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NON-DESTRUCTIVE TESTING OF THERMOPLASTIC CARBON COMPOSITE STRUCTURES

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Abstract

The article is in line with the contemporary interests of companies from the aviation industry. It describes thermoplastic material and inspection techniques used in leading aviation companies. The subject matter of non-destructive testing currently used in aircraft inspections of composite structures is approximated and each of the methods used is briefly described. The characteristics of carbon pre-impregnates in thermoplastic matrix are also presented, as well as types of thermoplastic materials and examples of their application in surface ship construction. The advantages, disadvantages and limitations for these materials are listed. The focus was put on the explanation of the ultrasonic method, which is the most commonly used method during the inspection of composite structures at the production and exploitation stage. Describing the ultrasonic method, the focus was put on echo pulse technique and the use of modern Phased Array heads. Incompatibilities most frequently occurring and detected in composite materials with thermosetting and thermoplastic matrix were listed and described. A thermoplastic flat composite panel made of carbon pre-impregnate in a high-temperature matrix (over 300°C), which was the subject of the study, was described. The results of non-destructive testing (ultrasonic method) of thermoplastic panel were presented and conclusions were drawn.

Keywords: thermoplastic, pre-impregnate, non-destructive testing, ultrasonic method, Phased Array.

1. INTRODUCTION

The main purpose of the article is to verify the possibility of performing quality control using ultrasonic testing of thermoplastic materials. The article focuses on verifying the ability to detect various types of non-conformances that may occur in aircraft components.

Thermoplastic materials have been successfully used in many branches of industry for over 25 years. The most popular thermoplastics in industry are: Polystyrene (PS), Polyvinyl chloride (PVC), Low (LDPE) or High (HDPE) Molecular Density Polyethylene, PEEK (PolyEtero-EteroKeton), PEKK (PolyEtero-Ketone-Keton) and PPS (PolyPhenylene Sulfone). PEEK, PEKK and PPS, due to their high mechanical, chemical and thermal resistance of 400°C, are considered to be the best matrix materials. PEEK, PEKK and PPS. Despite their high price, they are willingly used for the production of glass and carbon pre-impregnates [1].

Until recently, the main materials used in aircraft production were aluminum alloys, titanium and steel. This was due to their high strength and mechanical parameters. In addition, these materials were well known and gradually improved so that they would not lose their properties when reducing the weight of the element. Despite the great progress in the improvement of aluminum alloys, the largest aircraft manufacturers focused their attention on composite materials. Every new Boeing product contains an increasing percentage of composite materials [2]. Figure 1 shows a comparison of the materials used in the production of different Boeing aircraft.

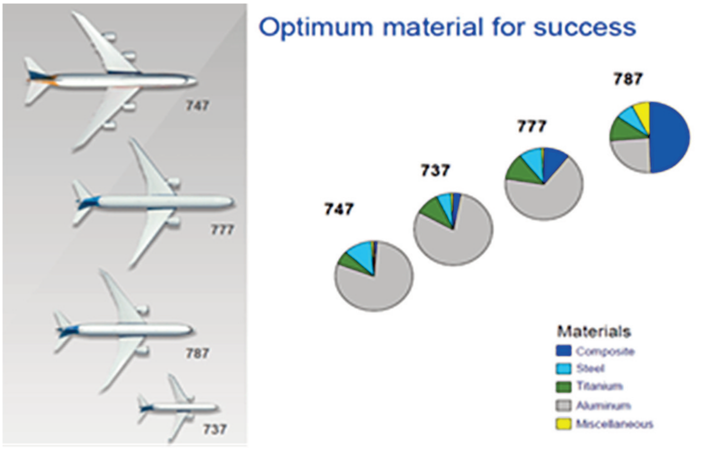


Fig. 1. Comparison of materials used in the production of Boeing aircraft [2].

Carbon prepregs in thermoplastic polymeric matrix have high strength parameters and low density in comparison to aluminum alloys. Thanks to this it is possible to produce a high quality element with a very low unladen weight. Reduction of aircraft weight in the aviation industry is very desirable, because lowering the aircraft's operating empty mas makes it possible to take on board more people/goods, smaller fuel consumption, greater flight range. Due to the great interest in thermoplastic materials by companies such as Boeing, Airbus more and more companies have in its offer pre-impregnates on the basis of high-temperature thermoplastics (TOHO, TENCATE, SUPREM) [3].

Observing the constantly developing aviation industry, the Institute of Aviation in its development policy wishes to follow the world technologies of aircraft manufacturing and research on the latest composite materials [4, 5]. The Institute already has experience in the production and research of monolithic and interlayers composites made of thermosetting even with advanced materials such as composites reinforced with graphene flakes [6]. The current challenge at the Composite Structures Manufacturing Division of the Institute of Aviation is the development of technologies for the production of aircraft components and structures from carbon fibre-reinforced thermoplastic materials. Another important task is to implement non-destructive tests to assess the quality of thermoplastic products.

2. INTRODUCTION TO NON-DESTRUCTIVE TESTING AND THERMOPLASTIC MATERIALS

2.1. Non-destructive testing

Non-destructive testing (NDT) is a broad group of analytical techniques used in industry and scientific entities. It is used to assess the properties of a material, component or system without causing damage [7]. The notion of NDE (NDE nondestructive examination, NDI nondestructive inspection, NDE nondestructive evaluation) can be found in different translations depending on the region of the world and they belong to the same methods of testing. The use of NDT allows to evaluate the tested object both at the production and exploitation stage. Wide application of NDT allows to reduce technology development time, reduce the number of prototypes and destructive testing [8, 9]. In the aerospace industry, the advantages of using NDT at the stage of production process and during cyclic testing of flying machines have long been noticed. Non-destructive testing is the basis for quality control of aircraft, without which no major aviation company can imagine functioning.

In the aviation industry the most frequently used non-destructive methods are:

- **Visual method** – is the basic and the most common non-destructive method consisting in the visual inspection of the examined object with an armed or unarmed eye. Figure 2 shows an example of a visual inspection.
- **Ultrasound method** – consists in introducing an ultrasound wave of a specific frequency into the structure of the examined object. On the basis of A-scan imaging (amplitude in time), the controller is able to determine whether there are defects inside the material or the structure has been damaged during operation. Figure 3 shows an example of an ultrasonic inspection during routine operational control.
- **Thermal imaging method** – consists in heating (with the use of lamps) the whole element or a specific fragment to a preset temperature, and then observing the loss of heat inside the structure. This observation is made with the use of a thermal imaging camera and a computer unit [12, 13]. Figure 4 shows the ideas of thermal imaging inspection.

Fig. 2. Visual inspection of the aircraft during operation [10].

Fig. 3. Ultrasonic inspection of an aircraft during operation [11].

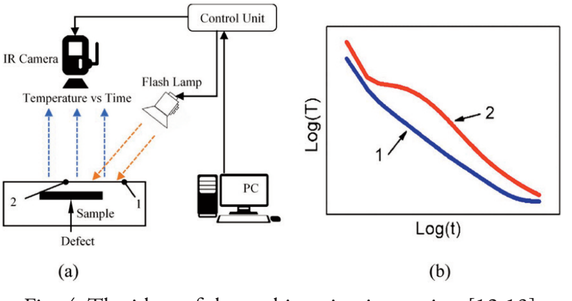


Fig. 4. The ideas of thermal imaging inspection [12,13].

- **Acoustic method (low frequency)** – the method consists in introducing mechanical (acoustic) vibrations into the material. Based on the height of the received sound, the controller determines whether there is a defect in the structure or not. Figure 5 shows a Tap test performed to detect the lack of adhesion of the coating to the filler [14].
- **Interferometer method (wide graphical)** – the method consists in loading the composite element and then through the reflection of optical laser light the local deformations of the element are observed.

