

CONTACT LASER ULTRASONIC EVALUATION OF COMPOSITES

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Abstract

Contact laser-ultrasonic evaluation (CLUE) is a novel technique for non-destructive testing of construction materials. It explores laser excitation of smart test ultrasonic pulses and extra wide-band piezodetection of scattered acoustic field. It can be effectively used for the investigation of texture, structure and failure of composites, metals, ceramics and plastics.

The review of application of CLUE for non-destructive testing and material evaluation of fiber reinforced composites is presented. It is concerned on the materials, widely used in air-space industry.

Keywords: Laser ultrasound, attenuation of ultrasonic wave, wave scattering, carbon fiber reinforced composites, weld, porosity.

1. Introduction

Ultrasonic testing is one of the most widely used technique for defect detection and material evaluation. It's relatively simple, sensitive and save. Construction materials, such as composites, have complicated texture, that determines their mechanical properties. The size of the specific element of the texture of composite may vary in a wide range. So, it's necessary to provide wide frequency band of ultrasonic testing to investigate the composite. The traditional piezoelectric ultrasonic testing is faced with significant difficulties in solving this problem [1,2].

To provide ultrasonic testing over wide frequency range it's reasonable to explore laser excitation of acoustic waves. The technology of ultrasonic testing, exploring remote laser excitation acoustic pulses and remote optical detection of ultrasonic vibrations is termed as "laser ultrasonics" [3]. This technology is developed during more than 30 years and is described in details in several books and a lot of publications. The advantage of this technology is remote sensing and a possibility to investigate the object with the short acoustic pulse containing wide range of ultrasonic frequencies (practically, from kHz to GHz). The disadvantage of laser ultrasonics is low efficiency of acoustic pulse excitation at free object surface, low sensitivity of ultrasonic vibration detection and hard demands to the optical quality to the object surface.

It's well known, that mechanical loading of the surface irradiated by laser enhances the efficiency of acoustic pulse excitation 10-100 times [4]. On the other hand, using contact ultrasonic transducers with efficiently damped piezoelectric element, one can detect the acoustic waves over wide frequency band. The technology of ultrasonic testing using laser excitation of ultrasonic pulses and piezoelectric detection of acoustic waves with high temporal resolution is termed as "contact laser ultrasonic evaluation" (CLUE). Some applications of CLUE for the construction material testing is discussed below.

2. Basics of contact laser ultrasonic evaluation

2.1. Optoacoustic transducer

Optoacoustic (OA) transducer utilizes laser excitation of a sharp ultrasonic pulse and piezoelectric detection of acoustic transients with high temporal resolution [5]. Its schematics is presented in Fig.1. A laser pulse of 10 ns is delivered to the OA transducer with an optical fiber. Laser radiation is focused to the OA-generator, that is placed on the bottom surface of transparent OA prism. At the

upper surface of the prism piezoelectric detector is posed. A preamplifier transforms the high output impedance of the detector to low impedance of an electric cable.

