3D Terahertz Imaging of Hidden Defects in Oxide Fibre Reinforced Ceramic Composites

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Abstract. WHIPOX™ (Wound highly porous oxide composite) is an innovative all-oxide fiber-reinforced ceramic matrix composite for high-temperature applications. We are reporting inspection results generated using fully electronic terahertz sources running at 0.1 THz respectively 0.3 THz in a mobile unit. The system operates in reflection as a frequency modulated continuous wave (FMCW) radar. A comparison of the measured results with investigations using established NDT methods like X-ray microCT, lock-in thermography and air coupled ultrasound inspection show the great potential of the new method.

Introduction

Many dielectric materials are transparent to terahertz radiation [1]. Plastics, FRP, ceramics, paper and textiles can be inspected 3-dimensional using terahertz imaging. In recent years all-electronic terahertz sources have been made available and these units are compact and easy to use and therefore ideal for non-destructive testing purposes [2,3]. We are reporting results generated using sources running at 0.1 THz respectively 0.3 THz in a mobile FMCW radar unit (SynViewCompact, Synview GmbH, Bad Homburg, Germany).

WHIPOX™ (Wound highly porous oxide composite) is an innovative all-oxide fiber-reinforced ceramic matrix composite for high-temperature applications. A primary goal of DLR is the development of CMC components for environmentally and economically favorable gas turbine engines with stable lean-combustion. For example the burning chambers of these turbines will be designed with new highly damage-tolerant and corrosion-resistant high-temperature ceramic matrix composites. Investigations of WHIPOX™ assemblies using 3D terahertz imaging demonstrate the capability of this new NDT method to detect hidden defects efficiently. While the 0.3 THz results show medium penetration at a maximum lateral resolution the 0.1 THz investigation allows full penetration at lower resolution.

1. 3D Terahertz Imaging

1.1 Generation of Terahertz Radiation (T-rays)

Terahertz radiation is electromagnetic radiation in the frequency range 0.1 - 10 THz in between the microwave and infrared region. This correlates to a vacuum wavelength in between 3 mm and 30 µm. T-rays are not ionizing and therefore do not require costly protection measurements (like X-rays). Today there are several methods available to generate T-rays. Most popular are tunable laser based systems converting optical light into terahertz radiation. In recent years also all-electronic terahertz sources have been made available and these units are compact and easy to use and therefore ideal for non-destructive testing purposes. Available frequencies are e. g. 0.1 THz, 0.3 THz, 0.5 THz and 0.85 THz [2,3]. These sources can also be used to realize fast fully electronic THz cameras operating at room temperature [4].

1.2 All-Electronic FMCW Radar

Many dielectric materials are transparent to terahertz radiation [1]. Plastics, FRP, ceramics, paper and textiles can be inspected 3-dimensional using terahertz imaging. Depending on the frequency of the all-electronic source a penetration depth of up to 30 mm can be achieved (in some cases, e. g. for foams more than 50 mm) [2,3]. Both, transmission and reflection measurements can be performed. In reflection 3D terahertz imaging systems operate as a frequency modulated continuous wave (FMCW) radar. The signals reflected from different layers of the sample under inspection are time resolved to generate the 3D terahertz image which does also contain information about hidden defects inside the sample.

We are reporting results generated using sources running at 0.1 THz respectively 0.3 THz in a mobile FMCW radar unit (SynViewCompact, Synview GmbH, Bad Homburg, Germany). The achievable lateral resolution in material is approximately 0.5 mm at 0.3 THz and 1.5 mm at 0.1 THz.

2. Measurements

2.1 General Remarks

Two planar WHIPOX™ samples were inspected. The first sample is 280 mm x 120 mm in size and 10 mm thick. The second sample is 475 mm x 190 mm in size and 3 mm thick. Both samples were scanned with point-to-point distances of 0.5 mm or 1 mm in X and Y. While the first plate was inspected using 0.1 THz to achieve full penetration the second plate was inspected using 0.3 THz to get maximum resolution in Z-direction (depth) due to a higher band width at this frequency. The typical inspection time for each sample is 10-20 minutes, depending on the resolution.

