Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

Kompozyty 11: 1 (2011) 75-79

KOMPOZYTY
COMPOSITES

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Otrzymano (Received) 01.02.2011

TERAHERZ FREQUENCIES ELECTROMAGNETIC WAVES - A NEW TOOL FOR INVESTIGATING COMPOSITE DEFECTS

In this paper the possibility of using a modern NDT technique - THz electromagnetic waves for composite materials defects detection and identification was investigated. Two technological defects were investigated - voids and internal delaminating. The composite materials were hand lay up made. Several kinds of reinforcing fibers (glass, basalt, jute) and polyester resin were used. Glass micro spheres and mica plates were placed at different depths in order to simulate technological defects. The specimens were tested using terahertz frequencies electromagnetic waves. The goal was to verify if the NDT method is appropriate to identify technological defects, misuse damage as well as determine parameters such as depth or size.

Keywords: **non-destructive testing, polymer composite, composite defects**

PROMIENIOWANIE ELEKTROMAGNETYCZNE O CZĘSTOTLIWOŚCI TERAHERCOWEJ - NOWE NARZĘDZIE DO BADANIA WAD KOMPOZYTÓW

Celem pracy było sprawdzenie możliwości wykorzystania nowoczesnej techniki badań nieniszczących, jaką jest zastosowanie promieniowania elektromagnetycznego w zakresie terahercowym do wykrywania i oceny defektów struktur materiałów kompozytowych polimerowo-włóknistych. Badania przeprowadzono dla wybranych wad technologicznych - pęcherzy powietrza. Badania przeprowadzone zostały dla kompozytów wykonanych metodą laminowania ręcznego. Wytworzono laminaty poliestrowe z różnymi rodzajami wzmocnienia (włókna szklane, bazaltowe, jutowe). W laminatach umieszczono na różnych głębokościach mikrosfery szklane, płytki miki i inne materiały, aby zasymulować obecności wad. Próbki poddano badaniom metodą terahercową w celu zbadania jej skuteczności w wykrywaniu wad technologicznych oraz eksploatacyjnych oraz określaniu takich ich parametrów, jak położenie oraz wielkość.

Słowa kluczowe: **metody nieniszczące badań, kompozyty polimerowe, wady kompozytów**

INTRODUCTION

Today Non Destructive Testing methods (NDT) of polymer composites ranges from taping to X ray, through ultrasound and using intelligent materials. While for metals there are some well-established NDT methods, for polymer composites there is still an open research field. What is the cause?

It is the very specific feature of polymer composites that product manufacturing proceeds simultaneously with creating the material. Therefore the final properties of both the material and product are gained in the same technological process.

Many product properties, such as dimensional accuracy, mechanical strength etc. as well as their repeatability are strongly dependent on the quality of the manufacturing process. This is the reason why the diagnostics of composites defects is so important. Diagnostics include:

- Detecting methods, both quantitative and qualitative describing defects
- Classification of defects
- Methods of both defects and damages repair
- Risk estimation for use in future
- Determination of defects causes as well as their prevention
- Analysis of customers' claims

What seems particularly difficult is to select an appropriate method for detecting and describing the defects and damage size. The reasons are the requirements for polymer composite testing methods. The testing method should be:

- Non destructive
- Touchless (without coupling agents)
- High-sensitive
- For infield inspection
- Appropriate for very large structure units inspection
- Appropriate for inspection of elements in operation
- Appropriate to use in the production line - providing fast information for technology correction

- Able to detect and locate internal defects
- Able to quickly provide information
- Suitable for rapid results interpretation
- Suitable for computerization (digitalisation of signal)
- Simple to calibrate
- Comparable - allowing simple results comparison between different labs and different devices
- Able to deliver map of material flaws
- Simple in use - routine maintenance of devices and result interpretation without the need of deep knowledge from human operator - every process engineer should be able to draw conclusions
- Inexpensive - low costs of tests as well as testing devices

In this paper the possibility of using terahertz (THz) electromagnetic waves for composite material defects detection and identification was investigated. Two technological defects were investigated - voids and internal delaminating. Because of the difficulties with obtaining composites with defined flaws materials such as microspheres and mica simulated them.