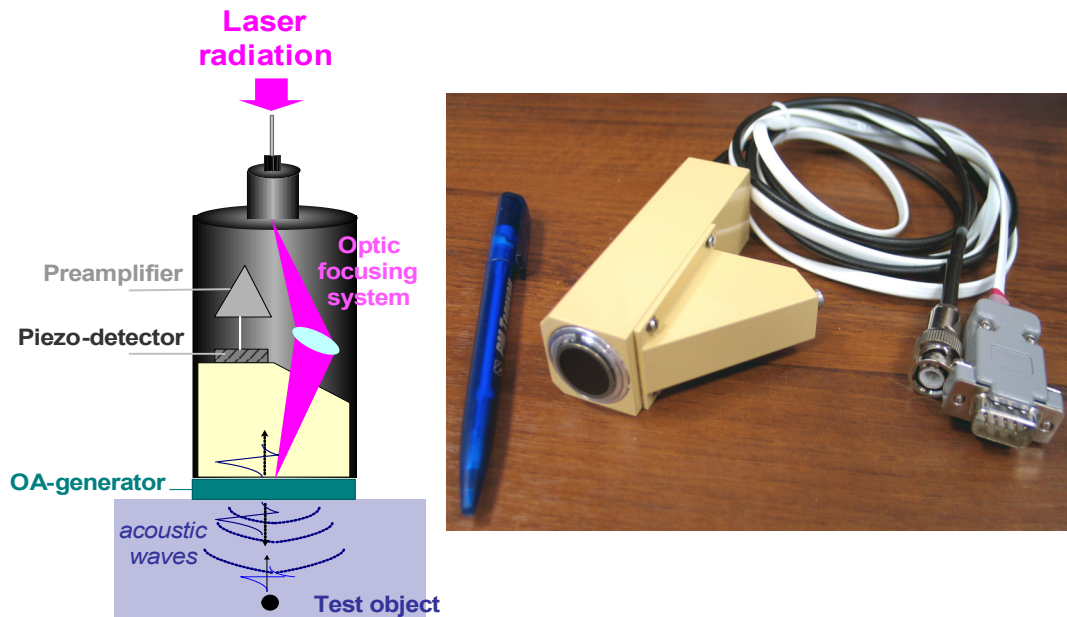


Figure 1. Schematics and picture of an optoacoustic transducer CLUE-P-6.

In a course of absorption of laser pulse instant heating of OA-generator takes place. Due to thermal expansion of heated layer, the acoustic pulses are launched into the OA-prism and a test object attached to the rear surface of the OA-generator. The rear surface of the OA-generator is the “object” surface of the OA-transducer.

The OA-transducer integrates laser excitation and piezoelectric detection of ultrasonic pulses. This makes it possible to optimize both the efficiency of thermooptical excitation and piezoelectric detection. So, low energy laser pulse produces high amplitude ultrasonic pulse and wide-band detection provides high sensitivity> high temporal resolution and wide dynamic range,

2.2. Contact laser ultrasonic evaluation

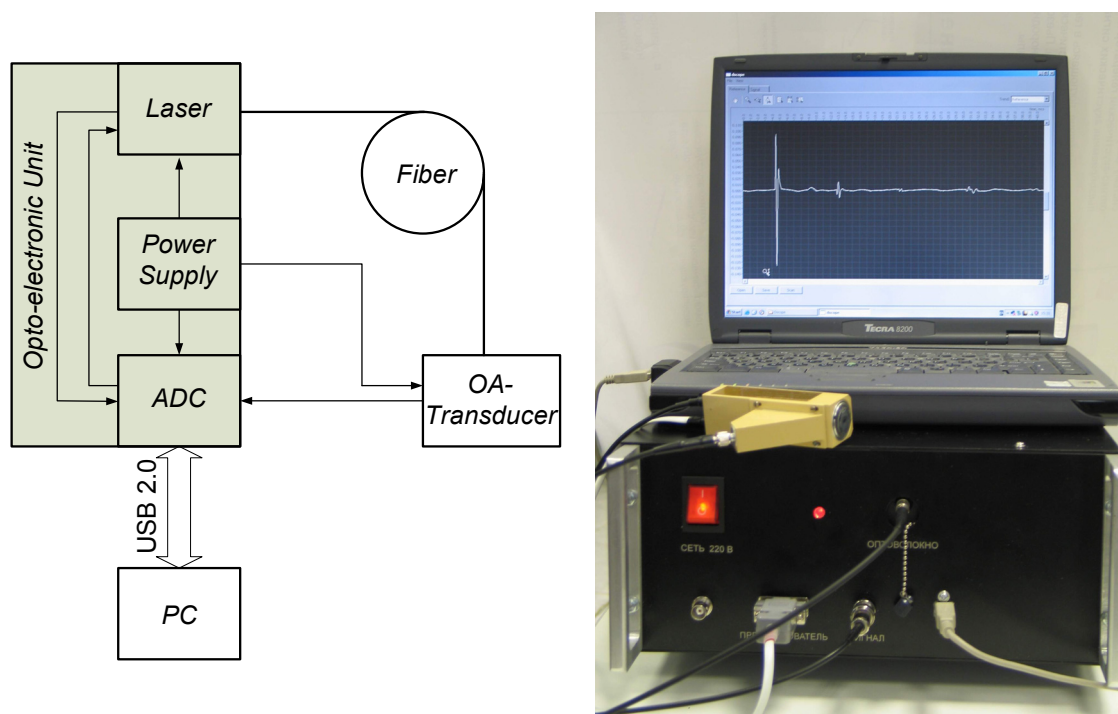


Figure 2. Schematics and picture of CLUE.

