Determination of the depth of folds in fiberglass products using ultrasonic waves

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Abstract. The article discusses the existing methods of ultrasonic testing of polymer composite materials, reflected in the literature, allowing to determine the size of discontinuities, a method is proposed for determining the depth of folds of fiberglass products of complex shape by subsurface ultrasonic waves using original ultrasonic piezoelectric transducers with conical waveguides designed and manufactured. An experimental development of a method for determining the depth of folds of fiberglass products and a comparison of the results of ultrasonic testing with the results of X-ray computed tomography was carried out. **Key words:** polymer composite materials, ultrasonic method, X-ray computed tomography.

1 Introduction

Fiberglass is one of the most common polymer composite materials (PCM) in various industries, combining high strength, low density, and good dielectric properties [1, 2]. In aviation and rocket and space technology, fiberglass is used for the manufacture of critical structural elements, including the head elements of aircraft, which, as a rule, have a complex shape due to aerodynamic conditions [3].

In the process of manufacturing fiberglass products of complex shape by pressure impregnation, folds are inevitably formed – defects in reinforced plastics in the form of folds of a reinforcing filler [4]. Folds increase the inhomogeneity of the material and are concentrators of mechanical stresses; their size, in particular depth, determines the strength properties of fiberglass and the performance of the entire product. In this regard, in order to ensure the high quality and required reliability of the structures of critical fiberglass products, it becomes necessary to determine the depth of the folds by non-destructive testing methods.

2 Determination of the depth of defects by non-destructive testing methods

For non-destructive testing of most PCM products in the process of development, production and operation, various methods are used based on the interaction of penetrating radiation or

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physical fields with a controlled object: acoustic, radiation, thermal, optical, electrical, etc. [5]. Among the PCM control methods, acoustic methods occupy the first place in terms of the scope of application [6]. Acoustic methods are based on the interaction of elastic oscillations of a wide frequency range with a controlled part or structure [7]. Let us consider the existing methods for determining the size of vertically oriented defects by acoustic control methods.

To measure the nominal height of vertically oriented flat defects (cracks), the ultrasonic testing method is used [7, 8] using an inclined piezoelectric transducer, moving which along the surface of the test object perpendicular to the defect, the nominal crack height h is determined (Figure 1).

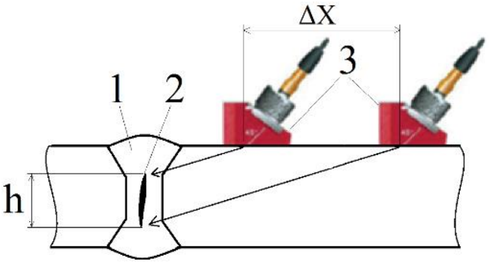

Fig. 1. Determination of the conditional height of a defect using an inclined piezoelectric transducer: 1 – defect, 2 – ultrasonic waves, 3 – inclined piezoelectric transducer.

This method is not applicable to fiberglass, due to the impossibility of registering reflected ultrasonic waves, due to their high attenuation (scattering, absorption, etc.), as well as the presence of acoustic noise from inhomogeneities in the fiberglass structure.

In [10], a method was proposed, according to which Rayleigh waves are excited in the controlled product in the direction of the open crack, the time interval between the moments of registration of the Rayleigh waves reflected from the near edge and the crack tip is measured, and then, according to the propagation velocity of the Rayleigh waves in the material of the controlled product calculate the depth of the crack (Figure 2).

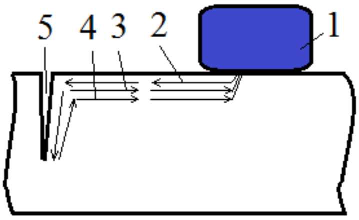

Fig. 2. Determination of the depth of surface cracks using Rayleigh waves: 1 – ultrasonic transducer, 2 – radiated Rayleigh wave, 3 and 4 – Rayleigh waves reflected from the near edge and tip of the crack, 5 – crack.