In places where there are defects, the imaging is definitely different from the rest of the element. Figure 6 shows an example of a wide-graphic inspection.

Fig. 5. Inspection of a composite structure by means of the tap lowering technique [15].

Fig. 6. Inspection of composite structure by means of the wide-graphic method [16].

2.2. Thermoplastic materials

Thermoplastic composite materials differ from widely used and known thermosets. As shown in Figure 7, in the initial phase the polymer resin has a low molecular weight and a very low density. The curing process in the polymer begins to form very strong cross-linked and cross-linked covalent bonds. Thanks to such a strongly cross-linked structure, after curing the material becomes very strong, but also brittle and unrecyclable. In addition, it undergoes degradation during long-term thermal operation [17].

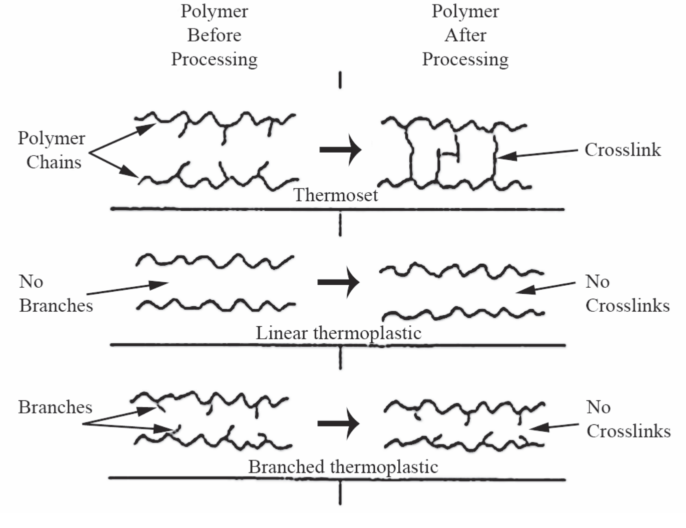


Fig. 7. Difference in polymer structure between thermoplastics and thermosets [17].

Thermoplastics, on the other hand, do not form a spatially cross-linked structure after curing. They have a high molecular weight, which due to their structure are capable of multiple transitions from plastic to solid state. In classical thermoplastic polymers, long chains of macromolecules form atoms connected by covalent bonds. These chains, on the other hand, are connected by weak secondary bonds. These materials, due to their construction, are more resistant to impacts with low energy in relation to thermosets. The impact resistance is strictly dependent on the content of the crystalline phase. The lower the share of the crystalline phase-ordered and the higher the amorphous phase-disordered, the better the energy absorption properties. The content of the crystalline phase can be controlled by the cooling speed of the material after the thermal forming process (transition of the material from viscous to solid state). Figure 8 shows the difference in the crystalline and amorphous phases.

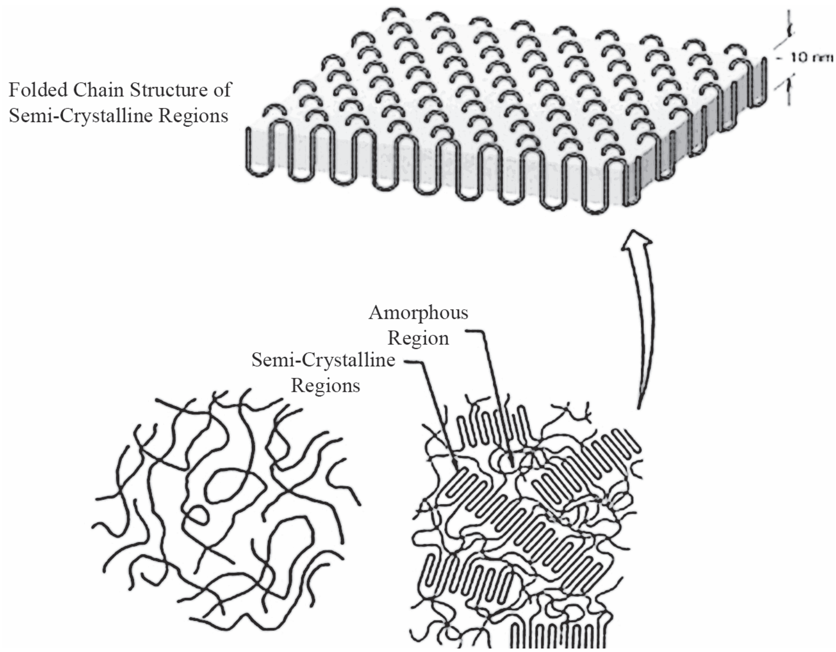


Fig. 8. Difference between the crystalline and amorphous phases [17].

Despite the lower strength of the thermoplastic matrix, the largest aviation companies are more and more willing to use carbon prepregnates in the PEEK matrix for the second and even the first-class composite structures. The main advantage of these materials is relatively good strength, almost infinite shelf life and multiple processing of the same material into different elements [18, 19]. For example, the Airbus A380 aircraft uses PEEK reinforced with carbon fibre for “central wing box” construction elements, floor beams of the upper deck, rear pressure rebate, thus reducing the weight of the aircraft by approx. 1.5 t [20]. Figure 9 shows the use of composite materials in the A380 aircraft.

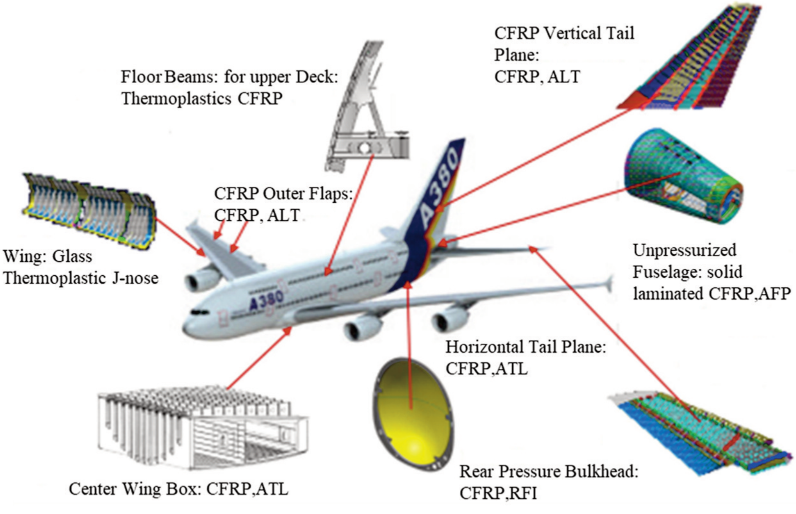


Fig. 9. Use of composite materials in the Airbus A380 [20].

3. ULTRASONIC TESTING OF A THERMOPLASTIC COMPOSITE ELEMENT

3.1. Types of defects in thermoplastics

Defects occurring during the production of composite materials can significantly weaken the entire structure. Too much weakening of the structure, in aviation may result in an air crash. For this reason, each composite element should be subjected to non-destructive tests to assess the quality and suitability of the element for further stages, e.g. for strength tests or operation. Thermoplastic materials usually have flat or low volume defects. They are located between the layers of carbon reinforcement and oriented parallel to the plane of the element. The most common defects in thermoplastic composite materials are shown in Figure 10.