The OA-transducer is explored in a system of contact laser ultrasonic evaluation (CLUE) which schematics is presented in Fig.2. It consists of an opto-electronic unit, optical fiber, OA-transducer and PC. The opto-electronic unit includes Q-switched solid state laser, power supply and ADC connected with PC. The OA-transducer is connected with the opto-electronic unit with optical fiber. The duration of the excited pulse is determined by the laser pulse duration and light absorption coefficient in the OA-generator. It can vary over wide range, specified to the problem to be solved. The OA-transducer CLUE-P-6 produces an ultrasonic pulse with the duration of the order of 0.07 μs . Its temporal shape is presented in Fig.3(a). It's smooth and has sharp compression phase of 0.07 μs duration and longer rarefaction phase. The last appears due to diffraction of excited ultrasonic beam (its diameter is ~ 3 mm). This short probe ultrasonic signal has limited frequency band (0.13-5.67 MHz) at half maximum (see Fig.2(b)).

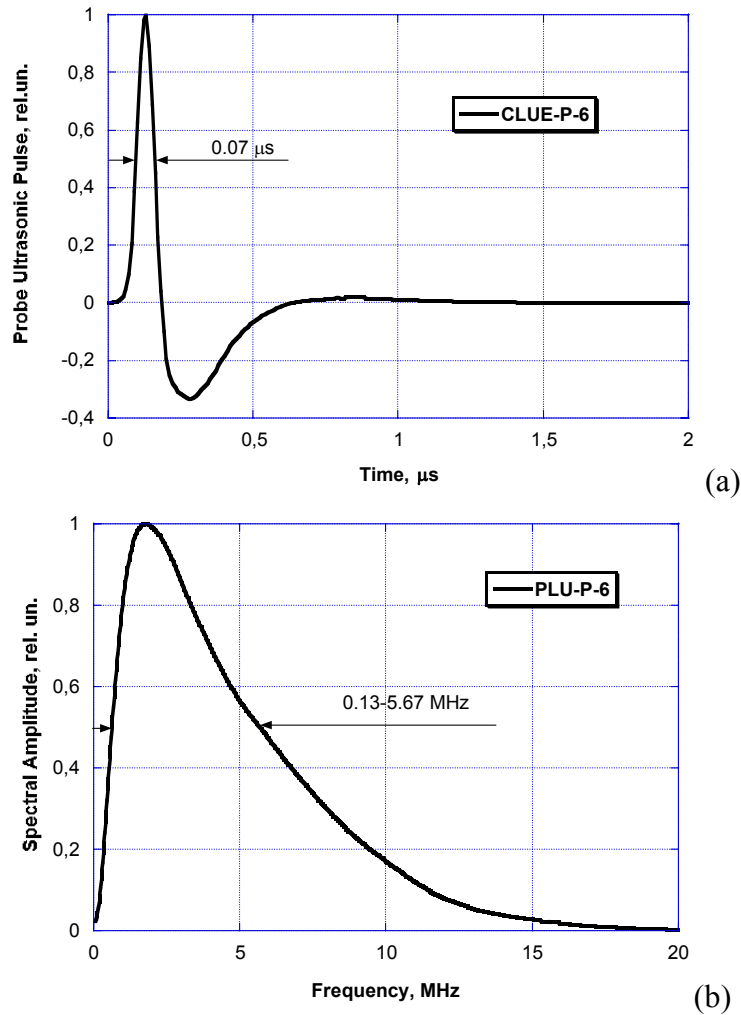


Figure 3. Temporal shape (a) and spectrum (b) of a probe ultrasonic pulse of CLUE-P-6.

Short duration of the probe ultrasonic pulse of CLUE provides high in-depth resolution of testing. On the other hand, ultrasonic wave (central frequency – 2.5 MHz) is affected to low attenuation in a course of propagation and provides long depth of testing. Bandwidth of the spectrum of the probe signal is two times greater, then its central frequency. This provides greater quantity of pixels in an image of a test object, then traditional ultrasonic testing.

2.3. Data processing

Wide frequency band and wide dynamic range of ultrasonic detection system makes it possible to efficient digital signal processing. Each OA-transducer is calibrated to measure its transient response. So, we use a deconvolution to take into account transient response of the transducer and

temporal shape of the probe ultrasonic pulse. This processing enhances the in-depth resolution of testing 1.5-2 times.

CLUE provides the quantitative ultrasonic testing and gives the information on ultrasonic wave velocity and attenuation over wide frequency band. It makes it possible to measure the cross-section of back-scattering with high in-depth resolution and sensitivity. These parameters of the object are affected to its texture and composition. Algorithms for data processing are specified to the problem to be solved. Delamination, disbanding, porosity, granulation etc. can be effectively investigated with CLUE. Some examples are presented below.