2.2 Results generated at 0.1 THz

Figure 1 shows the result of a 0.1 THz C-Scan of the first plate. The upper image shows the reflection signal at the Z-position (layer) indicated in the lower image (dotted line) and the lower image shows the B-Scan at the position indicated in the upper image (dotted line). The Z-position in Figure 1 is representing the upper surface of the plate.

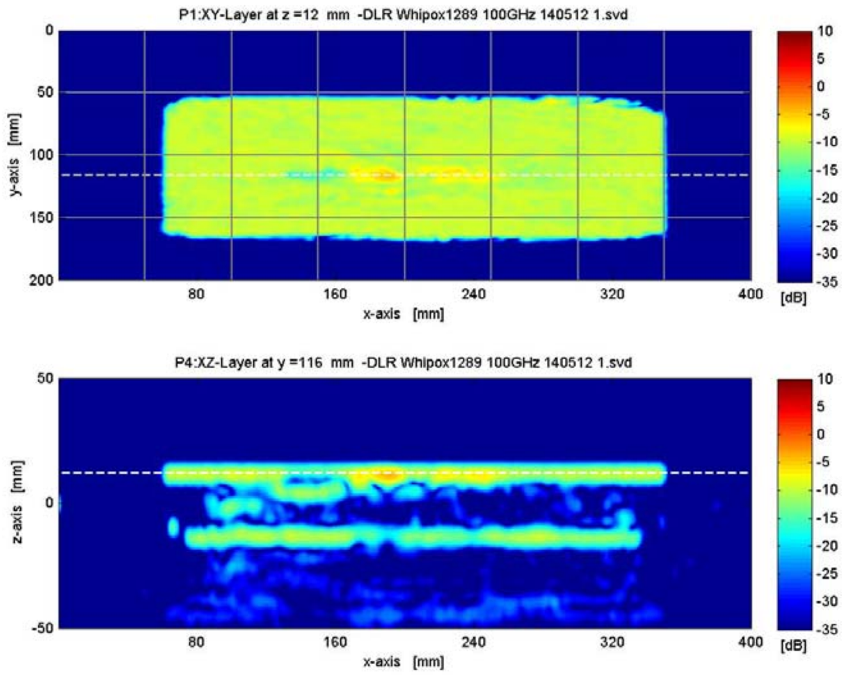

Fig 1. C-scan of the first sample at 0.1 THz. The Z-position (layer) is representing the upper surface of the plate.

Figure 2 shows the result of the same C-Scan like Figure 1, but the displayed layer (Z-position) is here 2.5 mm underneath the surface of the sample. Clearly visible is a region with increased reflection signal indicating a zone with cavities and/or delamination.