The use of this method to determine the depth of the folds is impossible, since ultrasonic Rayleigh waves are not reflected from the smooth boundaries of the fold (envelop it) or, being reflected, attenuate on the structural inhomogeneities of fiberglass.

The papers [10, 11] propose a method for measuring the height of vertically oriented flat defects using the diffraction of the first kind of ultrasonic shear waves at the edge of a crack (Figure 3, a) and an ultrasonic method for measuring the height of vertically oriented plane defects in glass-ceramic materials (Figure 3, b).

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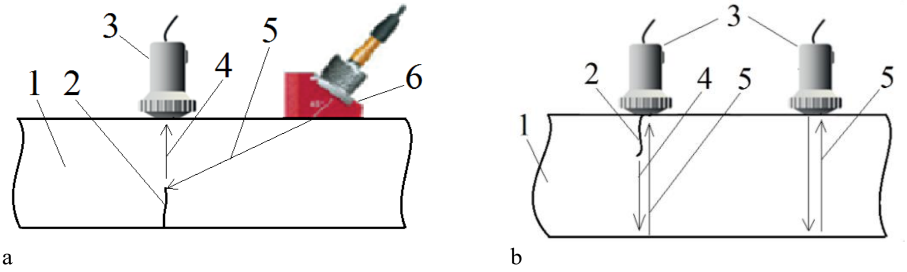


1 – test object, 2 – crack, 3 – direct ultrasonic transducer, 4 and 5 – ultrasonic waves, 6 – inclined ultrasonic transducer

Fig. 3. Defect height measurement using first-class diffraction of ultrasonic waves (a) and a decrease in the amplitude of the diffracted wave (b).

These methods are not suitable for determining the depth of folds due to the high attenuation and scattering of ultrasonic waves in fiberglass, which does not allow identifying and registering an ultrasonic wave diffracted or reflected from the bottom surface against the background of acoustic interference from structural inhomogeneities of fiberglass.

In addition to acoustic methods of non-destructive testing, X-ray computed tomography can be used to solve this problem, which makes it possible to determine the geometric parameters and location of folds in fiberglass materials with high accuracy. However, in order to achieve the maximum spatial resolution of the tomograph (the minimum pixel size in the image is 18 μm), it is necessary to use the principle of geometric magnification, which is based on the maximum approximation of the test object to the radiation source (IR). When carrying out computed tomography of a large-sized product, it is not possible to bring it closer to the AI in order to obtain the maximum spatial resolution of the system, because with such an arrangement of the product relative to the IS, its diametrical size is much larger than the size of the working radiation beam, and in this case it is impossible to carry out a full scan of the controlled section, which in turn limits the use of this method for identifying folds on the tomogram itself and the accuracy of measuring its depth. Also, the disadvantages of radiation monitoring in comparison with ultrasonic methods include low efficiency, high cost of equipment, as well as the presence of harmful factors for humans.

The need to determine the depth of folds in large-sized complex-shaped fiberglass products using non-destructive testing methods in order to ensure the quality and required reliability of critical structural elements substantiates the relevance of research in this direction.

3 Results of experimental work

To conduct research on the development of a method for measuring the depth of folds in fiberglass products using the ultrasonic method, samples were made with dimensions of 55×50×7 mm and 25×50×7 mm, repeating the shape and material of the product, and having characteristic folds of fiberglass. The size of the samples is due to the possibility of obtaining high-resolution X-ray tomograms. The sample material is fiberglass based on a phenol-formaldehyde binder with oblique reinforcement with TS 8/3-K-TO satin-weave quartz fiberglass. The appearance of the samples is shown in Figure 4.