3. Experimental cases

3.1. CLUE signal of test samples

To figure out the specific features of CLUE some simple sample were tested. In Fig.4 the multiple reflections of CLUE pulse in 0.42 mm thick aluminum plate are presented. The first positive pulse is the probe pulse of OA-generator. Its shape detected is presented in Fig.3(a), deconvolution gives the profile of the pulse, depicted in Fig.4.

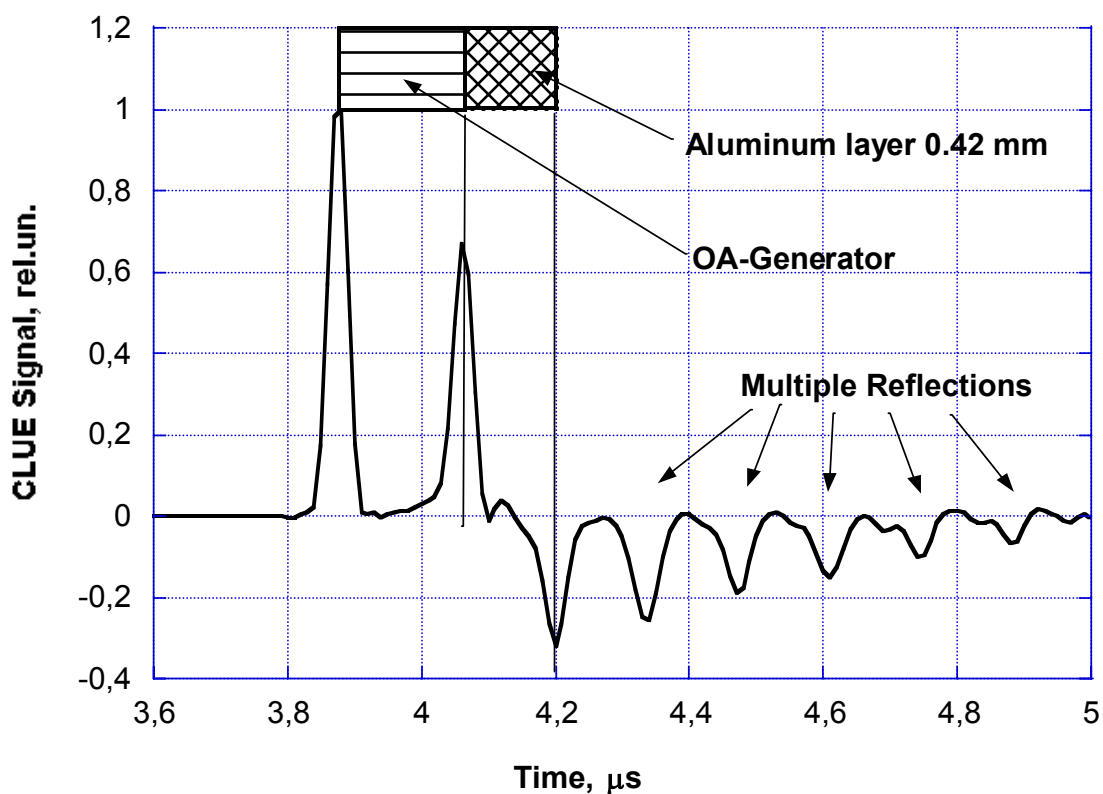


Figure 4. Multiple reflections in thin aluminum plate tested with CLUE.

The second positive pulse (arrived at $t=4.06 \mu s$) is the reflection of the probe pulse at the interface between the OA-transducer and the test aluminum plate. As the acoustic impedance of the sample is greater, then that of OA-generator, the reflection takes place in phase. The relative amplitude of this pulse gives the coefficient of acoustic wave reflection.

The negative pulse (arrived at $t=4.2 \mu s$) is the first reflection of transmitted into the sample probe pulse at rear surface of the plate. The reflection takes place out of phase due to low acoustic impedance of plate backing (air). The duration of the reflected pulse is approximately the same as the duration of the probe and the front-surface reflected pulse. This shows negligible attenuation of ultrasonic wave in aluminum. Knowing the thickness of the aluminum layer one can determine the density and ultrasonic wave velocity in the layer by measuring the time of flight, the reflection coefficient and the decay of the amplitude of multiple reflections.