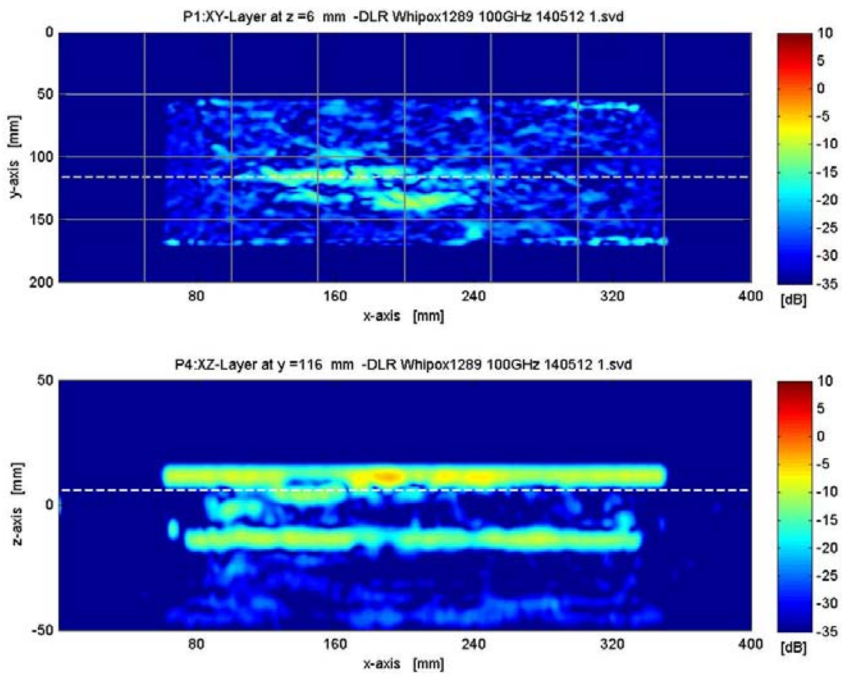

Fig 2. C-scan of the first sample at 0.1 THz. The Z-position (layer) is representing a layer 2.5 mm underneath the surface.

Figure 3 shows the result of the same C-Scan like Figure 1 and 2, but the displayed layer (Z-position) is here 5.5 mm underneath the surface of the sample. Clearly visible is another region with increased reflection signal indicating a smaller zone with cavities.

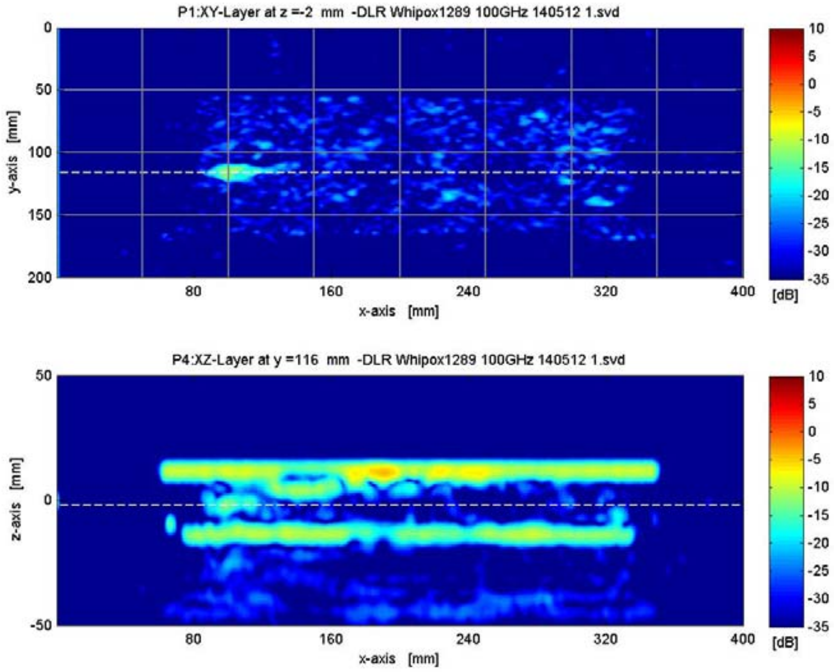

Fig 3. C-scan of the first sample at 0.1 THz. The Z-position (layer) is representing a layer 5.5 mm underneath the surface.

2.3 Results generated at 0.3 THz

Figure 4 shows the result of a 0.3 THz C-Scan of the second plate. The upper image shows the reflection signal at the Z-position (layer) indicated in the lower image (dotted line) and the lower image shows the B-Scan at the position indicated in the upper image (dotted line). The Z-position in Figure 4 is representing the upper surface of the plate. Clearly visible are the two rectangular fibre orientations and the vertical crossing regions of the fibres.

Figure 5 shows the result of the same 0.3 THz C-Scan like Figure 4, but the displayed layer (Z-position) is here 1.5 mm underneath the surface.