TERAHERTZ SPECTROSCOPY

In the last years, terahertz spectroscopy has gained more interest because of its unique capabilities. THz radiation lies above the frequency range of traditional radio and microwaves but below the range of infrared waves (Fig. 1) [1]. THz radiation has a very good spatial resolution and penetration depth. Many dry, non-metallic materials like polymers, ceramics, etc. show little THz absorption, which allows one to imagine their internal structure with THz. Moreover, THz has the potential for a higher resolution than microwaves due to its shorter wavelength.

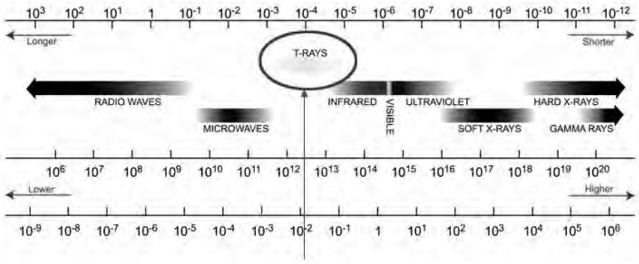


Fig. 1. Electromagnetic spectrum and THz (T Rays) frequency range

Rys. 1. Spektrum fal elektromagnetycznych i zakres promieniowania THz (T Rays)

THz radiation is also non-ionising which makes it less risky for service staff and attractive for biological applications. Unfortunately, THz cannot penetrate metals and materials with some water content.

There are two types of THz radiation technology in use: continuous wave and pulsed. Continuous wave technology works at single frequencies and cannot provide spectroscopic information but is easier to use. Pulsed technology uses ultra short current pulses, which are generated by femtosecond laser pulses in photoconductive dipole antennas [2]. The THz pulse is sent to the sample, received by a second antenna of similar design and the results in a waveform are recorded in a time domain. The obtained data are temporal data, i.e. time domain. By means of the Fourier transformation, this waveform can be analysed in frequency.

All the measurements described in this paper were carried out using a time domain spectroscope T Ray 4000 from Picometrix. Photoinductive antennas were used as transmitting and receiving devices, which means that the system was configured in the reflection mode [2, 3]. The photo of this system is shown in Figure 2.

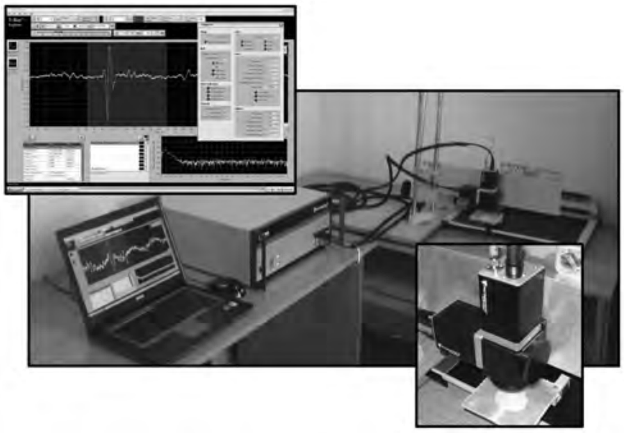


Fig. 2. Time domain spectroscope T Ray 4000 from Picometrix

Rys. 2. Spektroskop T Ray 4000 firmy Picometrix

THz time domain imaging can basically provide three types of data collection modes: A-scan, B-scan, C-scan. The A-scan is a signal provided during a single point measurement - the receiving waveform consists of reflected and transmitted pulses. The amplitude, shift in phase and time provide the information about the investigated structure and its flaws. The B-scan consists of a set of A-scans. During 2D inspection a 3D signal can be acquired. The plane for a chosen delay time value constitutes a C-scan. Depth *z* in the investigated material is correlated with the value of delay time, so a C-scan is a depth-specific slice [2, 3]. All the data collection types are shown in Figure 3.

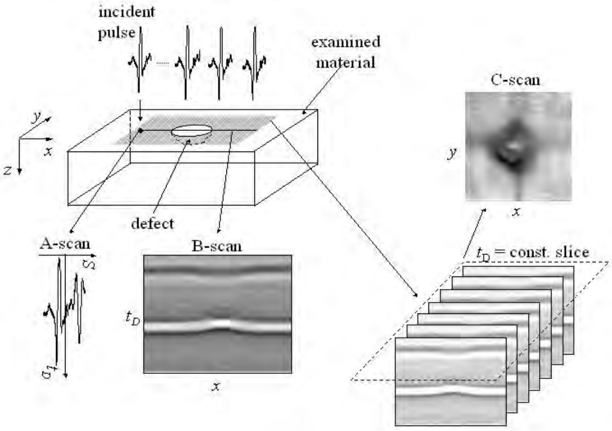


Fig. 3. Data collection types in THz time domain

Rys. 3. Sposoby obrazowania danych w metodzie impulsowej terahercowej spektroskopii czasowej

INVESTIGATED MATERIALS - STAGE I

All the composites were made by a hand lay up method. After polymer matrix curing, the polymer plates for THz measurements were cut out. The specimens were tested with the THz pulsed time domain method in the reflection mode. The results of the investigations were gathered in Table 1.

