Development of the algorithm for modelling autoclave curing conditions and calculation of temperature fields into elements of sandwich structures

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Abstract. To study the distribution of temperature fields into a large-sized combined parts, it is necessary to devote a great attention for all the design features. A specimen for investigation the "behavior" of the material in different zones of a typical PCM panel must simultaneously contain both a monolithic and sandwich part of the structure.

1. Problem statement, object of research and experimental specimens

The modern technology of manufacturing makes it possible to produce parts from PCM with increased overall dimensions and an increased degree of integrality, which leads to a reduction of cost and industrial cycle of modern aircraft at all.

In order to optimize the weight of the structure, the manufactured part may have a very heterogeneous internal structure, characterized by a significant change in thickness, and even a combination of several types of construction (monolithic and sandwich structure).

A special feature of manufacturing PCM products with a heterogeneous internal structure is a special mode of curing them, since during the heating process there is an uneven distribution of temperature fields into the volume of the package prepared for curing process. It is known, that temperature and pressure as functions of time are the main parameters of technological processes that can be controlled during the processing of raw materials into products. Proper distribution of temperature fields in the system "equipment - heating agent – tool - technological package – part" is crucial for achieving optimal characteristics of the composite in the product. For parts of the combined type, it is not an easy task to develop the manufacturing process, since it is necessary to ensure the required quality of the part, which is a combination of structurally different elements with specific technological and thermal characteristics.

In order to study the temperature fields, experimental composite specimens consisting a monolithic zone and a zone with a honeycomb structures were made. A quasi-isotropic reinforcement scheme is selected for certainty in the production of specimens. The number of layers is chosen based on the need to ensure the thickness of the skin in the honeycomb part of the sample is about 1.5 mm, and in the monolithic zone-about 9 mm. Some thermocouples were installed in three characteristic zones for studying the distribution of temperature fields during vacuum-autoclave molding: in the middle of the cross-section thickness of the monolithic zone, in the skin sided to the
tool, and in the skin laid over a honeycomb core. Two types of tool were used, which are typical for a real production process: made of metal and composite material.

The metal tool consisted of steel elements of two variants:
- 4.5 mm thick steel plate with overall dimensions of 700 x 1000 mm, 4 mm thick sheet;
- cast milled steel plate with overall dimensions of 500 x 900 x 300 mm, the average thickness of the tooling is 35 mm.

The composite tool was a 6.2 mm thick carbon fiber panel with overall dimensions of 650 x 1200 mm.

Both metal and composite tools were placed on the lodgments during curing, which ensured their direct contact with the environment (air) of the autoclave.

Specimen blanks (figure 1) were made from prepreg of widely used in the aviation industry CFRP VKU-30 type and GFRP VPS-32 type. Was used a honeycomb core made of aluminum alloy AMg2N according to OST 1 00728-75.

![Figure 1. Scheme of the manufactured experimental sample](image)

The technological package was formed using a perforated anti-adhesive film of the Wrighton 4600 brand, a fiberglass caul plate with a thickness of 1...1.5 mm. The size of the installed caul plate was approximately on 20 ... 25 mm less than the size of the laid out specimen blanks. To determine the temperature in the required zones according to the experiment plan, thermocouples were installed. Thermocouple № 1 was installed in the monolithic part of the sample. Thermocouple № 2 was installed on the surface of a thin skin over a honeycomb core. Thermocouple № 3 was installed in the honeycomb part of the sample between the skin and the surface of the tool. Non-woven fabric of the AirWeave brand by Airtech was used as the breather.

The quality of the material (in particular, the absence of micro- and macro-defects, the required fiber-matrix ratio) of the molded part depends on the correct choice of autoclave molding parameters: the amount of vacuum, temperature, overpressure, as well as the order of their change and duration of process. That is, by the end of the polymerization process of the layers of the specimen should be removed air pockets. The pores in the material must be removed by the end of the process. The resin should be evenly distributed between the layers, while the excess should move to the breather layers [1 - 3].

It is shown that the reduction of the number of air inclusions in the package contributes to its vacuuming. Moreover, air inclusions in the process of their removal from the material block the outflow of an excess amount of resin. Effective removal of excess resin occurs only after creating pressure in the autoclave. The intensification of these processes is facilitated by a decrease in the viscosity of the resin when the temperature increases. However, an increase in temperature, in turn, leads to a reduction in the time during which the reduced viscosity of the resin is lasts [4].
That is why, the quality of the plastic obtained in the molding process is provided by the optimal law of changing the technological parameters of autoclave molding, which must be set in accordance with the rheokinetic parameters of the resin at the same time.