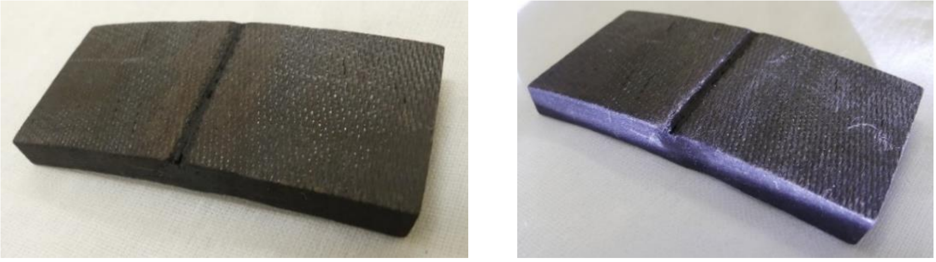
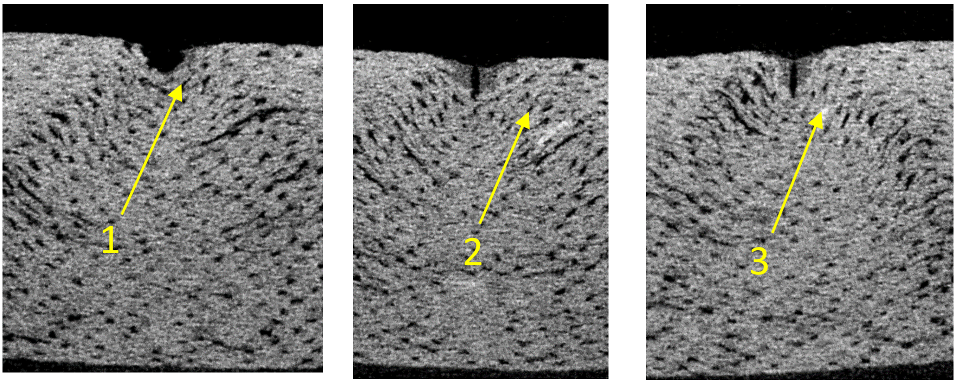


Fig. 4. Appearance of fiberglass samples with folds.

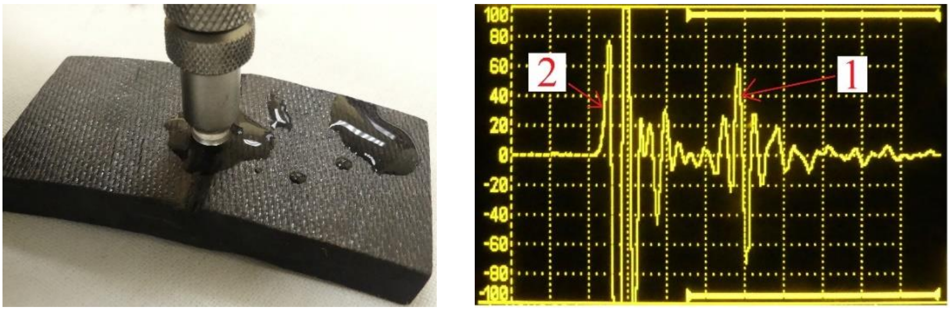
According to the results of the study of the structure of the material by X-ray computed tomography, the folds were divided into three groups: not filled with a binder (Figure 5, a); partially filled with a binder with a crack extending to the surface (Figure 5, b) and partially filled with a binder with an internal crack (Figure 5, c).



a b c

Fig. 5. Fragments of tomograms with folds in the studied samples. 1 – fold not filled with binder, 2 – fold partially filled with binder with a crack emerging on the surface, 3 – fold partially filled with binder with an internal crack.