Composite I

Polymer matrix - polyester resin Polimal 109, cured with cobalt accelerator and initiator Metox 50.

Reinforcement - glass roving fabric 200 g/m², reinforcement content 32 wt.%, plate thickness 4 mm

Composite II

Polymer matrix - the same as in composite I

Reinforcement - jute fabric 300 g/m², reinforcement content 21 wt.%, plate thickness 6mm

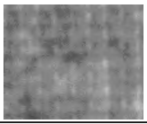
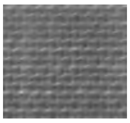
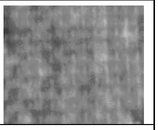
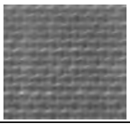
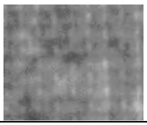
Material simulating composite flaws: glass microspheres Scotchlite 3M E22/400 with diameter 35 μm, glass microspheres Reiter Q-CEL-300 with diameter 90 μm. Glass microspheres were placed under each layer of reinforcement.

Results - Stage I

Here is no image of voids in the B-scan or C-scan. This might be caused by too small resolution of the received images and the lack of electromagnetic wave deflection from the glass microspheres. Because of the negative results, tests were performed only for specimens with voids under the first layer.

TABLE 1. **Example of THz tests results for composites with microspheres simulating voids**

TABELA 1. **Przykład rezultatów badania THz dla kompozytów z mikrosferami imitującymi pustki**

Com-posite	Specimen No	Defect	Specimen picture	B-scan	C-scan
I	1	No flaws			
	6	Voids Microspheres diameter 35μm under first layer			
II	1	No flaws			
	6	Voids Microspheres diameter 90μm under first layer			

INVESTIGATED MATERIALS - STAGE II

Composite III

Polymer matrix - the same as in composite I

Reinforcement - 6 plies of glass mat Vetrotex Unifilo 4750-138, 450 g/m², reinforcement content 30 wt.%, plate thickness 6 mm.

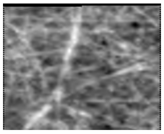
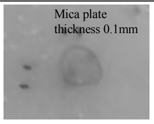
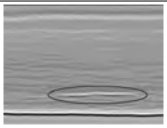
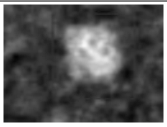
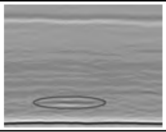
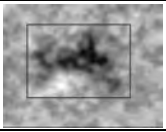
Material simulating composite internal delamination: mica plate thickness 0.10 mm, piece of PTFE thickness 0.58 mm.

Results - Stage II

Both inclusion materials can be observed in the B-scan and C-scan. It allowed the determination of the defects locations (depth) and their dimensions. In the case of using mica plates, it is possible to determine relatively precise dimensions and shape of the inclusion.

TABLE 2. **Example of THz tests results for composites with mica and PTFE simulating delaminations**

TABELA 2. **Przykład rezultatów badania THz dla kompozytów z miką i PTFE symulującymi delaminacje**

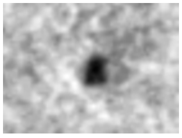
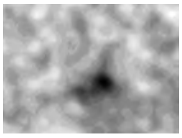
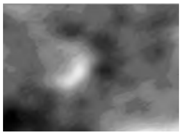
Com-posite	Speci-men No	Specimen picture	B-scan	C-scan
III	1			
	2			
	3			

INVESTIGATED MATERIALS – STAGE III

Since the best results were obtained using mica plates, composites with different kinds of fibres and mica plates simulating inner delaminations were produced. Subsequently, all the composites were made by a hand lay up method.

