Detection of delaminations and porosity in glass fiber reinforced polymer composite with ultrasonic method

Zoran BERGANT, Joseph JANEZ, Janez GRUM

Abstract: In this paper, the pulse-echo ultrasonic C-scan method was used for the examination of various processing defects in a composite plate produced by vacuum infusion (VI). Several artificial defects were embedded into the test plate, varying in shape, volume and depth. During the specimen preparation with VI, air was introduced through a small non-sealed spot in the vacuum membrane. In the selected location, the PVC and aluminium foils and aluminium chips were inserted between layers. The immersion ultrasonic system with water couplant was used to study the defects in the plate with the 4D C-scan method using different frequencies and gate settings to find the optimum set of parameters to detect defects. The C-scan images show that the detection and location of PVC foils and aluminium chips were successful. Also, porosity can be clearly detected for individual layers. The thin, 0.04 mm aluminium foils were not detected with this method.

Key words*:* Ultrasound examination, C-scan, GFRP, epoxy, composite, vacuum infusion

1 Introduction

Composite materials consist of two or more elements, one of which, the fibre, is dispersed in a continuous matrix phase [1]. The two elements work together to produce material properties that are different to the properties of the elements on their own. Composites offer the designer a combination of properties not available in traditional materials.

The production process for polymer matrix composites has the potential to introduce a variety of processing defects. Fibre misalignment can occur when fibres are laid up. Fibres in the same layer may be misaligned relative to each other or misalignment between layers might occur. Foreign inclusions such as dirt and debris may contaminate the matrix or act as a local stress concentration in the finished product. These defects can lead to delamination either during the production process or later on when the component is in service.

The use of composite materials is constantly increasing in aviation, aerospace and energy (wind turbines) where reliable inspection methods must be applied frequently to ensure safe operation. There are many detection principles which are continuously evolving. Among those, ultrasonic and thermographic methods are the most successful and widely used [1]. Composite materials are highly anisotropic with a high amount of boundaries which lead to high noise levels which limit detection accuracy. With improved transducers and signal processing methods, modern C-scan methods have become very effective for composite testing. C-scan analysis provides information of the location and size of the impurities, fibre layup plan and misalignment, delaminations, impact damage, fibre fatigue damage, water filled cores, etc. [2-3]. There are also new ultrasonic methods being developed with guided ultrasonic waves [4]. Hasiotis et al [5] studied different C-scan techniques, focusing on two materials: glass fibre reinforced polymer (GFRP) and carbon fibre reinforced polymer (CRFP). In general, it is more difficult to detect defects in glass fibre reinforced composites due to the high reflectivity of glass fibres.

Vacuum infusion (VI) is a widely used technique for the production of large composite parts [6]. A typical mistake in vacuum infusion is the non-sealed vacuum membrane with a large impact on quality and in most cases a waste of component and many hours of work. The aim of our research is to study and detect the various artificial defects in glass fibre reinforced polymer composite using the 4D C-scan technique.

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Table 1. *Composite properties*

Fibre	Epoxy matrix	No. of layers	Thickness [mm]	Density [kg/m^3]	Fibre volume content [%]
Twill weave biax, Glass fibres 280 g/m^2	Renlam LY 5138/HY 5130 Mix. Ratio: 100:23	6	1.88	1267	54

2 Experimental setup

2.1 Specimen preparation

For the ultrasonic C-scan inspection, glass fibre reinforced epoxy specimen was prepared using the vacuum infusion (VI) process. The specimen consists of 6 layers of bi-directional twill weave glass fibres (280 g/m^2) impregnated with cold curing epoxy resin Renlam LY 5138/HY5130 by Huntsmann. Defects were introduced by inserting round pieces of aluminium and PVC foils between layers.

2.2 Vacuum infusion

Vacuum infusion (VI) is a widely used moulding process for the production of large composite structures. Its popularity is partly due to the low cost of the tooling and the environmental safety [6]. In addition, low operator involvement increases the repeatability of the process compared to open mould techniques, such as hand lay-up or spray-up, and the components are of relatively high fibre content, up to 60 % of the volume. On the other hand, the complex preparation procedure of VI could easily lead to defects, such as air voids, because of not sufficiently sealed spots. The VI mould lay-up is shown in *Figure 1*.

The lay-up consist of 6 layers of 280 g/m^2 glass fabric, an inlet connection in the bottom left corner and outlet connection in the upper right corner, horizontally placed inlet and outlet resin channels, peel-ply and permeable infusion medium, vacuum bag and sealant tape. The layers were placed on a flat glass surface, coated with the release wax. Four types of defects were embedded: (1) Al-foil, thickness 0.04 mm, (2) PVC foil, thickness 0.1 mm, (3) Al-chips in random locations, (4) air voids (clusters) in random locations. The Al- and PVC-foils were cut to circular shape with dimensions from Æ 4 to 12 mm with 2 mm increments in size. Two sets were placed between layers. The first row of defects from Æ 4 to 12 mm was placed in the middle of the plate thickness, between the 3rd and 4th layer. The second row was placed between the 1-2nd layer, 2-3rd, 3-4th and 5-6th layer, consequently. The plate was cured at room temperature.