The depth of folds not filled with a binder, with an opening of 0.5 mm (Figure 5, a) can be measured instrumentally by direct measurement or by taking a cast of the fold and measuring its dimensions, as well as by ultrasonic method by filling the fold with a liquid (for example, water), installing a direct high-frequency piezoelectric transducer on the fold, emitting ultrasonic longitudinal waves, followed by recording the ultrasonic wave reflected from the “liquid-fiberglass” boundary, measuring its propagation time and determining half of the path traveled by the ultrasonic wave, equal to the depth of the fold (Figure 6). The described ultrasonic method for determining the depth of folds with an opening of less than 0.5 mm or partially filled with a binder (Figure 5 b, c) is not applicable due to the impossibility of identifying the pulse echo from the “liquid-fiberglass” boundary against the background of acoustic noise.

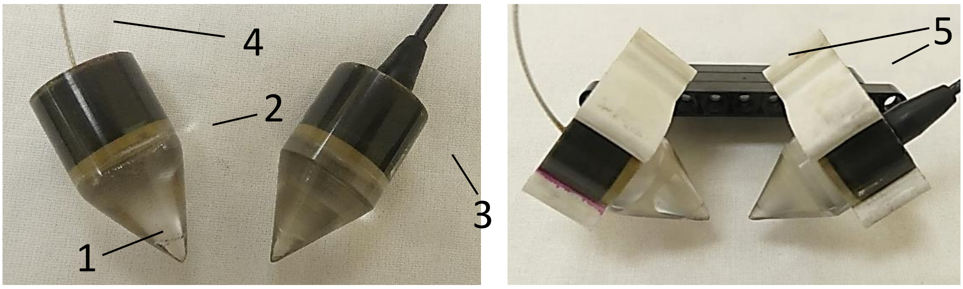


a b

a – installation of the transducer on a fold filled with water, b – oscillogram from the screen of an ultrasonic flaw detector (1 – echo pulse from the "delay line–liquid" boundary, 2 – echo pulse from the "liquid–fiberglass" boundary).

Fig. 6. Determination of the depth of the fold with an opening of 1 mm, not filled with a binder.

For non-destructive testing of surface cracks in flaw detection, Rayleigh waves are used – elastic waves propagating along the surface of a solid body or along the boundary of a solid body with other media and rapidly damping with depth [7]. The use of Rayleigh waves to determine the depth of folds with a crack in the binder that does not reach the surface can give an incorrect result. In this regard, to determine the depth of the folds, with a crack in the binder that does not come to the surface, special piezoelectric transducers with an operating frequency of 1 MHz were designed and manufactured with conical organic glass waveguides (Figure 7), which focus the ultrasonic field of the transducer, and also make it possible to provide optimal angle of input [12] of longitudinal ultrasonic waves into fiberglass for excitation of subsurface ultrasonic waves. The frequency of piezoelectric transducers is 1 MHz due to the optimal ratio of control sensitivity and attenuation of ultrasonic waves in the fiberglass under study. When testing glass-reinforced plastics with lower attenuation of ultrasonic waves, the frequency can be increased in order to improve the accuracy of testing.

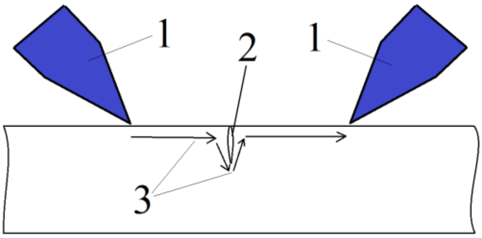


a b

1 – conical waveguide, 2 – piezoelectric element, 3 – damper, 4 – radio frequency cable, 5 – transducer fixation mechanism with the possibility of changing the input angle

Fig. 7. External view of ultrasonic transducers with a conical waveguide (a) and fixing the transducers at a constant distance with a possible change in the input angle (b).

When surface or subsurface ultrasonic waves propagate across the fold, their propagation time increases by increasing the path they travel by an amount proportional to the depth of the fold (Figure 8).