TABLE 3. **Example of THz tests results for polyester-glass composites with mica plates simulating delaminations**

TABELA 3. **Przykład rezultatów badania THz dla kompozytów poliestrowo szklanych z płytkami miki symulującymi delaminacje**

Composite	Specimen	Defect	B-scan	C-scan
IV	4	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under first layer		
	5	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under third layer		
	6	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under fifth layer		

Composite IV

Polymer matrix - polyester resin Polimal 1094 AWTP-1, cured with initiator Metox 50.

Reinforcement - 6 plies of glass mat Vetrotex Unifilo 4750-138, 450 g/m², reinforcement content 30 wt.%, plate thickness 4 mm

Material simulating composite internal delamination: mica plate 5x8mm, thickness 0.15mm

Composite V

Polymer matrix - the same as in composite IV - 6 plies of basalt fabric 200 g/m², reinforcement content 30 wt.%, plate thickness 2 mm

Material simulating composite internal delamination: mica plate 5x8 mm, thickness 0.15 mm

Composite VI

Polymer matrix - the same as in composite IV - 6 plies of jute fabric 300 g/m², reinforcement content 21 wt.%, plate thickness 6 mm

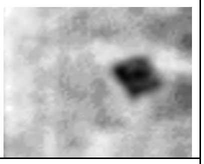
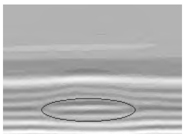
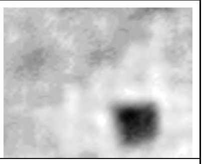
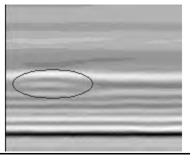
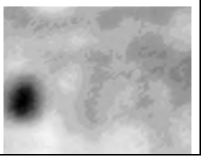
Material simulating composite internal delamination: mica plate 5x8 mm, thickness 0.15 mm

Results – Stage III

The specimens were investigated with the THz pulsed time domain method in the reflection mode. The tests results were gathered in Tables 3-5.

TABLE 4. **Example of THz tests results for polyester-basalt composites with mica plates simulating delaminations**

TABELA 4. **Przykład rezultatów badania THz dla kompozytów poliestrowo bazaltowych z płytkami miki symulującymi delaminacje**

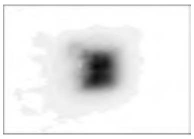
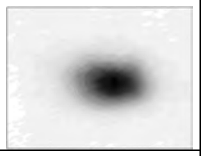
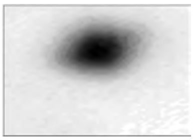
Composite	Specimen	Defect	B-scan	C-scan
V	4	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under first layer		
	5	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under third layer		
	6	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under fifth layer		

As might be seen in Tables 3-5, despite the kind of reinforcing fibres used, the inclusion of mica is noticeable in the B-scan and C-scan on each depth. Of course with an increase in depth of where the inclusion was induced, the picture on the C-scan looses sharpness, especially when glass reinforcement was used. However, in the case of basalt reinforcement, the changes in structure might be easily observed in the B-scan, so it could be noticed under which layer the defect is placed.

For the unknown character of the flaw, the B-scan and C-scan allowed us to determine quite precisely the diameters (including thickness) as well as the location of the defect.

TABLE 5. **Example of THz tests results for polyester-jute composites with mica plates simulating delaminations**

TABELA 5. **Przykład rezultatów badania THz dla kompozytów poliestrowo jutowych z płytkami miki symulującymi delaminacje**

Composite	Specimen No	Defect	B-scan	C-scan
VI	4	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under first layer		
	5	Delamination, inclusion Mica plate 5x8mm, thickness 0.15mm under third layer		
	6	Delamination, inclusion Mica plate 5x8mm, thickness 0,15mm under fifth layer		

CONCLUSION

The THz pulsed time domain method in a reflection mode allowed the detection of structure flaws in polymer composite materials containing different kinds of reinforcement, such as: glass, basalt as well as natural fibres. It was not possible to detect voids smaller than 90 μm.

This testing method is still under research but already has some advantages over other NDT methods, such as the eliminating of direct contact necessity with the testing material or coupling agent.

THz imaging technology seems to be very promising for identifying and evaluating polymer composite defects and damage, however additional progress in scanning speed as well as data processing is necessary to implement THz as an effective tool.

Acknowledgment

This work was supported by the Polish Ministry of Science and Higher Education under project no N 510 538039

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