If we assume that the design of the tool is dictated mainly by considerations of providing a given geometry, strength, rigidity, durability, weight restrictions, it is possible to achieve equal temperature both on opposite surfaces of the molded product and on its area only by regulating the heat flow through the technological package. That is, by changing the design of the caul plate, the number of breather layers, or by introducing additional thermal insulation materials on top of the vacuum bag. However, slowing down the heating speed of the upper surface of the sample relative to the tooling by reducing the thermal conductivity of the process package may have the opposite side: with active heat generation during polymerization, the degradation of heat removal may also affect the value of self-heating of the part.

Due to significant heterogeneity of the internal structure of the manufactured samples we studied changes in temperature of different areas of experimental panels at various stages of forming: changing the temperature of the skin of honeycomb of the sample placed on the side of the vacuum case, the change in temperature of the skin adjacent to the forming tooling (the surface temperature of the snap), and also change the monolithic part.

The experimental molding mode is divided into two stages: the first stage includes heating and holding at a temperature of 125 °C. The second stage begins with the creation of excess pressure in the autoclave and consists in creating the conditions necessary for the polymerization of the resin.

2. Evaluation and discussion of the experiment results
The experiment described in this article is devoted to the first stage of the above-mentioned molding mode.

Figure 2 shows diagrams of temperature changes in the opposite paneling of the cellular part of panels made on metal and composite equipment, the forming surface of which was a sheet material.

![Figure 2. Sample temperature change diagrams](image)

The color indicates: 1 - the temperature of the working body of the autoclave, 2 - the skin temperature for a standard technological package, 3 - the surface temperature of the tooling, 4 - the skin temperature with twice amount of breathers

The figure shows that the rates of temperature change displayed by all thermocouples are almost identical. The metal tooling and, accordingly, the sample surface adjacent to it, reach a certain fixed temperature with a delay of about 10 minutes relative to the temperature of the working body of the autoclave. The opposite skin of the sample, if using a standard process package, reaches the same temperature one minute earlier. To analyze the possibility of controlling the heating rate of the skin located on the side of the vacuum bag, using the method described in [5], an additional thermocouple was installed, over which an increased amount of breather material was laid out. The obtained result
confirmed that a double increase in the number of breather layers reduces the temperature difference between the opposite paneling of the sample – in this case, the paneling on the side of the process package reaches the same fixed temperature by about 30 s later than the surface of the tooling. A similar pattern was obtained for the sample on the composite tooling. At the same time, the difference in the time of reaching a certain fixed temperature by the opposite skins of 1,5 minutes can not be critical for the design of the molding mode. That is, it can be concluded that in the case of tool usage, the forming surface of which is made of sheet material, and the heat exchange surfaces with a working medium of the autoclave is not hampered by its structural features to control the parameters of molding of sandwich parts only determine the temperature of one of the casings.

The experiment allowed us to obtain initial data for creating a mathematical model of the temperature changing of the molded product, reflecting the features of heat exchange between the working environment of the autoclave and the molded product, taking into account the thermophysical properties of the technological package and tool.

In the continuation of experimental work at the second stage of autoclave molding, the influence of the design type (monolithic or sandwich structure) and the material of the tool for the distribution of temperature fields in the material of the molded product under constant external influence was shown. In particular, a significant self-heating of the monolithic section of the product cured on a composite tool was noted. Moreover, as shown in [6], the amount of heat released was also determined by the rate of self-heating. Similar results were obtained using the developed mathematical model. In the manufacture of a specimen on a metal tool, this phenomenon was practically not observed due to the more effective removal and redistribution of heat released during polymerization, between the zones of the specimen with greater and lower material consumption.

3. Conclusion
From the results obtained, it can be seen that under the same external conditions, metal tool quickly takes and redistributes excess heat released during the exothermic curing reaction of the resin due to high thermal conductivity. At the same time, due to the thermophysical features of the composite tool, the rate of heat transfer to the tool was insufficient to equalize the temperature field over the specimen area. The excess of heat generated led to increase temperature in the local area of the material to values significantly higher than recommended one.

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