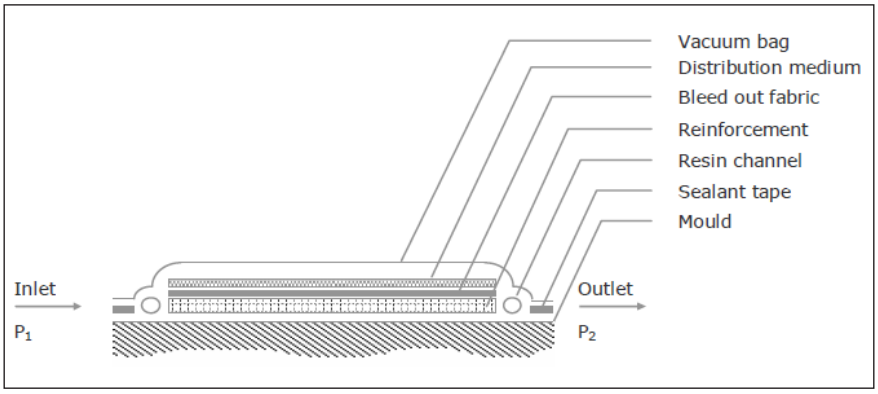

Figure 1. *Vacuum infusion mould lay-up, p_1=inlet pressure, p_2=outlet pressure [6]*

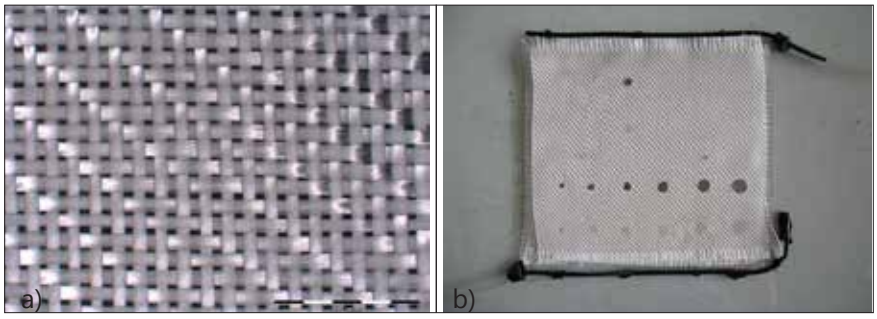

Figure 2. *Glass fibres and preparation for vacuum infusion,* (a) *Glass fibres, (b) embedded defects: Al and PVC foils*

2.3 Generation and distribution of air voids

A common processing defect during vacuum infusion is the air leakage through the non-sealed or damaged vacuum bag. Air was introduced into the plate through the small damage in the vacuum bag. The travelling direction of air voids was the same as the infusion front direction. After the disconnection of the air compressor, air voids dispersed throughout the entire plate. After approx. 1 h, air clusters formed

Table 2. *GFRP specimen thickness measurements*

#	1	2	3	4	5	6	7	8	Avg	Stdev
t [mm]	1.9	1.86	1.95	1.8	1.9	1.9	1.87	1.84	1.88	0.05

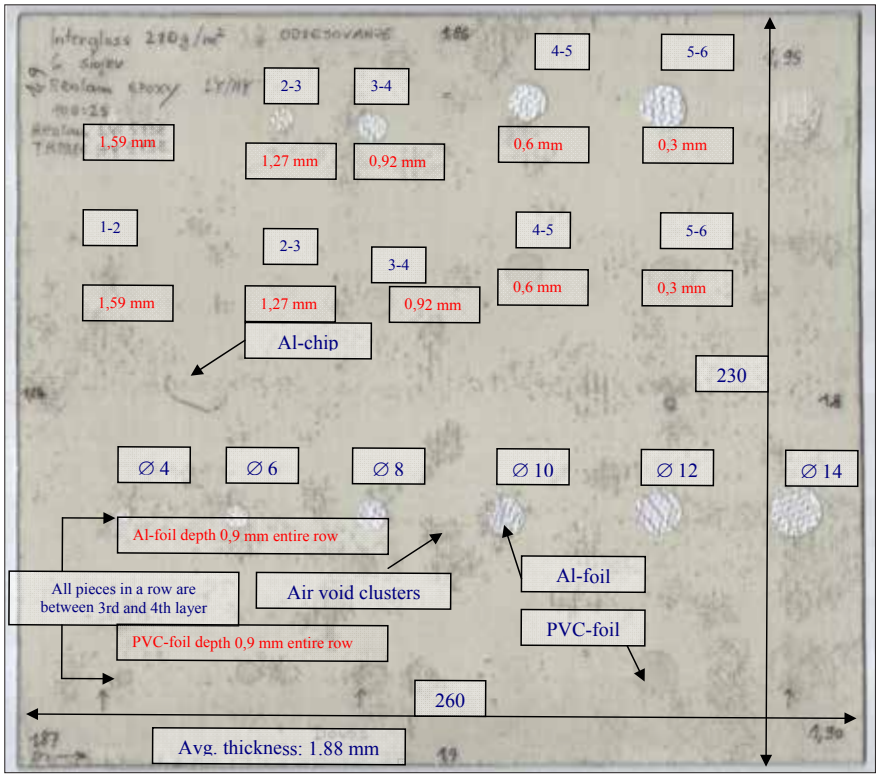

Figure 3. *GFRP specimen and defect location (rough side of the plate)*

in the direction of fibres at various depths and on both surfaces. The specimen for the ultrasonic inspection with indicated defects through the transparent material is shown in *Figure 3*.

2.4 Ultrasonic testing C-scan setup

The ULTRAPAC immersion ultrasonic testing system consists of an UPK-T24 5-axis motorized immersion tank with 5 motorized axes, controlled and computer composed by a SMC-8 motion control board and an IPR-AD1210 ultrasonic acquisition board, *Figure 4*. Acquisition board includes the high voltage stage and the signal conditioning and digitalization.

The system is used to perform an automated ultrasonic inspection of the GFRP plate by the immersion pulse-echo method. The aim of this inspection is to optimize the settings for GFRP plate inspection in order to provide the maximum possible information about the indications of defects in the GFRP specimen. The C-scan experimental setup is shown in *Figure 5*, and the testing parameters in *Table 3*.

In preliminary tests, different transducers were tested on the specimen. To obtain an accurate cartography of the plate in order to minimize the ultrasonic attenuation because of the specimen material, a transducer of 10 Mhz, 3/8", focused at 2", was used.

