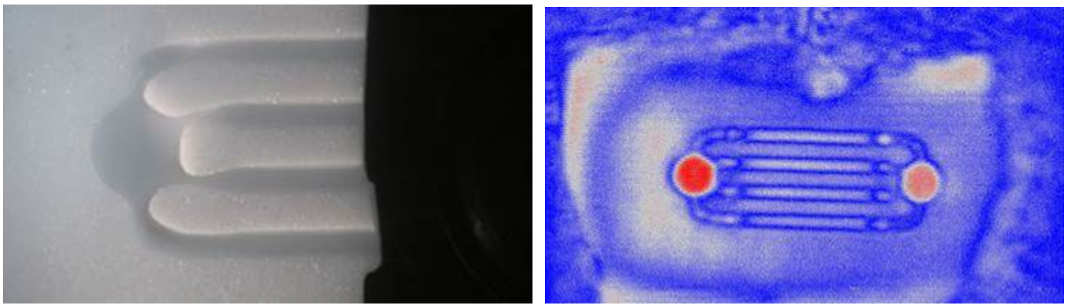

Figure5: a) Optical details of alumina micro-fluidic channels, b) defect localisation by THz imaging at 1.5 THz.

To demonstrate terahertz imaging capability with such ceramics materials, we inspect a micro-fluidics device made with alumina. Fig5.a) shows the area details where three micro-channels converge to mix a liquid in the central part. The dimensions are typically 10x10 mm2 and the structure is covered by a 1mm thick alumina layer. A typical drawback that could be encountered during manufacturing could be a partial or total closure of the channels during the 3D printing process. Until now, the only NDT technique that was able to both detect such defects and provides 3D image of the inner structure (allowing dimensional measurements) was X-Ray tomography (with several disadvantages such as the risk from radiation exposure and the cost). Thanks to THz-TDS time-of-flight analysis, we are now able to provide a in-depth inspection of this kind of sample, as illustrated on Fig. 5.b) where we clearly distinguish the inner structure of the sample. Indeed, at 1.5 THz, the resolution and the depth penetration are sufficient to perform a qualitative and a quantitative analysis.

4. CONCLUSION

We demonstrate successfully that several AM objects made of polymers and ceramics could be inspected by THz-TDS and/or 3D THz tomography. Preliminary spectral analysis of the materials used for 3D printing helps at determining the parameters to be applied for efficient 3D tomography. Moreover, for some samples having very specific shapes, time-of-flight THz imaging can be an alternative approach to tomography for 3D inspection. Achieving such NDT requires advanced image processing sequence and algorithms for reconstructing and analysis relevant data extracted from the acquisition. As an example of analysis tools, we have shown that surface and volume analysis can be performed and 3D rendered object dimensions can be compared with original CAD dimensions. Moreover, efficient defect detections can be carried out. Thus, THz imaging is an alternate and complementary technique to the well-known X-Ray tomography which is costly for routine controls.

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