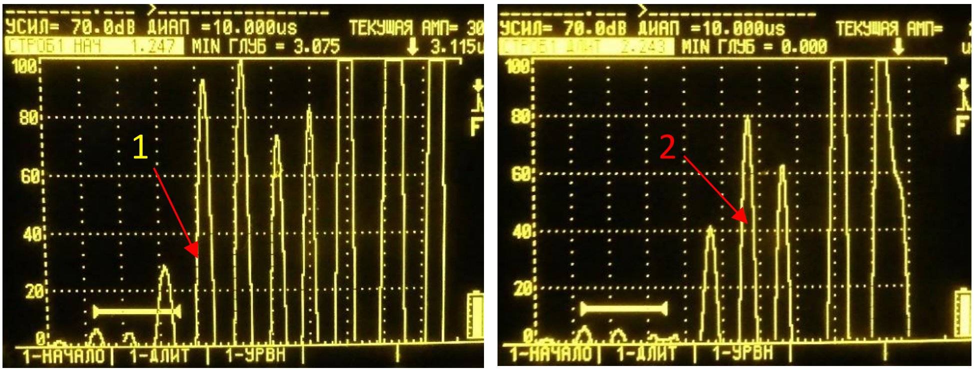


1 – source and receiver of ultrasonic waves, 2 – fold, 3 – ultrasonic waves

Fig. 8. Scheme of propagation of subsurface ultrasonic waves when passing through a fold.

Therefore, an increase in the propagation time of surface and subsurface ultrasonic waves Δt passing through the fold with respect to the propagation time of ultrasonic waves in the defect-free region when transducers are installed at the same distance can be used to determine the depth of the fold h using a linear relationship of the form: $h = a \times \Delta t + b$, where h is the depth of the fold, Δt is the increase in the propagation time of ultrasonic waves on the fold, a and b are experimentally determined coefficients. To take into account the effect of structural inhomogeneities and material anisotropy on ultrasonic waves [13 16], it is necessary to determine the average value of the propagation time of ultrasonic waves on a fixed base in a defect-free area on both sides of the fold and calculate the increase in the propagation time of ultrasonic waves on the fold according to the formula: $\Delta t = t - \frac{t1+t2}{2}$, where t is the propagation time of ultrasonic waves enveloping the fold; t1 and t2 are the propagation time of ultrasonic waves in defect-free areas on both sides of the fold.

Figure 9a shows an oscillogram from the screen of the flaw detector when measuring the propagation time of subsurface ultrasonic waves in the area of the sample without wrinkles, in Figure 9b – in the area with a wrinkle. The resulting oscillograms show an increase in the transit time of ultrasonic waves in the presence of a wrinkle.

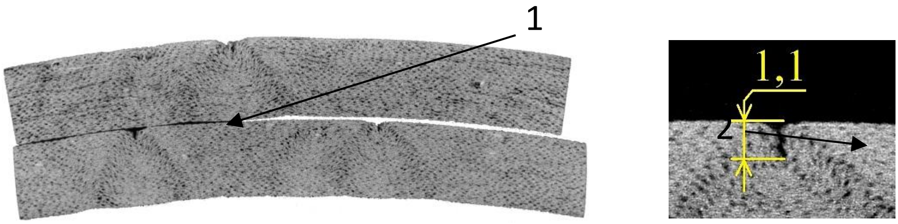


a b

1 – ultrasonic pulse propagating in a defect-free area, 2 – ultrasonic pulse propagating in the fold area

Fig. 9. Oscillograms from the screen of an ultrasonic flaw detector during measurements on a sample area without wrinkles a and on a sample area with a wrinkle b.

To build an experimental relationship between the increase in the time of passage of ultrasonic waves on the fold Δt and the depth of the folds, computed tomography of the studied samples was performed. Examples of tomograms of the studied samples are shown in Figure 10.



a b

1 – folds on tomograms, 2 – fold, with a specified depth

Fig. 10. Examples of tomograms of the studied samples (a) and a fragment of the tomogram with the specified wrinkle size (b).