The water couplant was used to maintain consistent coupling while moving and manipulating the transducer which was set to face the sample surface orthogonally at a distance of 2" (50 mm) to optimize the acquired signal. The entire specimen was inspected from both sides, moving the transducer with a 5-axis motorized arm.

To obtain a C-scan cartography of the specimen, a waveform is acquired on each acquisition point. The waveform can be seen on the A-scan cartography. The pulser and receiver settings given in *Table 3* were selected to optimize the waveform shape.

Echoes on the A-scan, shown in *Figure 7*, come from the reflecting surfaces in the material which are created by the presence of defects in the sample material.

Figure 4. *ULTRAPAC system (on the left); GRPC plate in the immersion tank (on the right)*

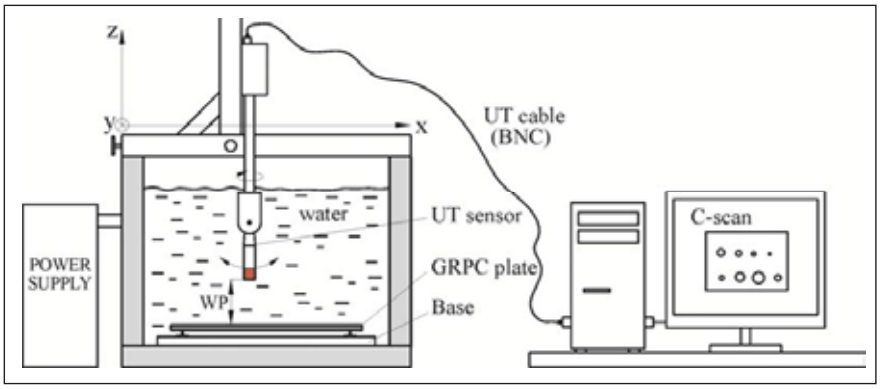

Figure 5. *Experimental setup of GRPC plate C-scan (water couplant)*

Table 3. *C-scan settings*

	Scanning length [mm]	Scanning resolution [mm]	Scanning speed [mm/s]
Scanning Axis	240	0.5	120
Index Axis	220	0.5	120
	Frequency	Voltage	Damping
Pulser	10 MHz	400 V	2000 □
	Filter	Gain	
Receiver	8-12.5 MHz	20 dB	

On the A-scan, echoes are analyzed by means of time analysis gates which provide the maximum amplitude [%] and the associated time of flight [µs] on a time section of the waveform.

The A-scan graph in Figure 7 represents the voltage received from the transducer based on the material thickness where the time is converted into mm through the calibration method.

The signal values range from the positive to the negative values of 1 V to –1 V, respectively. Analyzed amplitudes used for C-scan are absolute voltage values expressed in %. For example, both, –1 V and 1 V are the 100 % amplitude of the C-scan. When an echo with a peak at –0.6 V is detected, the amplitude value used for the C-scan is 60 %.

When performing the conventional C-scanning, 3 gates are used to analyze the front wall echo (Gate 1), echo coming back from the material thickness (Gate 2) and the back wall echo (Gate 3).

In our study, a single gate on the whole signal from the plate was used, which allowed us to detect the presence of defects and their depth more efficiently. This method produces 4D C-scan cartographies. The single gate (Gate 4) was divided into 14 slices. Each slice corresponds to a narrow depth interval. All slices have equal width (2.174 mm/14 = 0.155 mm). The UTwin software algorithm locates and records the signal peak amplitude within the sliced part of the waveform. Those two methods are presented in *Figures 6* and *7*.

The sound velocity in GRPC material was calibrated by measuring the back wall echo time of flight and the sample thickness. The time of flight, which can be measured on the whole signal, equals zero at the beginning of the front wall echo. This calibration gave a velocity of 3000 m/s for longitudinal waves along the sample thickness.

3 Analysis of the results

The 3 following C-scan graphs (*Figures 8*, *10* and *12*) are the result of the scanning with the transducer on the smooth side of the composite plate.

The C-scan in Fig. 8 shows the back wall echoes amplitude using the 13th slice. The darkest areas descri-