The other test sample was 49.8 mm thick aluminum block with the 1mm in diameter 3.6 mm in depth drill. The CLUE signal of this sample is presented in Fig.5. The probe pulse and reflection at front sample surface looks like that in Fig.4. The pulse reflected at the rear surface of the sample

appears as a sharp out of phase transient. Due to diffraction of the ultrasonic beam its shape follows the derivative of that of the probe pulse. Small signal arrived 3.6 μs before the reflection at the rear surface is the pulse scattered at the bottom surface of the drill. As the scattering surface is not flat, and due to its small size, the temporal shape of the scattered signal follows the second derivative of the probe pulse. This result demonstrate high sensitivity and resolution of CLUE.

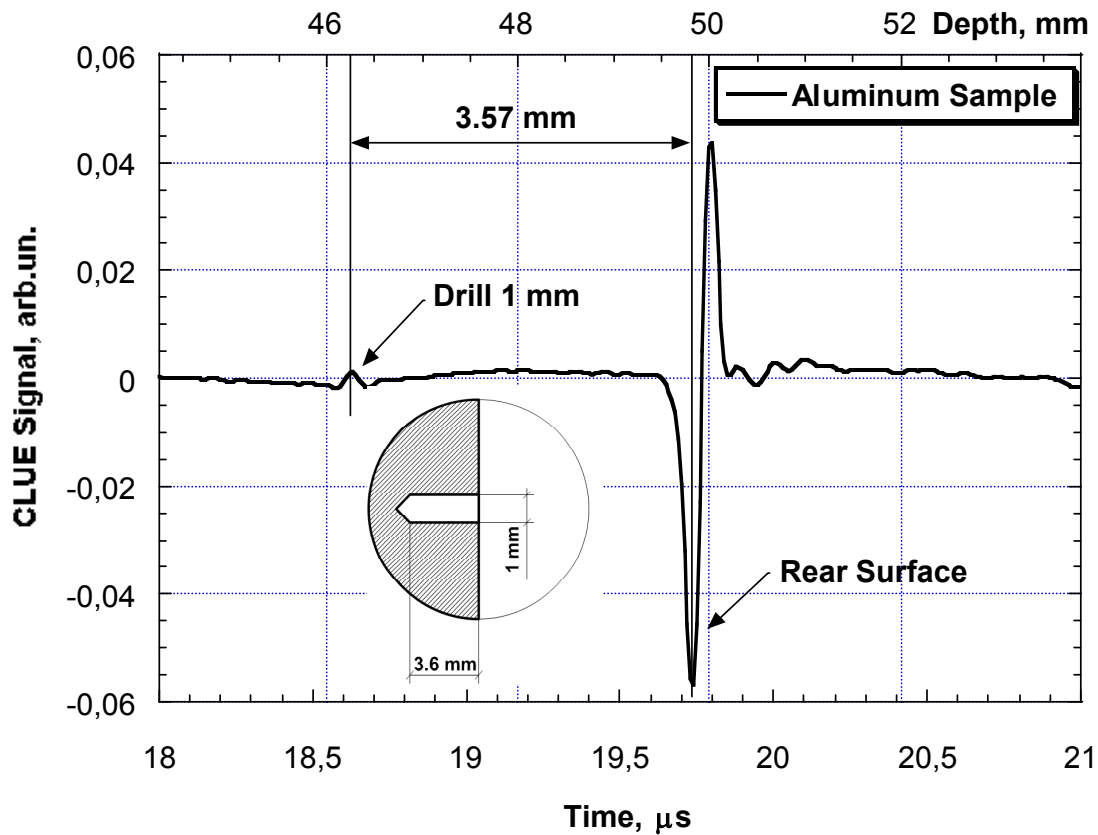


Figure 5. CLUE detection of drill in aluminum block.

3.2. CLUE investigation of composites

CLUE is efficient for an investigation of heterogeneous construction materials such as fiber reinforced composites. Tested sample was 1-D CFRC that has 50 μm brass foil as an artificial inclusion between 10th and 11th ply. B-scan of this sample is presented in Fig.6. The upper bright line shows the reflection at the surface of the sample.