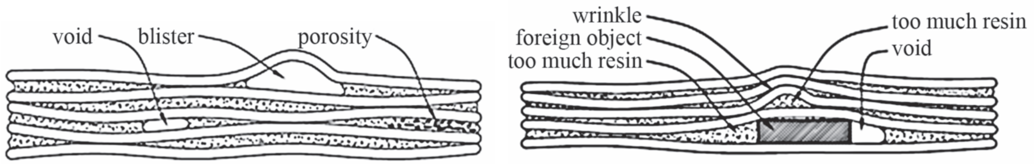


Fig. 10. Typical defects in thermoplastic composite [21].

As shown in Figure 10, defects in thermoplastic materials are mostly air trapped in the material. This type of defect is most often detected by ultrasonic testing. The following part of the article focuses only on the above-mentioned method of non-destructive testing.

After non-destructive testing and detection of non-compliance, each indication should be evaluated, which consists in determining the type of non-compliance outstanding, specifying the location, evaluating the size and possibly determining the energy drop of the bottom echo from a given indication. On the basis of the above mentioned data and information placed in appropriate procedures, the decision-makers (controller, calculator) decide on further handling of the product. The element in which the non-compliance has been detected may be accepted, repaired or rejected. Often, it is not an easy and unambiguous decision, because while the inspector should not have problems with the exact location of defects and their dimensioning, the determination of the type of defect is a problem. Difficulties are great, because images on the defectoscope amplitude as a function of time are very similar as well as non-uniform for various types of defects.

3.2. Description of the tested object

The tested element was a flat plate of thermoplastic material. The reinforcement was a carbon fabric with a high-temperature warp. The plate was manufactured in accordance with the manufacturer's procedures and material card (curing temperature over 300°C, pressure over a dozen bar). A pressed thermoplastic panel is shown in Figure 11.

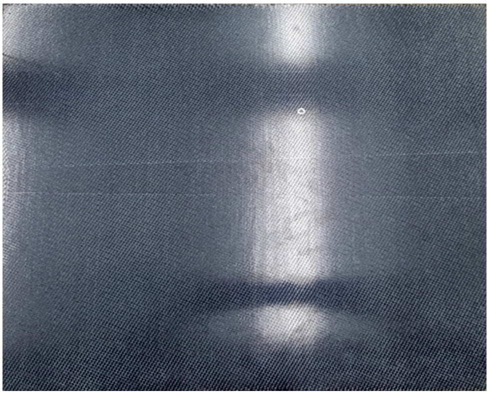
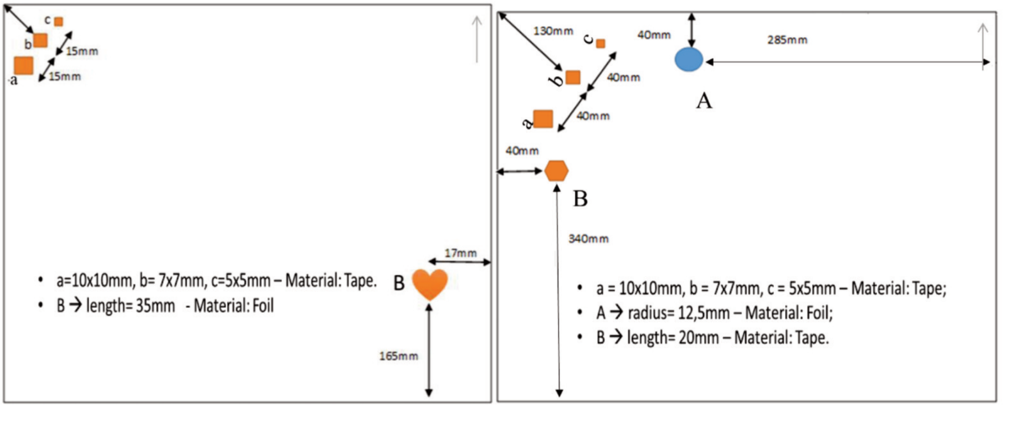


Fig. 11. Thermoplastic panel [author 2018].

The purpose of creating a test panel was to verify the manufacturing technology and to develop a testing methodology for thermoplastic material. In order to achieve this goal, various types and sizes of artificial defects had to be introduced during the production of the panel. The minimum defect meant the smallest defect threatening the structure (the size was determined on the basis of our own experience). Subsequent defect sizes were introduced in the laminate in order to verify what minimum defect size the controller is able to detect at particular depths (in the case of not detecting a minimum defect). The shape of defects was determined freely, the idea was to introduce defects of different shapes in order to verify the reflection of the actual shape during the test. The laying of the panel together with the introduction of artificial defects is shown in Figure 12.



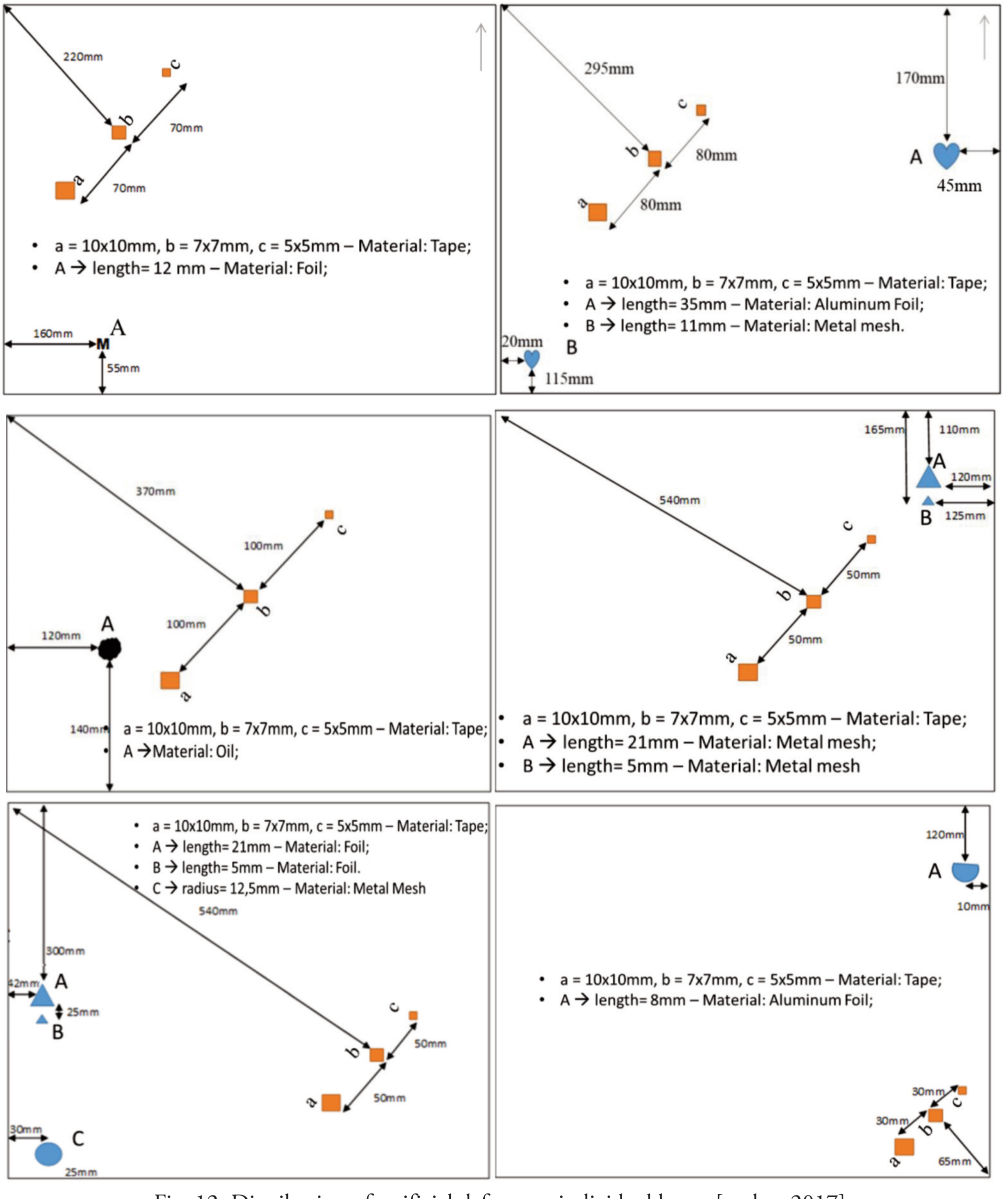


Fig. 12. Distribution of artificial defects on individual layers [author 2017].