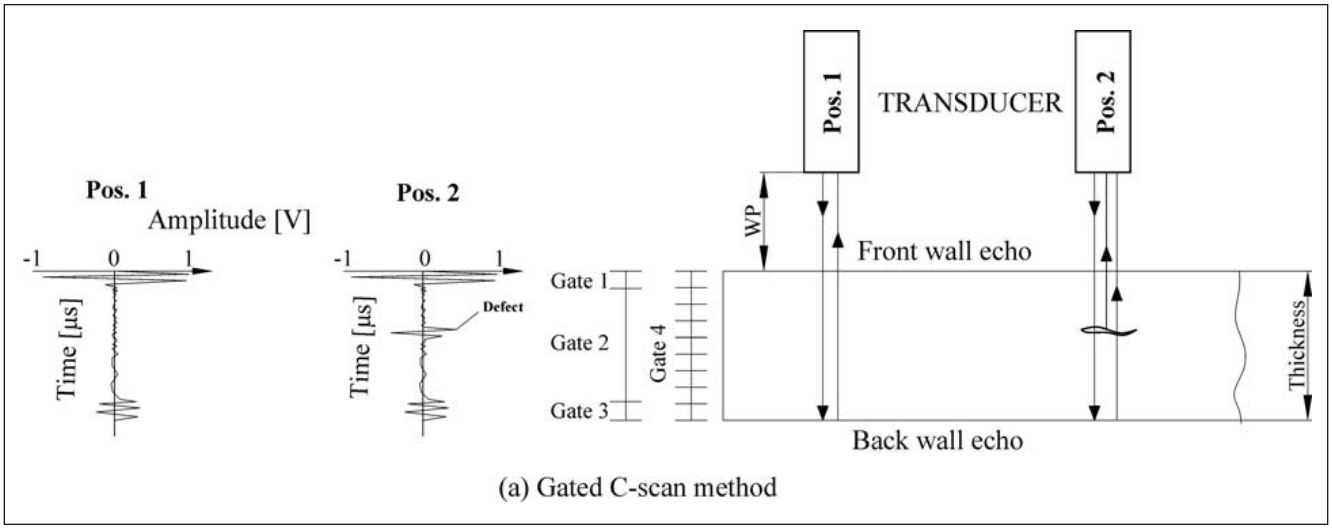

Figure 6. *C-scan method with a single gate through the entire signal*

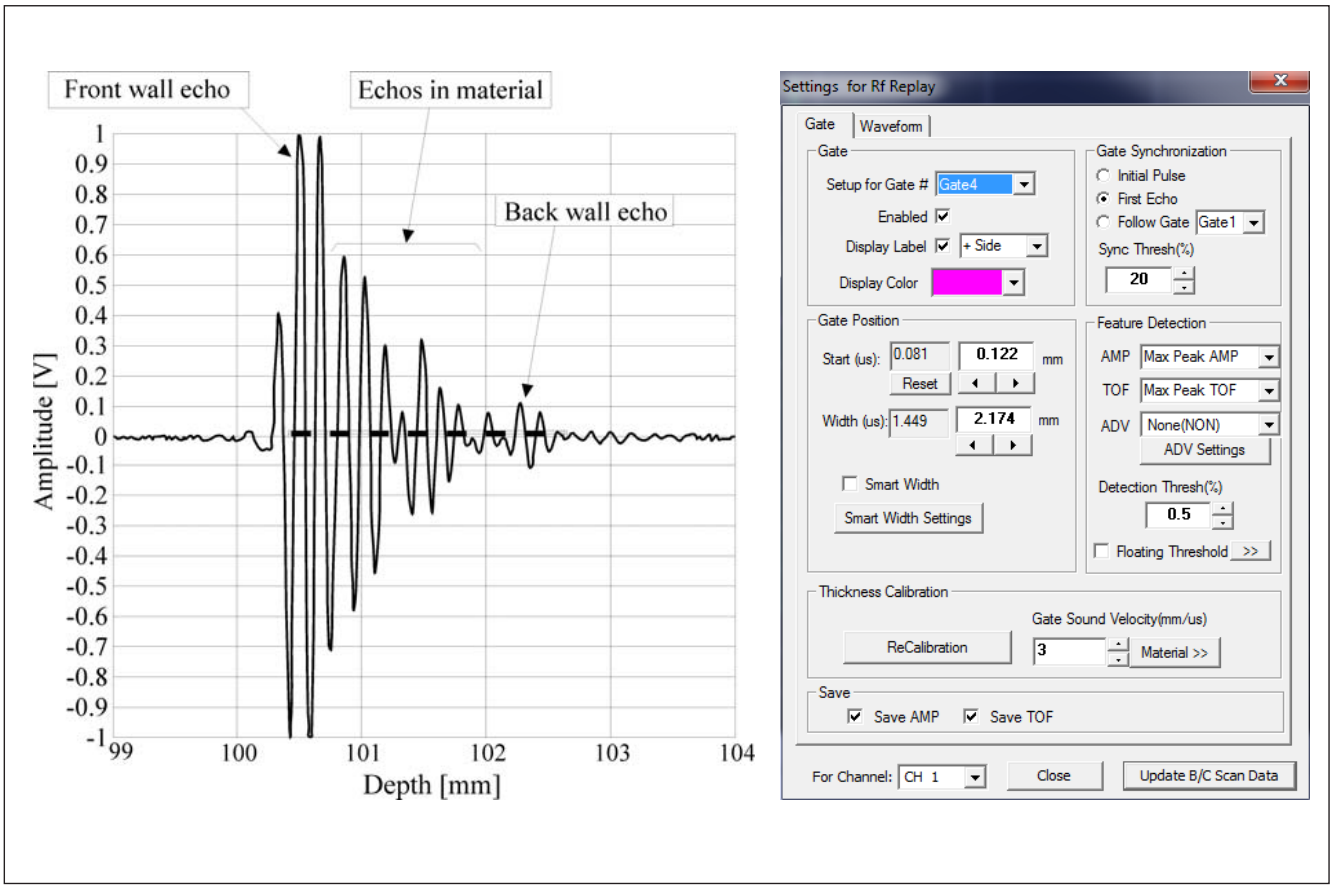

Figure 7. *A-scan graph with the Analysis Gate (on the left); Gate settings (on the right)*