Figure 11 shows the experimental dependence between the depths of the folds h_t, determined from X-ray tomograms, and the increase in the propagation time of ultrasonic waves on the folds Δt.

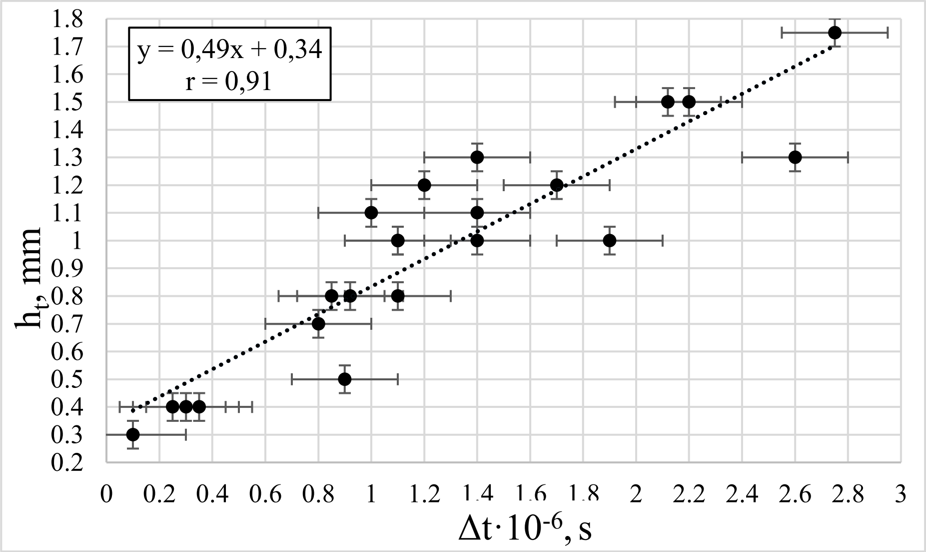


Fig. 11. Dependence of the increase in the propagation time of ultrasonic waves Δt on the fold on the depth of the fold h_t.

Figure 11 shows that there is a dependence between the depth of the folds obtained by computed tomography and the increase in the propagation time of ultrasonic waves on the folds Δt. To assess the degree of relationship between the studied parameters, in accordance with [17, 18], the correlation coefficient r = 0,91 was calculated. The calculation was carried out according to the formula:

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})}}, \qquad (1)$$

where x_i and y_i are separately measured values; $\bar{x}$ and $\bar{y}$ are the arithmetic mean; n is the number of measurements. The high value of the correlation coefficient indicates the possibility of determining the depth of the folds by changing the propagation time of ultrasonic waves on the folds.

Using the least squares method [18], a regression line was determined, described by the equation: h = 0,49×Δt + 0,34, which makes it possible to determine the depth of the folds based on the results of measuring the time of ultrasonic waves. The maximum deviation of the wrinkle depth determined using a computed tomograph from the value of the regression equation is 0,3 mm, which may be caused by inaccurate positioning of the sample sections in which X-ray tomography was performed and ultrasonic waves propagated, as well as the influence of structural inhomogeneities of fiberglass on the propagation of ultrasonic vibrations:

4 Conclusion

A non-destructive method for determining the depth of folds in glass-reinforced plastics by subsurface ultrasonic waves using specially designed and manufactured special piezoelectric transducers with conical waveguides has been proposed and tested. The high accuracy of the proposed method has been experimentally shown by comparison with the results of X-ray computed tomography.

A regression equation for fiberglass based on a phenol-formaldehyde binder reinforced with TS 8/3-K-TO quartz fabric was experimentally obtained to determine the depth of folds through an increase in the propagation time of ultrasonic waves in the fold.

Efficiency, high accuracy of determining the depth of the fold (0,3 mm) and the absence of harmful factors for humans are the advantages of the proposed method, which determine the prospects for its use in the mass production of highly critical fiberglass structural elements in order to increase their reliability.

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