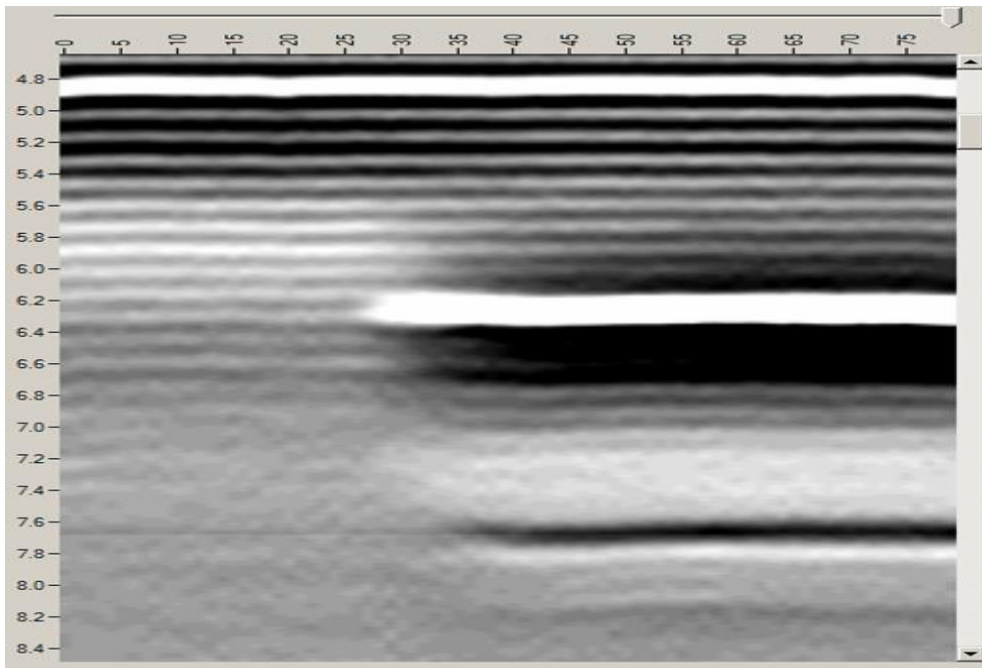


Figure 6. CLUE image of 1-D CFRC with metal foil.

White lines below the surface correspond to the carbon layers, black lines – to the matrix layers. The thickness of the ply was 0.14 mm. So, the resolution of CLUE image doesn't exceed 0.1 mm for CFRC. Bright line between 10th and 11th ply shows the position of brass foil. The dark line below the foil shows the successive reflection of the probe pulse in the layer between the surface and the foil. As the plane of the foil is parallel to the surface, its image is sharp. If the delamination between the plies takes place, it'll look like a dark line. B-scan of the test sample of CRFC with the delamination is presented in Fig.7. The thickness of covering composite layer was 1.6 mm. It was attached to the honeycomb structure. The interface between them looks like dark line. The artificial delamination takes place at 1 mm depth in the covering. It's image is dark line to.