3.3. Description of the test method

An ultrasonic pulse-echo method was used to examine the panel made of thermoplastic material. The ultrasonic method is the most commonly used method when testing aircraft made of different construction materials. The testing of thermoplastic materials is difficult because, unlike isotropic materials such as steel, aluminum alloys, laminates have different acoustic impedances inside the material. The second limitation is the anisotropy of the composite material itself. The strong anisotropy of carbon laminate on a macroscopic scale is due to two factors. Firstly, a targeted arrangement of reinforcing fibres in individual layers, and secondly, the fact that the carbon fibres themselves have different modulus of elasticity in the longitudinal and transverse direction. The Young's modulus of carbon fibre (graphite) in the longitudinal direction is much higher than in the transverse direction. It is this property that makes the anisotropy of carbon laminates much higher than that of laminates with other types of reinforcing fibres (e.g. glass, aramid) [22]. The third issue that poses problems during the analysis of ultrasonic research results is the influence of the crystalline phase on the ultrasonic wave. The formation of the crystalline phase can be controlled to some extent by the cooling rate of the material during production.

The ultrasonic method is a volumetric test. The idea of ultrasonic testing is to create and introduce ultrasonic waves, i.e. mechanical vibrations of frequencies above 20 kHz into the material. In thermoplastic materials the heads of frequencies 2.5÷15 MHz are used in practice. In the pulse-echo technique, after the introduction of ultrasonic wave, this wave penetrates the material (into the depth), after which it is reflected from the opposite wall (bottom) of the material and returns back to the ultrasonic head. During the test, the controller observes the defectoscope screen, where the amplitude as a function of time (the so-called A-scan) is shown. On the basis of the obtained images, the controller evaluates the given structure. Figure 13 shows two images – without defects and with a defect.

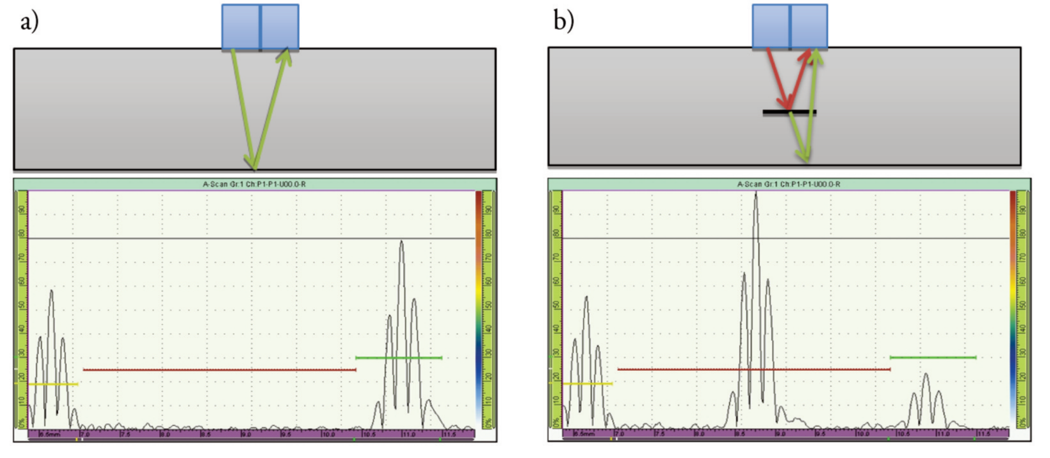


Fig. 13. A-scan-type imaging: a) material without defects, b) material with a defect [author 2017].

Figure 13a shows the ultrasonic wave produced by the transducer penetrating the test material, then the wave is reflected from the opposite surface (bottom of the element) and returned to the transducer. In such a situation, the A-scan image contains two amplitudes. The first one (included in the yellow gate) comes from the upper surface (it is called the wave input or transmitting signal), the second (included in the green gate) comes from the reflection of the wave from the bottom of the material. Figure 13b shows the following situation: the UT wave introduced into the material penetrates the material, in which it encounters a defect and most of the energy is reflected from it back to the head. A small part of the wave further penetrates the material and returns to the head after rebounding from the bottom. On the defectoscope screen three amplitudes will be visible in the yellow and green gate, these are the amplitudes as in the previous example, while in the red gate there is the amplitude reflected from the defect.

At present, it is possible to use multi-processor heads in ultrasonic testing technology. These transducer heads have an advantage over conventional ones for several reasons. First of all, they allow to examine a larger area of the element at the same time, but most of all to obtain a larger number of images. In addition, it is possible to easily record the test performed and analyze calmly at any time (unlike conventional tests, where testing and evaluation is performed only in real time). Figure 14 shows the ideas of Phased Array heads.

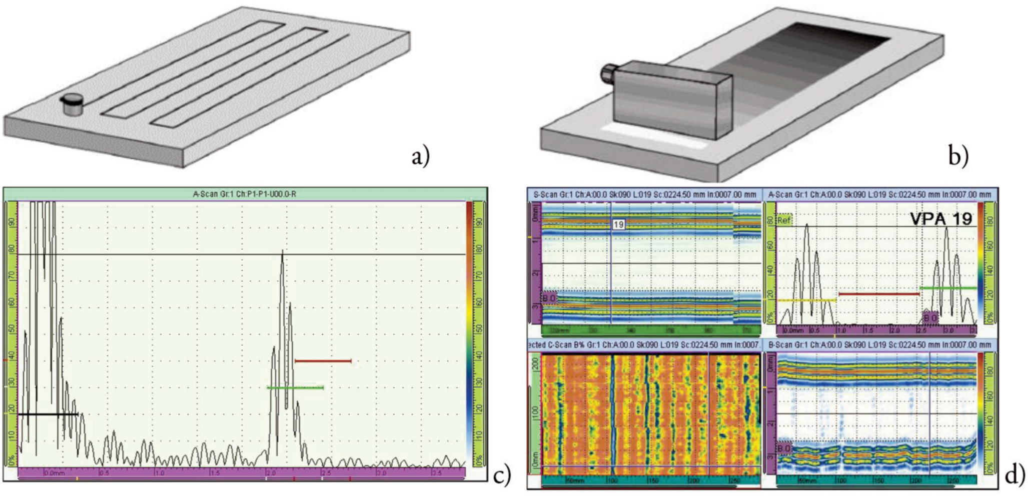


Fig. 14. Comparison of tests with conventional and multi-processor head: a) test surface with conventional head [23], b) test surface with multi-processor head [23], c) typical illustration for conventional head, d) typical illustrations at multi-processor head [author 2017].

Larger test area in a single shift of the head reduces the time it takes to perform a test, thus reducing the test costs. The higher number of images and the calm evaluation of the examined element translates into greater reliability and accuracy. The disadvantage of using multi-converter heads is that it is more difficult to calibrate the head.

Inspection of flat thermoplastic panels was carried out using the Omniscan MX system with the OMNI-M-PA32128 module. The panel was tested with a 5L64-NW1 multi-converter head with a frequency of 5 MHz and 64 transducers. Soft filtered water was used as a coupling medium. The instrumentation used is shown in Figure 15.

