To the question of the vibroacoustic methodology for the development of carbon plastics’ diagnostics

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Abstract: This article describes in detail the process of creating panels from a composite material by the method of vacuum infusion with various types of defects pre-installed in them. The most common types of defects that can arise in parts made of composite materials as a result of a violation of the technological process, the presence of defects in the original material, in particular, reinforcing fabric, as well as defects associated with the low qualification of the master are considered. The creation of such prototypes is necessary for the development of quality control methods for products made of composite materials. A vibroacoustic diagnostic method based on the passage of acoustic waves through a composite product is considered. It is shown that it is possible to estimate the size of a defect and the depth of its occurrence in a composite material by changing the intrinsic frequency characteristics of the wave field. Experimental data on diagnosing panels with defects is presented.

Key words: vacuum infusion, carbon fabric, composite part defects, adhesion, vibroacoustic diagnostic method, laser.

1. Introduction

One of the features related to composite products made of carbon fiber is difficult diagnostics for quality control. Despite the fact that other control methods allow exploiting the defect, the problem of a reliable diagnostic method remains. The quality of the product is not affected only by the presence of a defect, but by its size, type and depth of occurrence. Determination of these characteristics makes it possible to assess its degree of danger, therefore, the development of a new innovative diagnostic method is urgent.

2. Formulation of the problem

When creating new diagnostic methods at the final stage of their development, a problem of their verification arises. To assess the effectiveness of a particular diagnostic method, it is necessary to create a prototype product. As part of the problem being solved to develop a vibroacoustic method for diagnosing carbon-fiber-reinforced plastic products, it was decided to create a composite panel made of carbon-fiber-reinforced plastic using the method of manual laying, which is widely used in the production of products made of composite materials [1-2].

3. Experiment Description

For this purpose, by the method of vacuum infusion at the BMSTU center "Composites of Russia", a panel of 8 layers of carbon fiber was manually laid in layers. At the same time, it was marked and divided into 7 zones (Fig. 1). For the sample, the following stacking sequence of 8 layers was used: 0 ° / 0 ° / 0 ° / 0 ° / 0 ° / 0 ° / 0 ° / 0 °.
Let us consider in more detail each of the 7 zones and the (created) defects located in them, a full description of which is presented in Table 1.

Table 1. Defect description table depending on the zone number

| Zone | Defect description |
|------|--------------------|
| 1    | Completely **defect-free** in terms of manufacturing technology. |
| 2    | Defect of **lack of binder**. It is important to note that binder was applied to layers 1, 2 and 8 in this area. This was necessary in order for the panel after production to be a single monolithic composite material. |
| 3    | Defect in the ingress of **LUKOIL lux SAE 5W-40, API SJ/CF machine oil** (Fig. 2a). This oil was applied to zone 3 instead of the binder from the 4th layer to the 7th, inclusive. |
| 4    | Defect in the ingress of **universal grease WD-40** (Fig. 2c), the proprietary composition of which includes various products of oil distillation. It is important to note that this substance was originally developed as a water repellent agent to prevent corrosion. |
| 5    | A defect with a **different binder concentration**. For this, a curing agent, which is part of the binder as a whole, was locally applied abundantly. |
| 6    | A defect associated with **mechanical stress** (Fig. 2b). To do this, deep cuts resembling scratches were randomly made with a blade throughout the entire zone. The incisions were made only on the 4th layer. All other layers were not subjected to mechanical stress. |
| 7    | Zone 7 differs from all other zones in that an **additional piece of carbon fibre layer** of the same material was added between the 4th and 5th layers of the carbon tape, the size of which fully corresponds to the geometric parameters of zone 7 (Fig. 2d). Thus, zone 7 consists of 9 layers of carbon fabric with the same laying direction. |

4. **Technological process**

The technology of creating CM by the method of vacuum infusion can be divided into several stages [3]. The first stage is preparatory. It includes preparation and cutting the reinforcing fabric of the required size,
as well as mechanical and chemical cleaning of the tooling material. The surface of last one is repeatedly treated with a release agent, and the perimeter of the tooling, where the sealing strap will be further attached, is treated only with a solvent (acetone). At the second stage, a layer-by-layer manual laying of a reinforcing fabric impregnated with a binder is carried out (Fig. 2a). The third stage is associated with the laying of the technological layer. In this case, it is a sacrificial and conductive tissue, binder supply lines, and a sealing cord. At the fourth stage, the mold is sealed by fixing a vacuum polyethylene film along the perimeter of the sealing cord (Fig. 2b). At the fifth, final stage, evacuation, impregnation with a binder and polymerization of CMs take place [3-5].

Figure 2. Some stages of the technological process: a - laying out a layer of reinforcing fabric; b - package sealing.