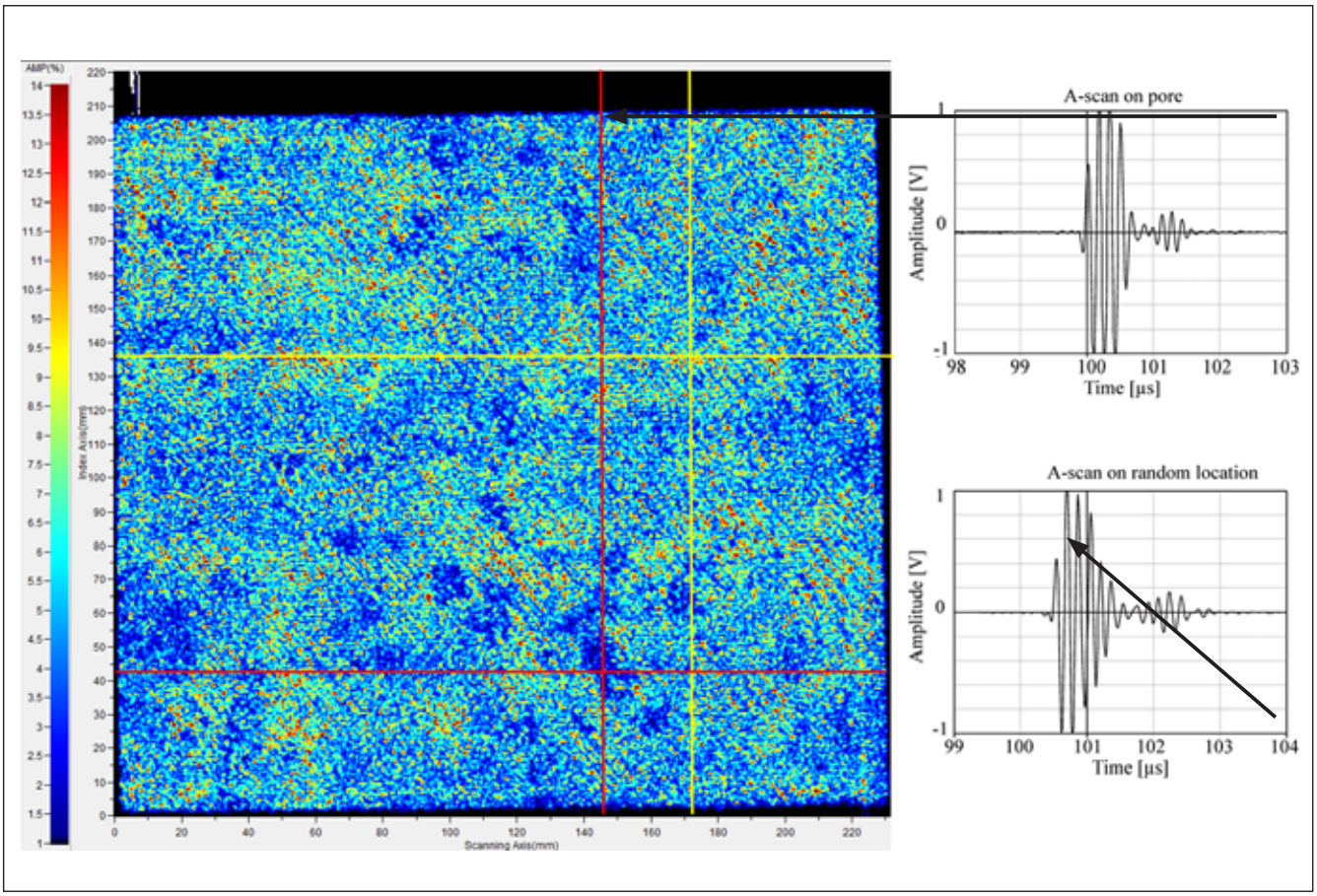

Figure 8. *C-scan for 14 slice gate, 13th slice display*

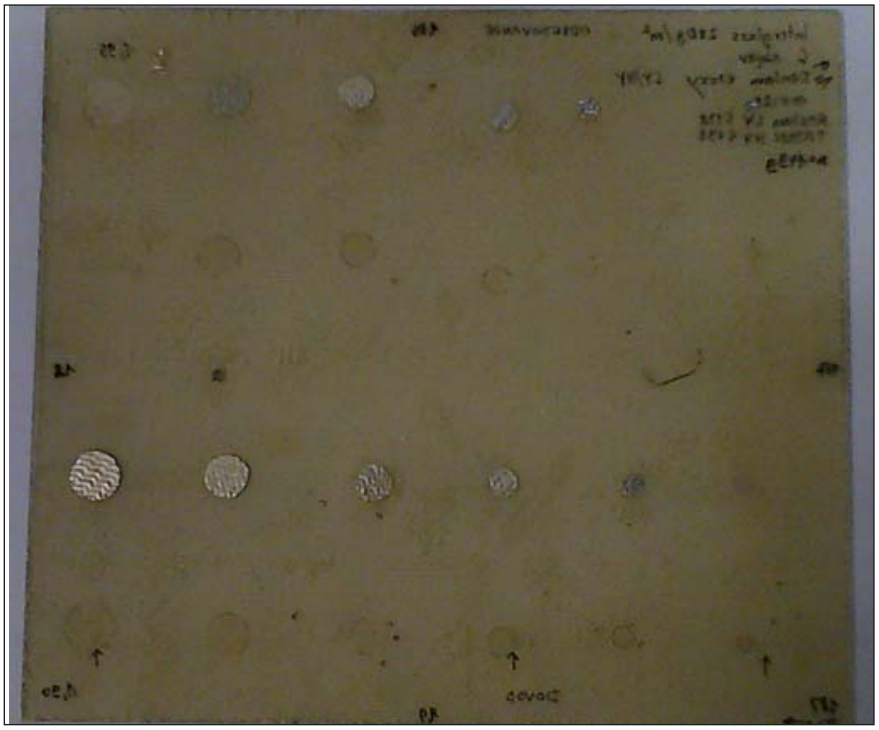

Figure 9. *Smooth side of the sample*

be an amplitude loss of these echoes, which means the signals have been reflected before reaching this depth. These indications of defects are located in the same areas as the porosities visible on the GFRP plate.

The C-scan on the left in *Figure 11* shows the back wall echoes amplitude using the 23rd slice (depth: 1.774-1.929 mm) of the 24 slice gate. The darkest areas describe an amplitude loss of these echoes, which means the signals have been reflected before reaching this depth. These indications of defects are located in the same areas as the porosities visible on the GFRP sample.

The C-scan in Figure 11 shows the back wall echo amplitude using the 13th slice (depth: of the large analysis gate). The darkest areas describe an amplitude loss of these echoes, which means the signals have been reflected before reaching this depth. This C-scan shows the amplitude of echoes coming from the depth interval.