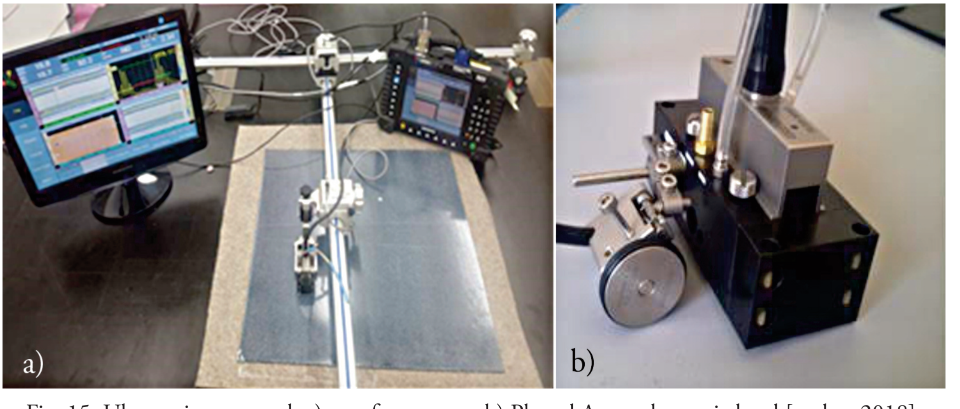


Fig. 15. Ultrasonic test stand: a) set of apparatus, b) Phased Array ultrasonic head [author 2018].

4. ULTRASOUND RESULTS OF THERMOPLASTIC COMPOSITE ELEMENT

4.1. Introduction to test results

Ultrasonic tests were performed in accordance with the procedures in force in the Department of Composite Structures Technology of the Institute of Aviation, where, on a daily basis, non-destructive tests of monolithic and interlayer composite structures are carried out. Before testing, the measuring equipment was calibrated. The calibration consisted in the selection of the appropriate ultrasonic wave speed, delay setting in the delay wedge, calibration of the head sensitivity, selection of aperture and focal length, calibration of encoders in the X and Y axes. The sensitivity of the test was set so that the amplitude from the bottom echoes was 80% of the FSH (screen height A-scan).

The thermoplastic test panel, as mentioned in section 3.2, was made by introducing artificial defects in certain layers of the laminate. Figure 16 shows an illustrative view from above of all defects, the colours indicate different depths of artificial defects. The picture also shows an approximate area that cannot be examined due to the construction of the Phased Array head delay wedge (this area is called the dead zone). All defects that are in the dead zone are undetectable.

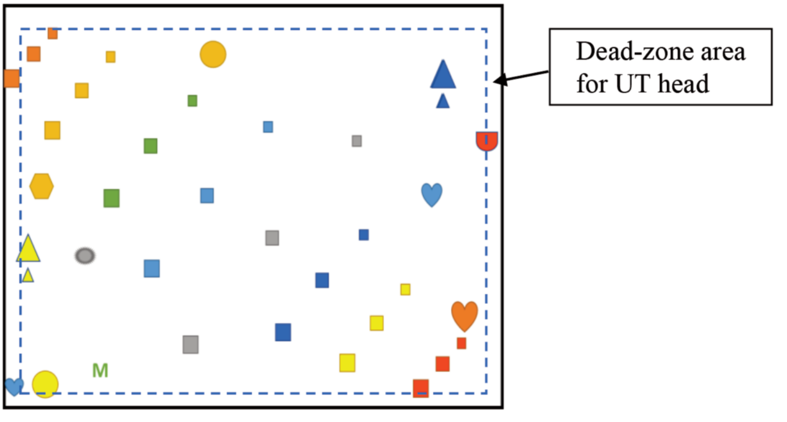
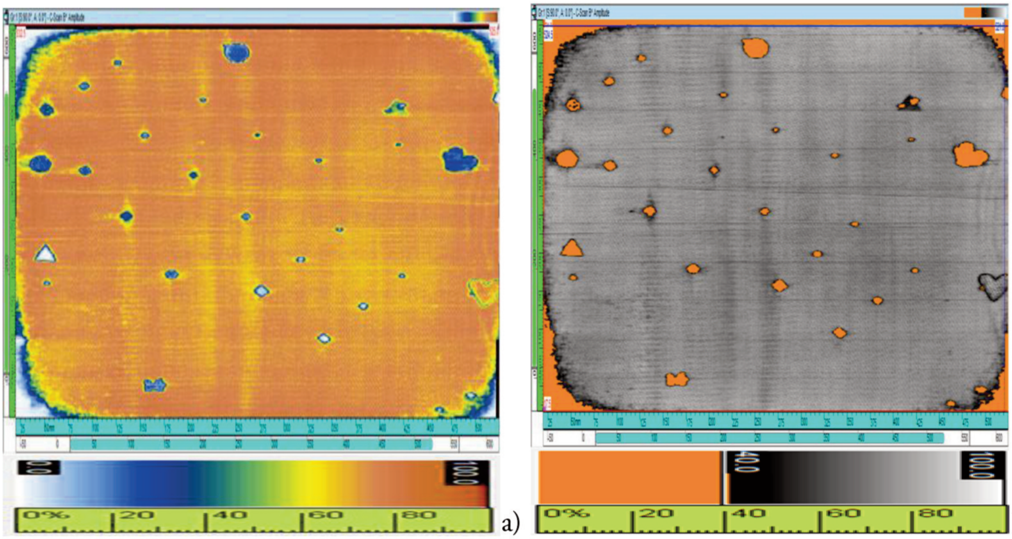


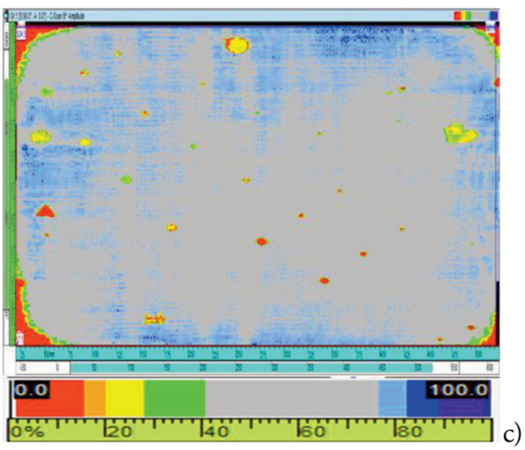
Fig. 16. Viewing sketch of artificial defects located at different depths [author 2018].

The Tomo View software was used to analyze the test disc, which allows for the full spectrum of images.

4.2. Bottom echo drop analysis

In the first stage of the analysis, the bottom echo drop was analyzed depending on the size, type and depth of the defect. From the physical point of view, each type of defect occurring in thermoplastic material should cause a decrease in bottom echo amplitude. Depending on the type of the size and depth of the defect, this decrease will be different. It is worth noting that the bottom echo drop does not always indicate that the defect has been deposited in the material. Such a slope may also cause a thicker layer of matrix between layers, deformed fibres, small cracks in the matrix, or surface defects both on the upper surface (UT wave entry) and bottom echoes. Figure 17 shows the height of the signal (amplitude) of he bottom echoes and the analysis of the bottom echo drop.





The description of amplitude drop for figure 17c:

0÷16% FSH	– red –	echo drop 14 dB and more;
16.01÷20% FSH	– orange –	echo drop 12÷14 dB;
20.01÷28.5% FSH	– yellow –	echo drop 9÷12 dB;
28.51÷40% FSH	– green –	echo drop 6÷9 dB;
40.01÷77% FSH	– grey –	decrease to 6 dB;
77.01÷83% FSH	– blue –	correct bottom echo amplitude;
83.01÷90% FSH	– garnet –	acceptable bottom echo amplitude in small amounts;
90.01÷100% FSH	– violet –	abnormal bottom echo amplitude;

Fig. 17. Analyses of the signal from the bottom of the material:
a) FSH height of amplitude from the bottom of the material, b) analysis of the defect criterion (6 dB bottom echo drop), c) amplitude drop from the bottom of the material [author 2018].