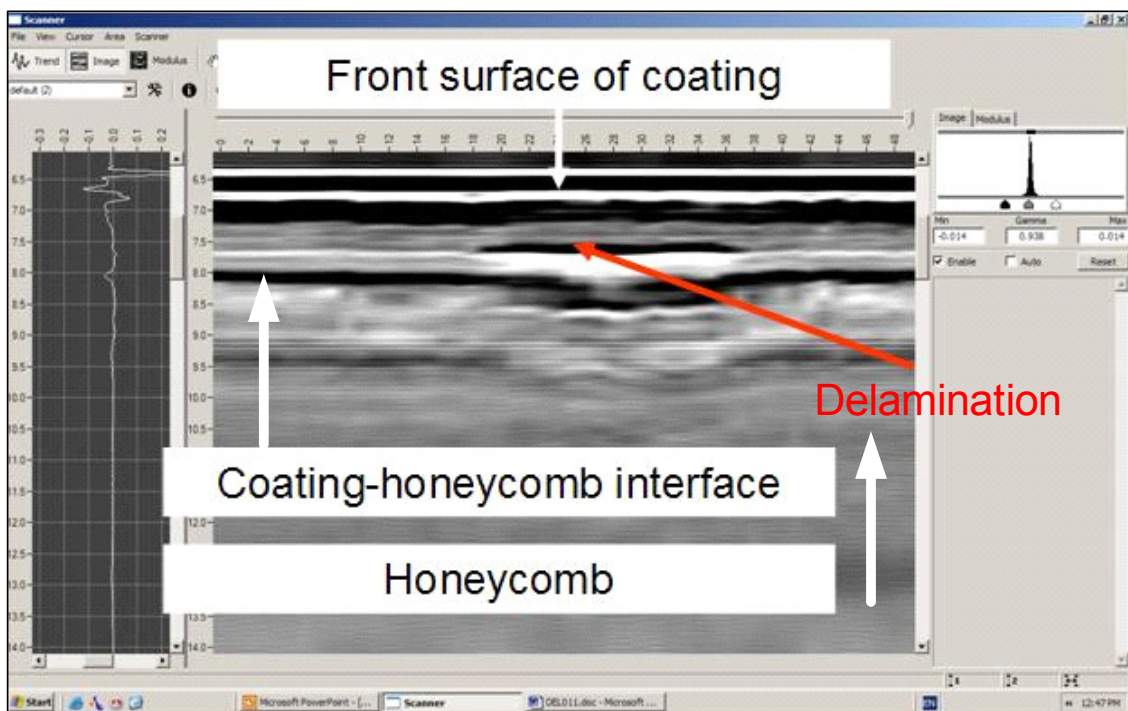


Figure 7. CLUE image of delamination in CFRC.

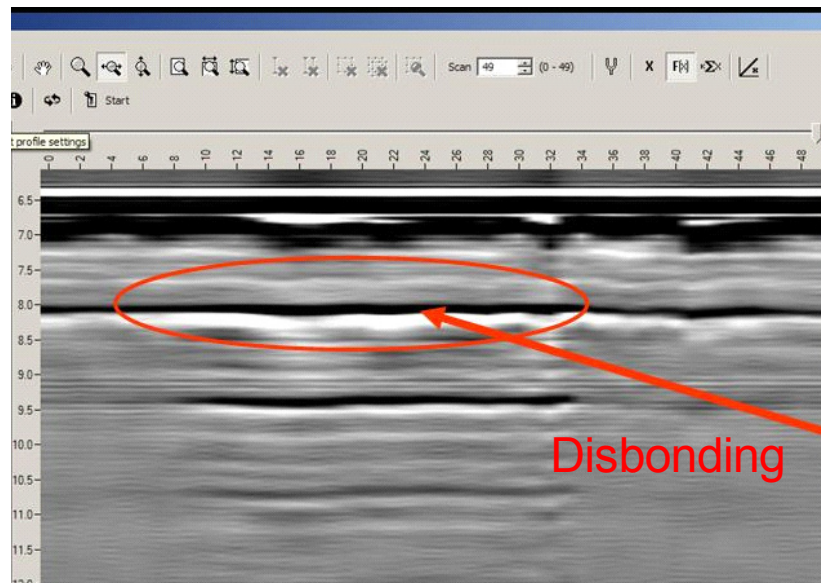


Figure 8. CLUE image of artificial disbonding in honeycomb structure.

CLUE image of artificial disbonding in honeycomb structure is presented in Fig.8. The thickness of CFRC coating was 1.6 mm as in Fig.7. In regular structure the multiple reflections in the coating are not manifested due to irregular rough surface of a glue. In disbonded area the rear surface of the coating is smooth and flat. So, the reflection from this surface is high and multiple reflections are present. In Fig.8 they manifest as successive dark lines below the coating-honeycomb interface.

Conclusions

Contact laser ultrasonic evaluation explores short probe ultrasonic pulse. This provides enhanced in-depth resolution for limited frequency band.

The probe ultrasonic pulse of CLUE has smooth temporal shape. It provides no “dead-zone” and discrimination of soft and rigid impurities.

Small diameter of a probe CLUE ultrasonic beam provides enhanced sensitivity of small defect detection.

CLUE is reliable technique for quantitative nondestructive testing of construction materials.

References

1. D.W.Fitting and L.Adler, 'Ultrasonic Spectral Analysis for Nondestructive Evaluation', Plenum Press, N.Y., 1981.
2. Physical Principles of Medical ULtrasonics, Ed.: C.R.Hill, J.C.Bamber, G.R. ter Haar, J.Wiley, 2004.
3. J.-P.Monchalain, 'Laser-Ultrasonics: Science, Technology and Applications', Laser Ultrasonics, Montreal, 2008.
4. V.E.Gusev, A.A.Karabutov, 'Laser Optocoustics', AIP, 1993.
5. A.A.Karabutov, E.V.Savateeva, N.B.Podymova, A.A.Oraevsky, 'Backward mode detection of laser-induced wide-band ultrasonic transients with optoacoustic transducer', J.Appl.Phys., **87**(4), p.2003-2014 (2000)