The ultrasonic inspection of the specimens

Figure 12 shows a small analyzed sample segment with aluminium foils and surface air voids.

Compared to the framed area on the photograph of the sample, the C-scan shows indications of defects that match with the surface porosity and a hair located very close to the smooth surface.

The following three C-scan graphs (in Figure 13) have been obtained with the sample's rough surface facing the transducer.

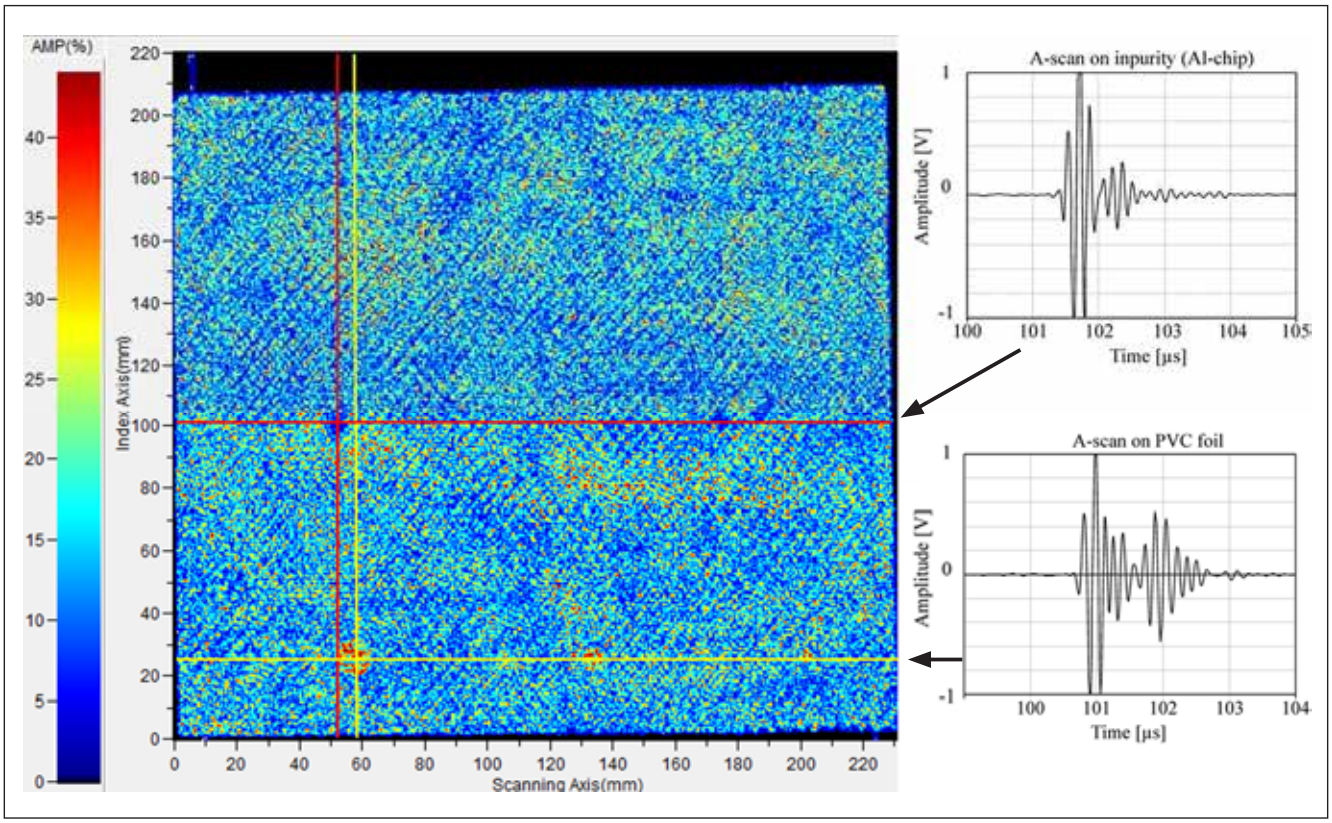

Figure 10. *C-scan for 24 slice gate, 13th slice display*

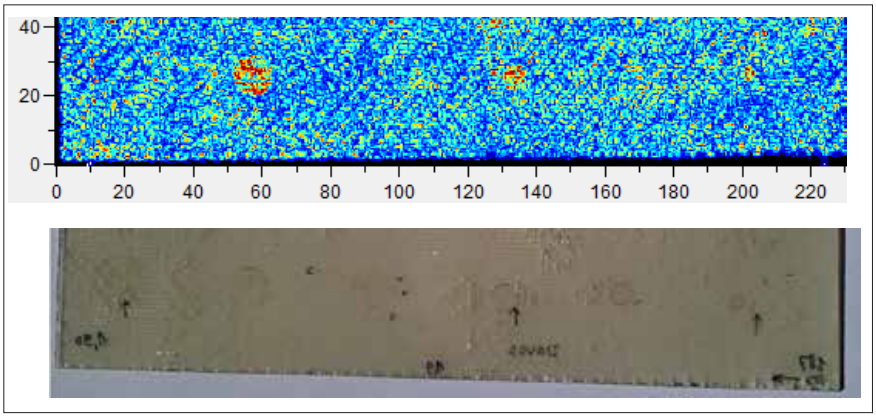

Figure 11. Detail of *C-scan for 24 slice gate, 13th slice display*

Unlike scanning through the smooth surface, scanning through the rough face allows us to detect the PVC foils placed at different depths.

The C-scans above show us indications of the PVC foils nearest to the rough face.

