Proceeding Paper

Terahertz Radiation in Non-Invasive Defect Inspection on Alumina Ceramics †

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Abstract: Alumina ceramics are widely used in the military as a component of ballistic covers due to their high number of mechanical properties such as strength, hardness, and wear resistance. However, alumina exhibits brittle fracture behavior which may lead to the catastrophic failure in construction. Due to that, it needs to be monitored during its lifetime. Thus, the non-destructive testing methods may be very important to ensure the safe and reliable use of these elements through non-invasive, contactless monitoring. In the frame of this work, the potential of Terahertz (THz) transmission measurements is demonstrated, and a selected application using THz systems is presented. The studies were conducted on military-designated ceramic materials at the frequency of 300 GHz. The data were next compared, with the images obtained via X-rays acting as a reference. As the results showed, there is a full agreement between the data obtained with the use of THz radiation and X-rays. This work shows the ability of THz radiation for contactless, non-destructive control of defects in alumina ceramics.

Keywords: ceramics; non-destructive testing; non-invasive detection; terahertz imaging; X-ray imaging

1. Introduction

In recent years, non-destructive testing (NDT) methods have received significant attention. The increasing interest is connected with the need to non-invasively monitor constructions in order to protect them from failure. The NDT methods are based on, among others, X-ray, ultrasound, thermography, eddy current, and optics [1,2]. Despite the fact, that these methods are widely used and developed, they still have some limitations which reduce their efficiency and versatility. Thus, novel methods enabling the identification of damages in construction, and monitoring their location and progression, are needed [3]. A very promising method of NDT is based on the use of terahertz radiation.

Terahertz (THz) frequency range is placed between infrared and microwave radiation on the electromagnetic spectrum and corresponds to the band from 0.1 to 10 THz [4]. It allows for the contactless detection of defects such as delamination, voids, or uneven reinforcement of various materials [5]. Their area of applicability includes, among others, non-conducting composites such as glass fiber-reinforced plastic, foam, ceramics, epoxy, and Kevlar which are widely used in the aerospace and military industries [6–8]. THz radiation is nonionizing (low photon energy which for 1 THz is ~4 meV); therefore, it is safe for the human body [9] which increases its competitiveness in relation to other methods, e.g., X-rays. THz radiation has already been successfully used to investigate various military-designated materials such as non-metallic composites [4,6,10], and rocket fuels [7].

There are two basic modes in which studies with the use of THz radiation may be carried out such as reflection (in which the THz wave emitter and scanner are on the same side in reference to the investigated object), and transmission (in which the THz
wave emitter and scanner are on the opposite sides of the investigated objects). Both configurations allow for fast inspection of the tested object; however, the transmission one is more accurate for detecting small defects because of a higher amount of signal reaching the scanner. It is a result of the reduction of the distance between the scanner and the THz source, and thus the reduction of signal loss caused by absorbing the THz radiation with water in the air. Since the power of the radiation source used in the presented work is relatively low, the transmission mode was used in the tests, which allowed for the use of testing materials almost twice as thick as the reflection mode.

In this work, the alumina samples with intentionally introduced defects were studied with the use of THz radiation. The results were next compared to the X-ray images in order to confirm the location of the defects and the effectiveness of the THz waves.

2. Materials and Methods

2.1. Materials

As the studied materials, the ceramic blocks consisting of alumina (Al$_2$O$_3$) were chosen. This material was selected due to its great mechanical properties and high applicability for ballistic covers. Because of that, it has wide application in many fields, including the military, e.g., as ballistic-cover material [11]. Samples were in the form of square plates with the dimensions of 93 × 93 × 14.5 mm. The tested objects had intentionally introduced defects in the form of holes with a diameter of 2 mm located in various locations, and with various depths beyond the samples’ surface. The series of samples contained six objects including the defected. Each of them were prepared in two copies. The front surface of the selected sample, as well as the list of tested samples with detailed descriptions of defect locations in their interior are presented in Figure 1.

![Figure 1](image-url)

Figure 1. (a) The front surface of the selected sample, and (b) the list of tested samples with detailed descriptions of defect locations in their interior.

2.2. Methods

2.2.1. X-ray

For preliminary non-destructive tests, the X-ray diagnostic System MU17F, supplied by YXLON International GmbH (Hamburg, Germany), was used. It allowed for real-time inspection of the materials’ interior. X-ray tests were performed subsequently on each sample which was placed vertically, in such a way that the larger surface of the sample was oriented perpendicular to the X-ray axis. The operating voltage was 200 kV, and the lamp cathode diameter was 0.4 mm.

2.2.2. Terahertz Testing Method

The equipment used was sourced from the company Terasense Inc. Labs. The terahertz setup consisted of a linear line scanner (512 × 1 pixels image resolution with a pixel pitch of 0.5 mm and frequency of ~300 GHz), and a terahertz source in the form of the generator THz IMPATT (frequency 292 ± 5 GHz and power of ~10 mW). This source
includes novel reflective THz optics based on a specially configured high-gain horn antenna, in combination with a metallic mirror. This generator considerably improves the THz imaging capabilities of our linear scanner by increasing the amount of power reaching the sensor array.

Figure 2 presents a schematical representation of the experimental setup. The sample placed on the displacement device was moved along the scanner which scans the sample linearly. The shift was carried out with the speed selected in such a way as to possibly reduce the disturbances caused by the movement of the sample in reference to the scanner. The data were registered using dedicated software.

![Figure 2. Schematic representation of the investigation setup in transmission mode [10].](image)

3. Results

Figure 3 presents sample results that show the X-ray image (a) and the results of THz measurements (b). The results of X-ray tests confirmed the location of damage in the tested samples, but they did not allow us to determine how deep below the surface they were.

![Figure 3. (a) RTG image and (b) THz image of sample 3; white arrows indicate defect.](image)

In each sample, the terahertz method detected defects in the same places as in the X-ray results. The visible holes (marked with white arrows in the pictures) are apparently larger than 2 mm in diameter. It is worth noting here that the holes are not so clearly visible in all examined cases. This is due to their different depth beyond the surface of the sample.
4. Conclusions

In this work, the THz and X-ray images were presented. The efficiency of the THz scanner is much better in comparison to previously reported data. The data gathered via transmission mode results demonstrated the location of defects in the alumina ceramic objects and will be a basis for future studies of reflection mode. The latter will be helpful in determining the depth at which the defects are located.

In summary, the results confirmed that the Terahertz-based methods are very promising for the non-destructive inspection of ceramic materials. Further studies will be focused on minimizing the environmental influence on the obtained data by reducing the vibrations during scanning and choosing the exact image-processing methods.

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