The above images show that an oil type defect does not cause an echo of the bottom and is not visible in the images and has therefore not been detected. Probably as a result of high temperature and pressure, the oil stain evaporated or mixed with the oil matrix and will only become visible during operation. The steel mesh triangle and the foil heart can be seen in the images of the amplitude drop. However, they were not considered as incompatibilities as the bottom echo drop was less than 6 dB. A steel mesh triangle causes too little UT-wave attenuation. The heart of the foil was not detected because the amplitude of the reflection of the wave from the defect is contained in the gate “B”. (bottom echoes). The reason for this situation is a defect too close to the bottom of the thermoplastic plate. It is worth noting that the defects made of high-temperature tape placed on the same layer better separated the pre-impregnation layers, thanks to which the amplitude from the defect found itself outside the “B” gate. The corners of the board are strongly suppressed, probably as a result of insufficient pressure exertion in these places during the pressing process. For this reason, some artificial defects were not detected. The best attenuation of the ultrasonic wave is plastic tape, followed by high-temperature foil, aluminum foil, and the weakest metal mesh.

4.3. Analysis of ultrasonic wave reflection from artificial defects

The second very useful imaging is the signal reflected by the incompatibilities in the material. This imaging is extremely useful when detecting delaminations, stratifications/ ply separations, non-adhesives, inclusions of foreign material. The reflection of the ultrasound wave depends, among other things, on the difference in acoustic impedance of the native material and defects, the size of defects, the depth and position of defects in relation to the UT wave. During the thermoplastic panel research two most useful types of images were used: amplitude and time. Amplitude imaging can be used to determine the amount of reflected energy from a given defect, while time imaging determines the depth of the defect. Figure 18 shows the analysis on the basis of these images.

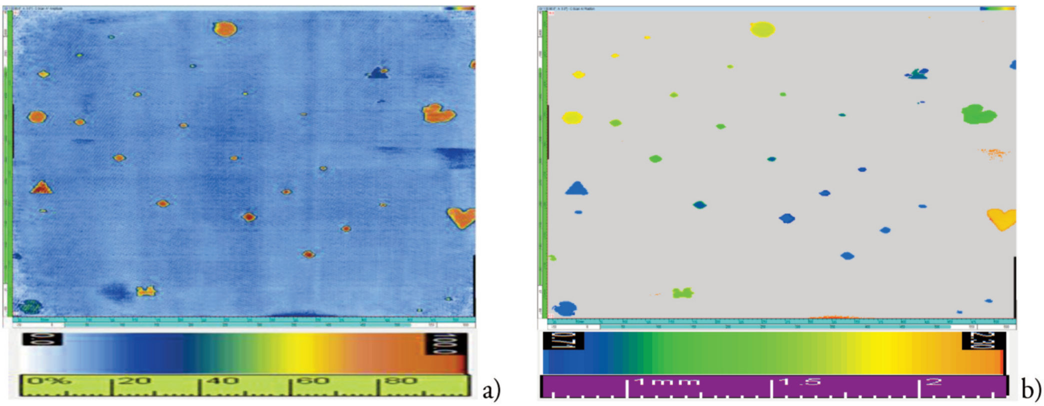


Fig. 18. Analysis of signal reflected from artificial defects:
a) amplitude imaging, b) time imaging [author 2018].

As in the previous images, an oil stain type defect was not detected. On the other hand, a defect invisible earlier was detected – a circle in the lower left corner of the plate and the heart and triangle described in point 4.2. On the time picture it is very easy to determine the depth of the artificial defects. In this particular case, the reflection of the ultrasound wave from the defects is better than that of the bottom echo drop. There are, however, types of defects which cannot be detected in the UT wave reflection imaging.

In order to determine which type of artificial defects are easier to detect and which are more difficult to compare indications from different types of defects lying at the same depth. The comparison is shown in Figure 19.

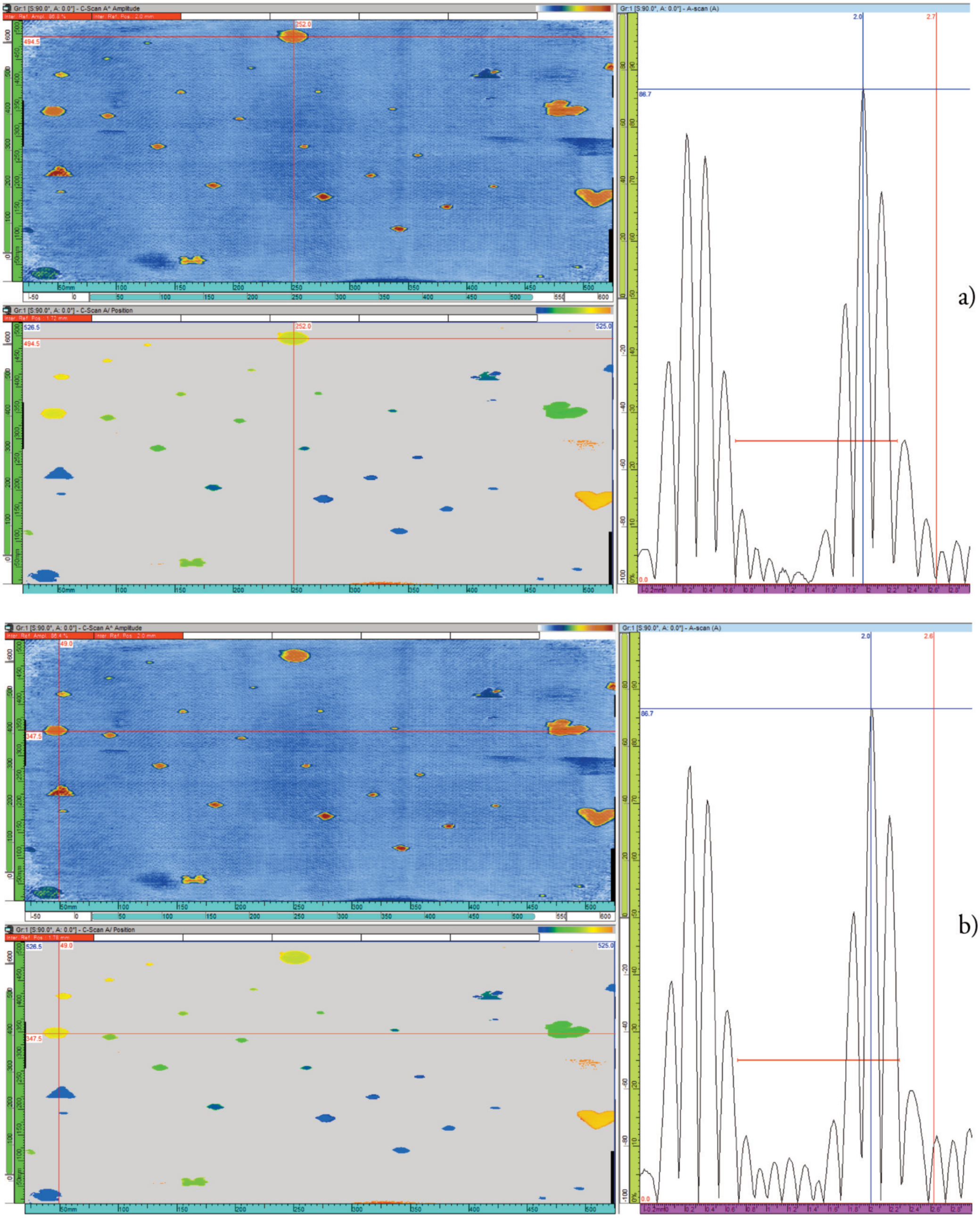


Fig. 19. Analyses of the reflected signal from artificial defects:
a) high-temperature foil of Ø20 mm dimension at the depth of 2 mm,
b) high-temperature tape of 12.5 mm dimension at the depth of 2 mm,