Only these have been detected in this area close to the rough face; the ultrasonic signal is not so attenuated although the front wall echo has a smaller amplitude (compared

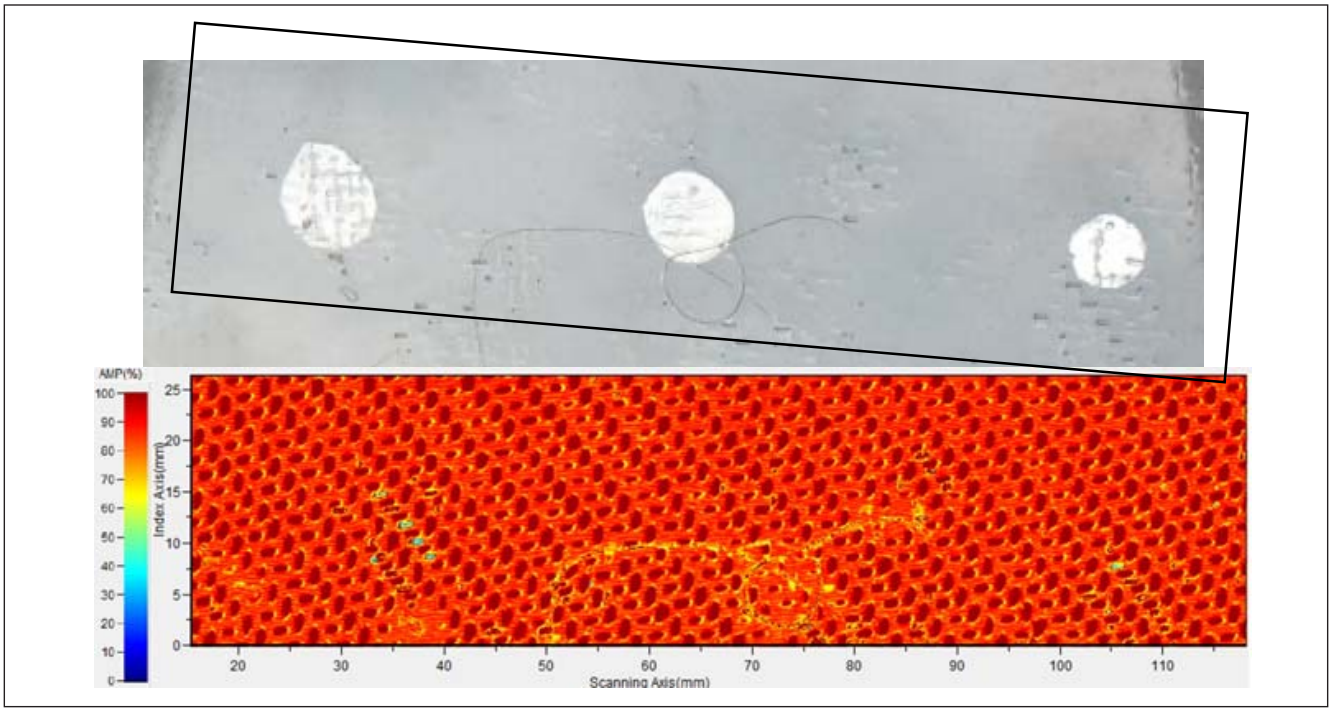

Figure 12. *Image of an analyzed detail (Scan resolution of 0.1 mm), slice 2 of 48 slice gate*

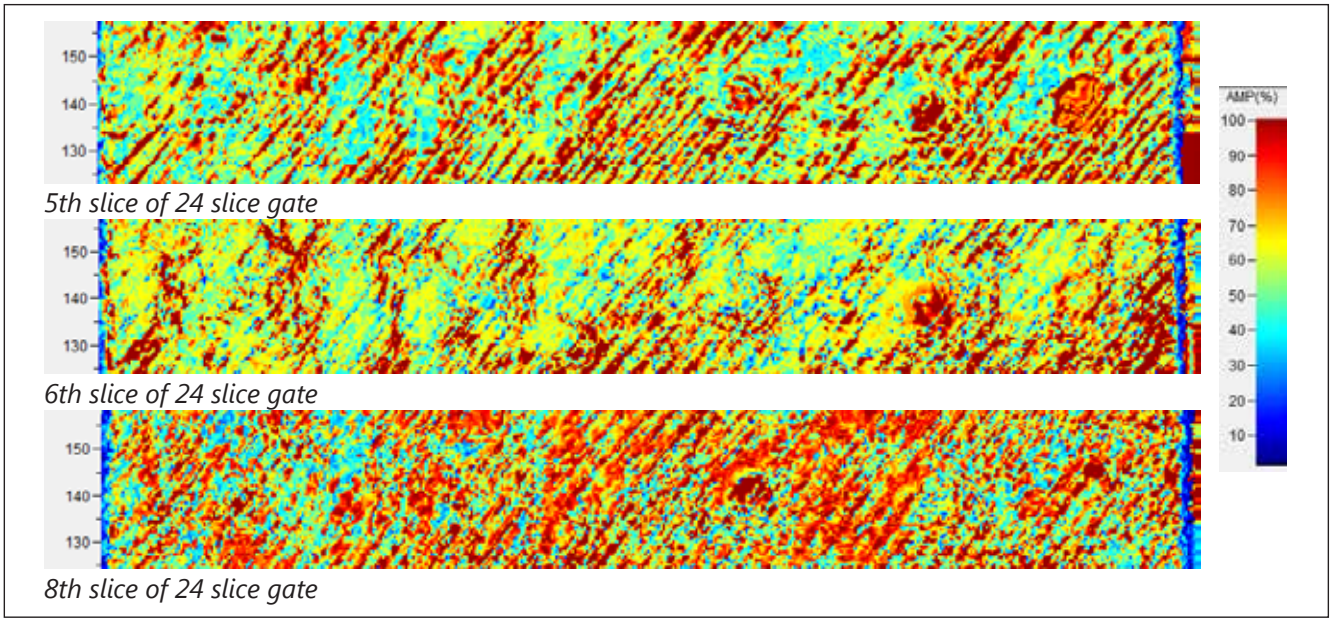

Figure 13. *C-scan for 24 slice gate, 5th slice display*

to the one measured through the smooth face) because of the surface roughness which diffracts the signal.