A feature of the technological process of obtaining a composite panel was the creation of defects that simulate various technological deviations that arise during the manufacture of products. The technological process of manufacturing the panel is shown in Fig. 3 in block diagram form.
Preparation of composite material components (cutting reinforcing fabric and making the binder)

Preparation of equipment (mechanical and chemical cleaning of the working surface of the equipment)

Hand laid out reinforcing fabric

Is defect needed in this layer?

Need to lay out a layer reinforcing fabric?

Defect creation

Binder impregnation

Laying the technological layer

Sealing, evacuation and polymerization

Additional, two panels of 8 layers of carbon fiber were hand-layered. In this case, one panel was laid according to the traditional stacking sequence, and in the second panel the stacking sequence was deliberately violated to create a stacking defect [6].

Laying sequence of the 1st panel (no defect): \(0^\circ / 0^\circ / 0^\circ / 0^\circ / 0^\circ / 0^\circ / 0^\circ / 0^\circ\)

Laying sequence of the 2nd panel (defective): \(0^\circ / 90^\circ / 90^\circ / 90^\circ / 90^\circ / 90^\circ / 90^\circ / 0^\circ\)
The technology of creating panels from CM using the vacuum infusion method with defects included sequential laying of layers of cut reinforcing fabric, which was not impregnated with a binder, but was fixed with a temporary fixing adhesive spray to ensure tight adhesion of the fabric layers to each other, as well as uniform high-quality pressing of the fabric along the entire surface of the tooling.

At the final stage of panel molding, resin impregnation was carried out by feeding it through a spiral tube of the binder supply line. During impregnation with a binder, at the initial stage, it is necessary to ensure a low vacuum for high-quality uniform distribution of the binder over the surface of the mold, which was ensured by installing a valve for adjusting the degree of vacuum [7-9]. In order to accelerate the polymerization process of the composite panels, curing with a Trommelberg IR3C Standard infrared short-wave drying was applied.

5. Important features of the created panels

It should be noted that these panels have the following technological features that must be considered later when interpreting the results of their diagnostics. In the first series of production of a panel with seven zones, the first and second layers of carbon tape were sequentially impregnated with a binder, then 3 more layers were laid. Starting from the 5th layer, zones with various types of defects were created. Thanks to the technology of vacuum infusion, during the vacuuming process, the concentration of the binder is gradually equalized throughout the material. Therefore, the binder penetrated into zone 2 due to the capillary effect at the last stage of the panel production and evenly filled this zone too.

6. Approval of the vibroacoustic diagnostic method

The created defective panels were used to test various flaw detection methods and evaluate the effectiveness of each of the methods for detecting various types of defects in CM products [10-12]. This task is very relevant for ensuring the quality and reliability of aerospace technology products in the absence of guidelines for the application of existing methods. An independent task is the development of new methods of control and diagnostics, as well as their development, considering all the specifics of CM products [13-15]. One of the innovative methods of control and diagnostics of composite is the vibroacoustic method of diagnostics, which consists in the action of a laser on a sample from a CM and analysis of the natural modal oscillations arising in it.

The physical basis of this process is that the acoustic wave will bend around the defect zone and pass through it, changing the amplitude-frequency characteristics of the wave. The obtained frequency values allow one to see changes in the CM structure, and their amplitude makes it possible to judge the depth of the defect. A clear confirmation of the effectiveness of the wave diagnostic method is shown in Fig. 4.

![Figure 4](image)

**Figure 4.** Comparison of the amplitude-frequency characteristics of the two regions of the carbon panels: a — defect-free area; b — area with a defect (zone 3)
For carbon fibre, the filler frequency is 140Hz, for matrix 180-200Hz, and the natural frequency of the composite material is 170Hz. Any microdefects in their wave flow, due to their smallness, lie above 300Hz. Fig. 4b shows how the presence of autohesional delamination in the product matrix led to strong differences at 140-170 Hz in comparison with the analogous signal of the defect-free zone (Fig. 4a). Thus, the vibroacoustic method of diagnostics makes it possible to effectively detect a defect, and the quantitative characteristics of the spectrum make it possible to carry out a correlation analysis between them and the depth of occurrence of defects.

7. Conclusion

Carbon panels were created, including various types of defects in composite materials, which in appearance did not differ from defect-free ones. A feature of the created panels is a priori knowledge of the characteristics of the defects embedded in them, namely, their type, size and depth. This circumstance allows us to recommend these panels for the effective development of various methods of quality control of composite material products.

Moreover, a new vibroacoustic method was tested for diagnosing a carbon fiber composite material, which is based on the effect of a laser on a product and an analysis of this effect by the amplitude-frequency characteristics of the resulting spectrum. The amplitude of the spectrum can be used to judge the depth of defects’ occurrence. The experiment showed the effectiveness of this diagnostic method using the example of a specially created panel with known defects deliberately embedded in it. However, due to its poor study, this method needs additional experiments to create a database and its complete verification, as well as the development of full-fledged recommendations for its application.

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