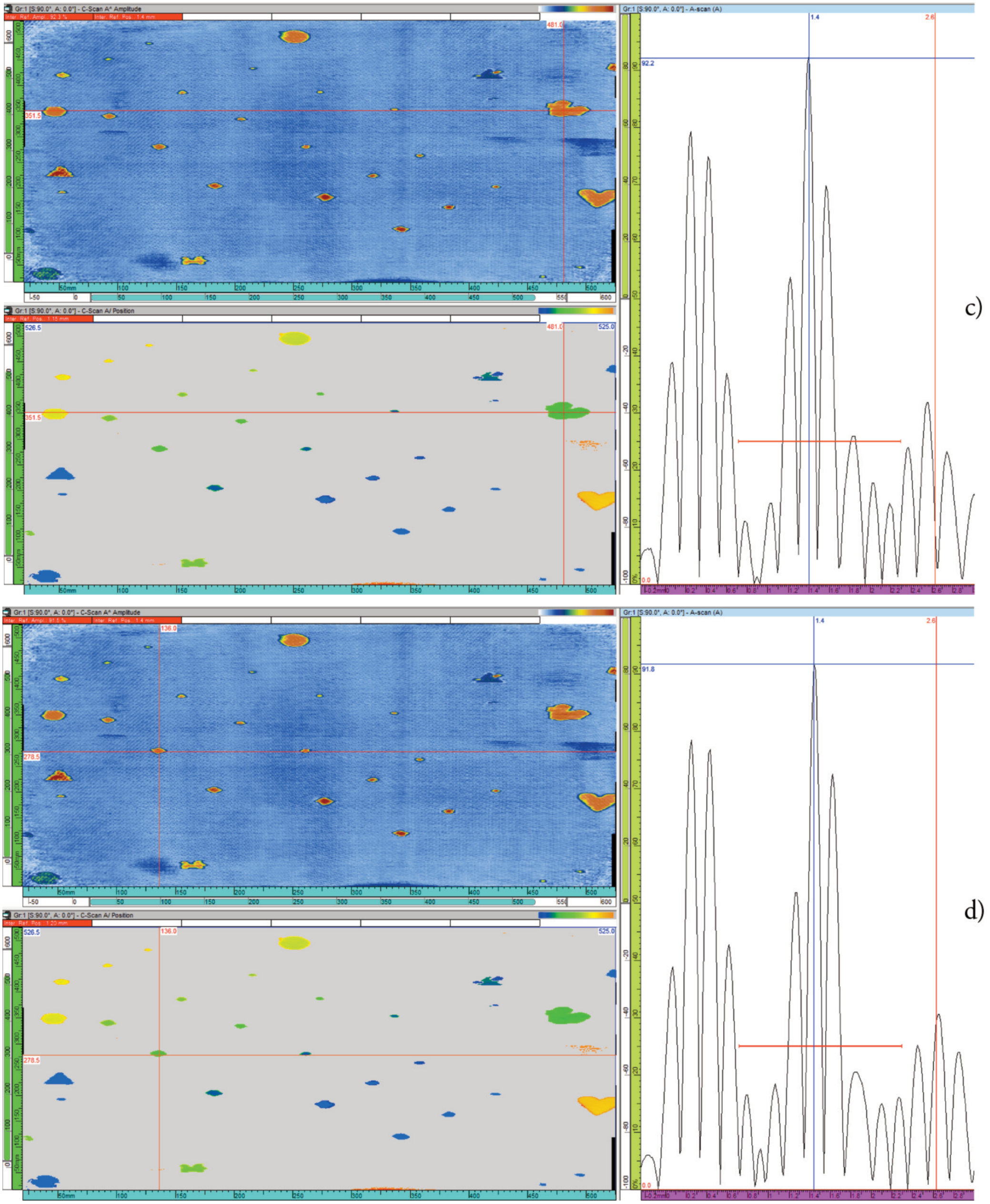


Fig. 19. Analyses of the reflected signal from artificial defects:
c) aluminum foil of 35 mm dimension at the depth of 1.2 mm,
d) high-temperature tape of 10 mm dimension at the depth of 1.2 mm,