4 Conclusions

The 4D C-scan method with a divided single gate signal is a powerful tool to obtain C-scan amplitude data for each depth interval along the thickness of the whole sample. For each increment, the algorithm determines the highest peak of the signal. The optimal selection of the number of intervals has to be made in order to maximize the visibility of the defect on the C-scans. Also, the depth of the analyzed defect can be determined after analyzing all depth intervals. The depth indication precision can be increased if the measurement is repeated with classical thickness C-scan, using a gate placed at the depth range where the defect indication is visible on 4D C-scan.
The detection of a defect is limited by its thickness and by the wavelength of the testing ultrasonic wave. This latter has to be smaller than the defect thickness to allow the signal reflection on the defect. Indeed, in our study, the pulse frequency was set to 10 MHz after testing optimization. So, as we determined a sound velocity of 3000 m/s, the ultrasonic signal has a wavelength of 0.3 mm.

For that reason, we were not able to detect the 0.04 mm thick aluminium foil. Nevertheless, by scanning both sides of the sample, the PVC foil with 0.1 mm of thickness was successfully detected in most cases when the gate was set to 24 divisions. The detection sensibility can be increased by increasing the testing frequency, but in this case, the level of noise caused by the sample structure and the attenuation of the ultrasonic signal increase drastically. However, a higher frequency could be used to estimate very shallow defects.

The presence of Al-foil can be detected using through-transmission scanning by analyzing the signal attenuation. In this case, the defect size can be obtained on the C-scan, but not the defect depth.

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Ultrazvočna preiskava delaminacij in poroznosti v epoxy- kompozitu s steklenimi vlakni

Razširjeni povzetek

S C-scan pulzno-odbojno ultrazvočno metodo je bila izvedena preiskava epoksidne kompozitne plošče, ojačane s steklenimi vlakni. Za izdelavo kompozitne plošče smo uporabili postopek vakuumske infuzije za impregnacijo 6 plasti biaksialne tkanine s keper tkanjem, s težo 280 g/m^2 in z enako orientacijo vlaken 0/90° v vseh slojih. Med posameznimi sloji smo na znana mesta vložili napake v obliki okroglih ploščic iz aluminijaste in poliestrske folije in ostružke aluminija. Za polimerno matrico smo izbrali hladno utrjevalno epoksidno smolo DGBA (diglicidil-eter-bisfenol-A), Renlam LY 5138, zamreženo s poliaminskim trdilcem Renlam HY 5130 v utežnem mešalnem razmerju 100 : 38. Za vakuumsko infuzijo smo dimenzionirali dovodne in odvodne kanale ter izvedli infuzijo preko permeabilne mrežice pri podtlaku –0,9 bar. Med vakuumsko infuzijo smo na dovodni strani povzročili puščanje vakuumske folije, s čimer je prišlo do nastanka makroporoznosti znotraj kompozitne plošče. Tako izdelana kompozitna plošča ima debelino 1,88 mm, gostoto 1267 kg/m^3 in 54-odstotni volumski delež vlaken.

Ultrazvočna preiskava s steklenimi vlakni ojačanih kompozitov težko zazna napake zaradi visoke reflektivnosti in sipanja odbitih ultrazvočnih signalov. Za neporušitveno preiskavo kompozitnega vzorca smo uporabili ultrazvočni sistem Ultrapac UPK-T24 s 5-osnim manipulatorjem z gibljivo glavo. Med preiskavo sta bila kompozitni vzorec in ultrazvočna glava potopljena pod vodo za boljši prenos ultrazvočnih signalov do preizkušanca. Na osnovi predhodnih preizkusov je bila izbrana ultrazvočna sonda (oddajnik-sprejemnik) s frekvenco 10 MHz in z oddaljenostjo 50 mm od površine preizkušanca. Izvedli smo C-scan z obeh strani po površini z inkrementom 0,5 mm in s hitrostjo 120 mm/s. Z izbrano metodo smo na vzorcu zajemali ultrazvočne signale le na enem vhodu, ki je bil glede na velikost plošče razdeljen na 14 ravnin. Amplitudne vrednosti signala smo razdelili v posamezne razrede s prikazom v psevdobarvah. Razpozna-

vanje oblike, velikosti in globine napak je odvisno od valovne dolžine testiranega ultrazvočnega signala. Glede na izmerjeno hitrost zvoka v kompozitni plošči, ki znaša 3000 m/s, ima ultrazvočni signal valovno dolžino 0,3 mm pri frekvenci 10 MHz. Z ultrazvokom je možno zanesljivo odkrivati napake, ki so večje od valovne dolžine zvoka. Možna pa je tudi detekcija napak, ki so nekoliko manjše od valovne dolžine. To se je potrdilo s C-scan kartografijo, s katero smo na večini mest zaznali poliestrsko folijo debeline 0,1 mm. Če povečamo občutljivost zaznavanja s povečanjem testne frekvence, se močno poveča šum zaradi številnih odbitih signalov iz kompozitnega materiala. Kljub temu smo pri višji frekvenci uspešno zaznali tudi zelo drobne podpovršinske napake, kot so npr. nečistoče in pore.

Ključne besede: ultrazvočna preiskava, C-scan, z vlakni ojačani kompoziti, epoksi smola, kompozit, vakuumska infuzija

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Znanstvene in strokovne prireditve

18. mednarodna konferenca o tesnjenju – Stuttgart 2014 – vabilo k prijavi aktivne udeležbe

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