Increased reflectivity indicates 2 smaller regions with cavities and also voiding in the vertical crossing regions of the fibres.

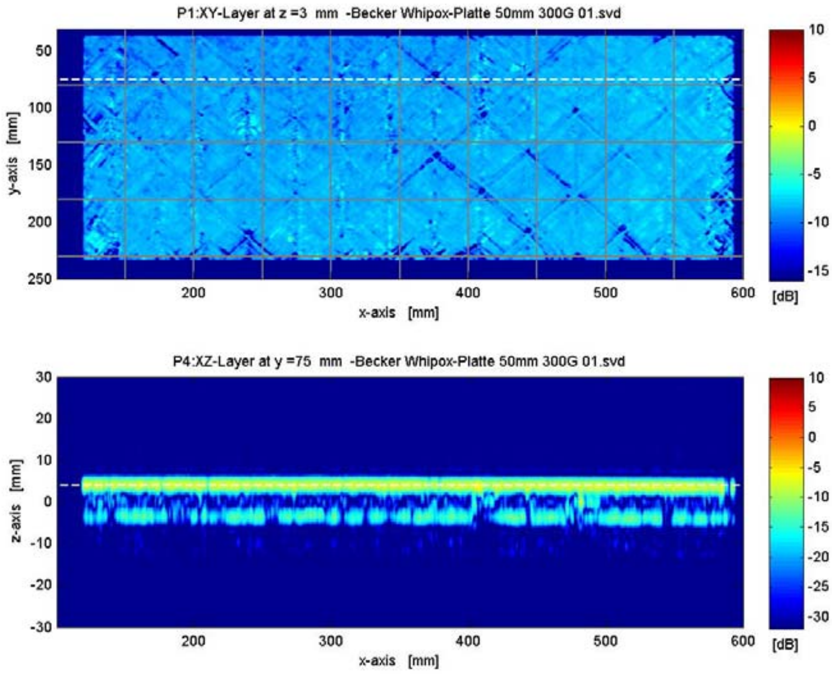

Fig 4. C-scan of the second sample at 0.3 THz. The Z-position (layer) is representing the upper surface of the plate.

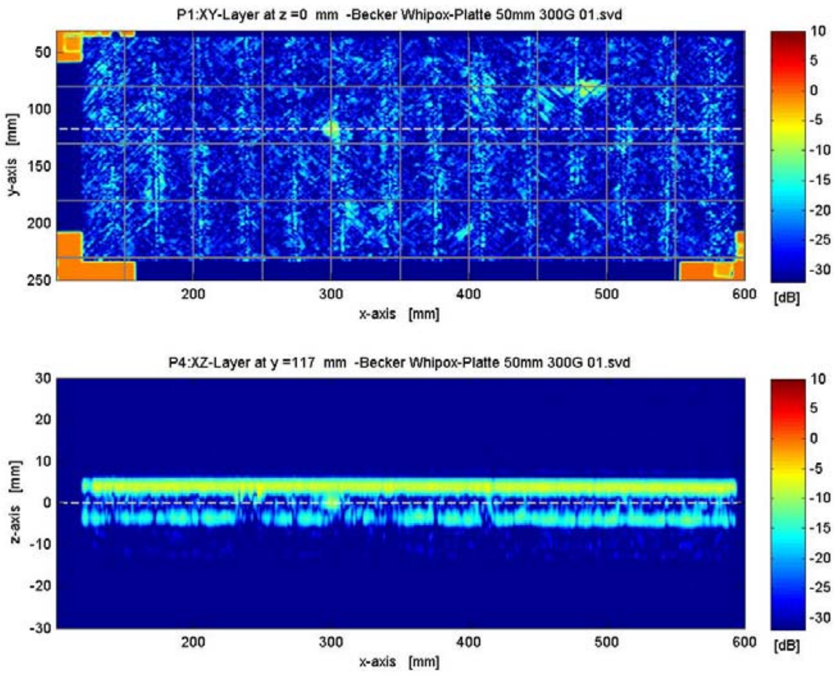

Fig 5. C-scan of the second sample at 0.3 THz. The Z-position (layer) is representing a layer 1.5 mm underneath the surface.