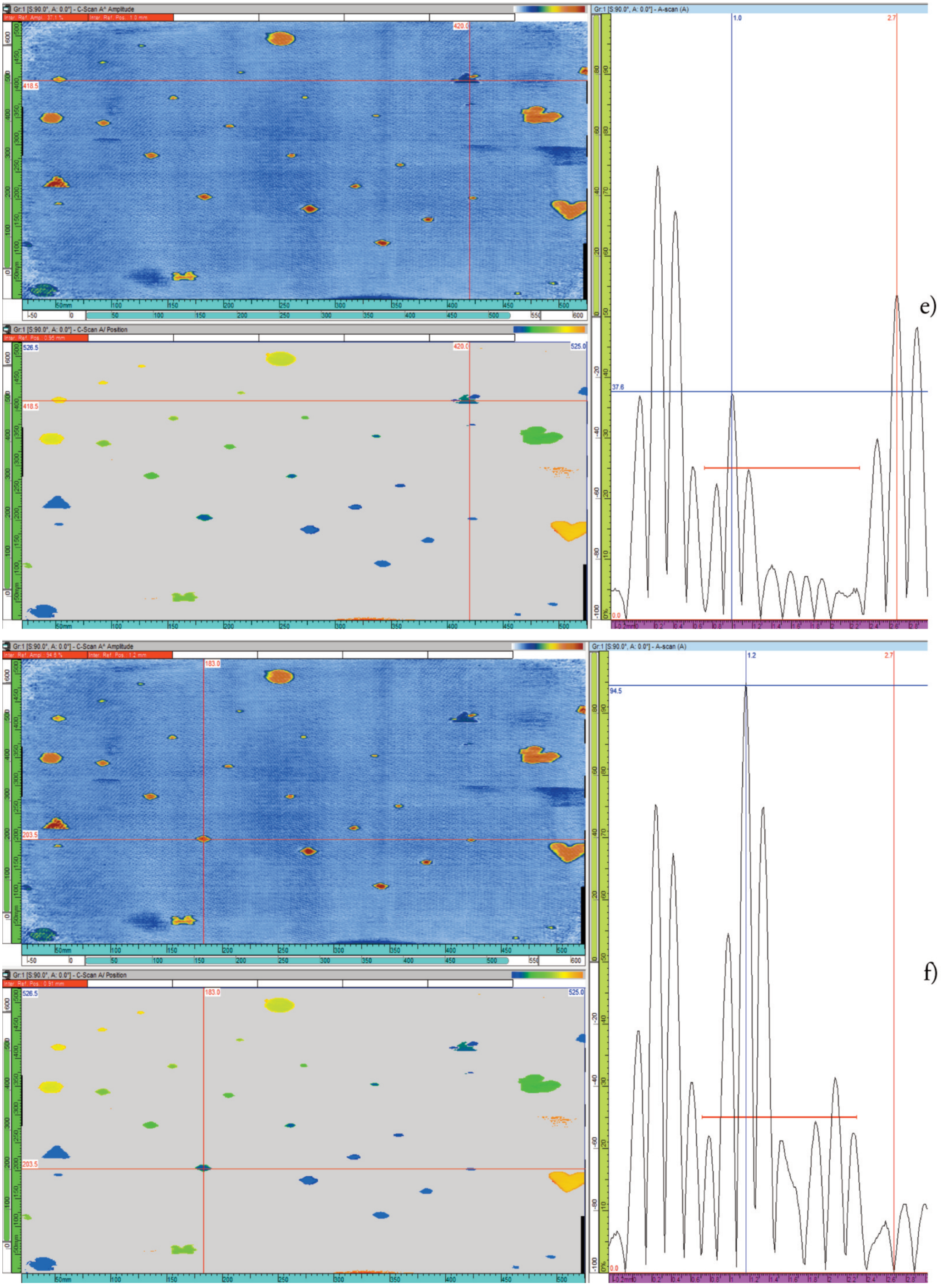


Fig. 19. Analyses of the reflected signal from artificial defects:
e) steel mesh (for welding) of 21 mm dimension at the depth of 1 mm,
f) tape of 10 mm at the depth of 1 mm [author 2018].

A comparison of the amount of reflected energy depending on the type of defect is shown in Table 1.

Table 1. Comparison of indications from different types of defects

Type of defect	Size of defect, mm	Depth of retention, mm	Amplitude reflected from defect, FSH%
High-temperature foil	20	2	86.7
High-temperature tape	12.5	2	86.7
Aluminum foil	35	1.2	90.2
High-temperature tape	10	1.2	91.8
Steel mesh	21	1	37.8
High-temperature tape	10	1	94.5

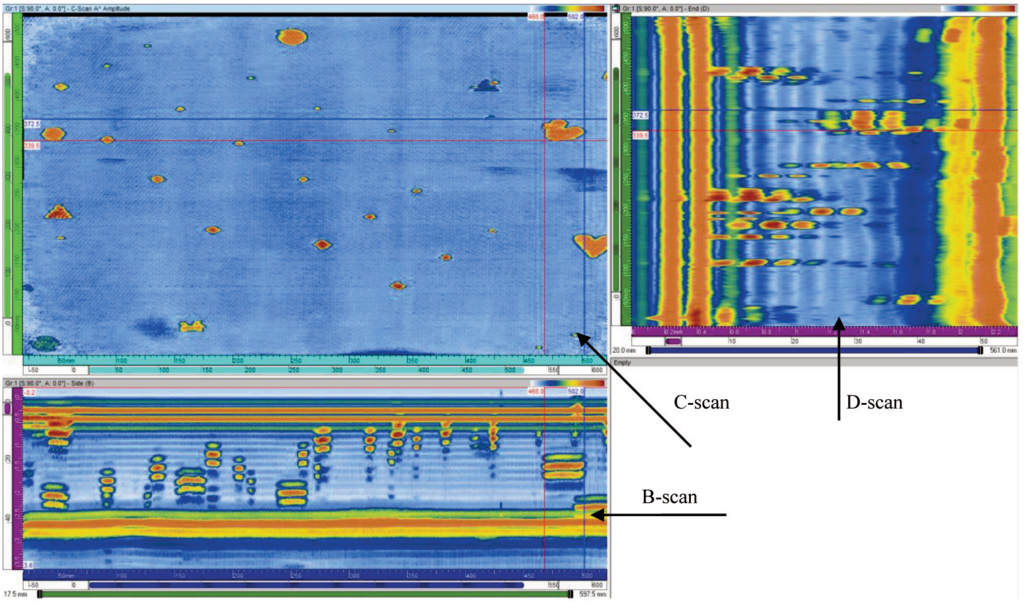


Fig. 20. Cross-sectional images of a thermoplastic plate [author 2018].

The comparisons were made for artificial defects made of different materials at the same depths. Comparing the foil with high-temperature tape it can be seen that the amplitude from the defects is the same. On the other hand, they differ in geometrical sizes and one should expect that the indication from high-temperature foil will be greater than that of the tape. Therefore, it should be concluded that a stronger reflection for the same dimensions of artificial defects will take place from the high-temperature tape. The next comparison concerned high-temperature tape with aluminum foil. Despite the fact that the geometric dimension of the defect made of aluminum foil is more than three times the dimension of the tape, the reflection signal is smaller. A similar situation can be observed when comparing steel mesh with high-temperature tape. The comparison shows that the best reflection of the UT wave was obtained from a defect made of high-temperature tape then: high-temperature foil, aluminum foil and at the end of the steel mesh.

The depth of the defects and their size can also be evaluated using images in the element cross-section (B-scan, D-scan). An example of such an imaging is shown in Figure 20, where all detected artificial defects are placed on the cross-sections.

5. CONCLUSIONS

On the basis of the ultrasound examination of the thermoplastic composite plate the following conclusions were drawn:

1. It is possible to inspect thermoplastic monolithic composite plates made using pressing technology. The inspection is possible with the use of ultrasound tests.
2. Ultrasonic tests have shown that the technological process of pressing high-temperature thermoplastic materials is properly developed.
3. The oil stain type defect was not detected. The presence of a defect in the laminate must be confirmed by a compression test of the section in which it should be located.
4. Some artificial defects were found in the dead zone of the test as a result of which it was not possible to register and further evaluate them.
5. Other defects within the scope of observation were detected and evaluated.
6. The full spectrum of images (A-scan, B-scan, C-scan amplitude, C-scan time, D-scan) was used to detect and assess artificial defects. It was insufficient to use only images of bottom echo amplitude decrease.
7. The smallest defect detected was a square of 5 mm side, which was 2 mm deep.
8. The highest signal from reflection from an artificial defect was obtained for high temperature tape. The weakest signal was obtained from a metal mesh defect that is used to weld thermoplastic layers.

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BADANIA NIENISZCZĄCE TERMOPLASTYCZNYCH WĘGLOWYCH STRUKTUR KOMPOZYTOWYCH

Abstrakt

Artykuł wpisuje się we współczesne zainteresowania firm z branży lotniczej. Opisuje materiały oraz techniki inspekcji stosowane we wiodących firmach lotniczych. Przybliżono tematykę badań nieniszczących obecnie stosowanych w do inspekcji lotniczych struktur kompozytowych oraz krótko opisano każdą ze stosowanych metod. Przedstawiono również charakterystykę preimpregnatów węglowych w osnowie termoplastycznej oraz wymieniono rodzaje materiałów termoplastycznych i przykładowe zastosowanie ich w konstrukcji statków powierzchnych. Wymieniono wady, zalety oraz ograniczenia dla tych materiałów. Skoncentrowano się na wyjaśnieniu metody ultradźwiękowej, która jest najpowszechniej stosowaną metodą podczas kontroli struktur kompozytowych na etapie produkcyjnym oraz eksploatacyjnym. Opisując metodę ultradźwiękową skupiono się na technice puls echo i zastosowaniu nowoczesnych głowic wieloprzetwornikowych (Phased Array). Wymieniono i opisano niezgodności najczęściej występujące i wykrywane w materiałach kompozytowych z osnową termoutwardzalną oraz termoplastyczną. Opisano termoplastyczny płaski panel kompozytowy wykonany z preimpregnatu węglowego w osnowie wysokotemperaturowej (ponad 300°C), który stanowił obiekt badania. Zaprezentowano wyniki badań nieniszczących (metodą ultradźwiękową) panelu termoplastycznego i wyciągnięto wnioski.

Słowa kluczowe: termoplast, preimpregnat, badania nieniszczące, metoda ultradźwiękowa, Phased Array.