3. Comparison with established NDT methods

To verify the results generated with 3D terahertz imaging several measurements using established NDT methods were performed. The first sample was investigated with high resolution microfocus X-ray CT, lock-in thermography and air-coupled ultrasound. All these measurements confirmed the presence of a defect area with cavities and/or delamination as shown in Figure 2 and 6 (upper image). The central area in Figure 6 (lower image) with significantly reduced ultrasound transmission correlates well with the area with an increased reflection in the 3D terahertz image.

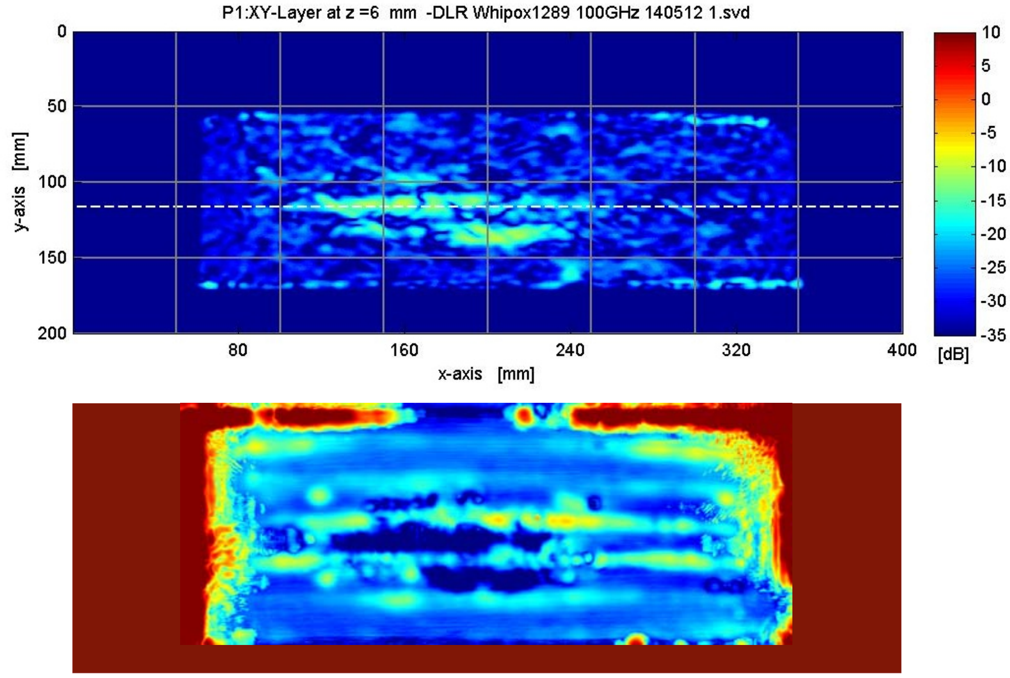

Figure 6. Upper image: C-scan of the first sample at 0.1 THz. The Z-position (layer) is representing a layer 2.5 mm underneath the surface. Lower image: Through-transmission air-coupled ultrasound inspection of the first sample. The central area shows significantly reduced transmission.

4. Conclusion

The comparison of the 3D terahertz imaging results with the results of above mentioned established NDT methods confirm the ability of the new method to efficiently detect typical defects in WHIPOX samples. Even more, 3D terahertz imaging does have several advantages. As can be seen in Figure 1 – 5 it is easy to not only determine the X-Y position of the defects, but also the Z-position by analysing the layer specific information (B- and C-Scans). As for lock-in thermography the method does only need access to the investigated sample from one side (FMCW radar, reflection mode), but compared to thermography 3D terahertz imaging often shows improved penetration depth and better vertical resolution.

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