Improving the Energy Efficiency of Autoclave Equipment by Optimizing the Technology of Manufacturing Parts from Polymer Composite Materials

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Abstract. Autoclaves used for the manufacture of parts from polymer composite materials (PCM) for structural purposes are equipment that consumes a significant amount of energy. In the manufacture of parts of a monolithic design from PCM in 2 transitions in order to reduce energy consumption, it was proposed: during the first molding, reduce the main exposure time, which reduced the operating time of the autoclave tens. In the workpiece, the complete polymerization of the adhesive binder occurs during the second molding transition. Also, it was proposed to manufacture parts of a honeycomb structure from adhesive prepregs for one molding with an autoclave under-molding at an elevated temperature instead of the first molding. The formation of a monolithic zone of honeycomb parts in one cycle eliminated the formation of unacceptable defects: "delamination" and "increased attenuation of the ultrasonic signal." A change in the technology of molding PCM parts has reduced manufacturing time, labor and energy consumption compared to the previously used mode in 2 transitions. The quality of gluing parts according to this advanced technology is confirmed by the results of acoustic control and mechanical tests.

1. Introduction
Currently, there is a significant increase in the use of composite materials in the aviation industry. The design of a new generation of fighters uses a large range of parts from PCM [1,2].

The main part of composite parts for structural purposes (frame) is made of adhesive prepregs. Adhesive prepregs are filler rolls with a layer of glue binder. An adhesive prepreg is a modern material in the form of a semi-finished product, ready for the manufacture of parts, in contrast to prepregs made by impregnation.

In aviation, molten adhesive prepregs of the KMKU brand (based on carbon tape) and the KMKS brand (based on fiberglass) are currently used, depending on the requirements for the parts. For example, power spars are made of KMKU, radiolabel wingtips are made of KMKS [3].

Details of adhesive prepregs have a high cost, which consists of the cost of materials (basic and auxiliary), technological equipment (devices for pasting and templates), labor costs for manual layering and machining, cost of equipment used (including energy costs).

Parts from aviation adhesive prepregs are made by autoclave molding [4,5]. Autoclave molding is the shaping of a part at elevated temperature and pressure with holding for a certain time to completely polymerize the adhesive binder.
Scholz autoclave plants are mainly used. Autoclaves are equipment that consumes a significant amount of energy to create heat.

With the ever-increasing volumes of composite production, the energy consumption of equipment increases, there is a serious reason for the urgency of the issue of energy saving methods [6,7].

Energy conservation and energy efficiency improvement are some of the most important issues at present. Energy conservation is a priority area of economic policy, focused on reducing the cost of developing basic products and reducing the load on production capacities [8,9,10]. Companies in the aircraft industry are interested in creating energy-saving technologies that will provide more efficient and the economical use of energy resources, including electricity.

2. Modes of moulding parts of different design

To find a way to save energy in the manufacture of parts from PCM, modes of forming parts of various designs are considered.

Parts with adhesive prepregs are divided by design: parts of a monolithic structure, consisting only of prepreg layers (Fig. 1) and parts of a three-layer honeycomb structure, consisting of two skins glued with honeycomb core (Fig. 2).

The modes of forming parts from adhesive prepregs of a monolithic and three-layer construction are identical in temperature and time parameters of molding and differ in the value of overpressure of molding: (5.5 + 0.5) kgf/cm² - for monolithic parts, (2 + 0.25) kgf/cm² - for honeycomb parts. Complete polymerization of the glue binder of the adhesive prepregs occurs during molding of parts according to the following mode:

![Figure 1. Monolithic ending of the keel.](image-url)
- creating a vacuum of at least 0.8 kgf / cm²,
- temperature rise to (125 + 5) °C with a speed of no more than 2 °C / min,
- exposure at a temperature of (125 + 5) °C for (60 + 5) min,
- pressure supply (2 + 0.25) kgf / mm² or (5.5 + 0.5) kgf / mm², vacuum shutdown,
- temperature rise to (180 + 5) °C with a speed of not more than 2 °C / min,
- the main exposure at a temperature of (180 + 5) °C for (5.0 + 0.5) hours,
- cooling under pressure to a temperature of not more than 40 °C with a speed of not more than 1 °C, pressure relief.

The molding diagram for this mode is shown in Fig. 3.

During molding, temperature control is carried out using a thermocouple installed in the technical allowance of the molded part. In the diagram (Fig. 3) air heating occurs much faster (red line in the diagram) than heating details (green line on the diagram). Monolithic parts of complex geometric shape (keel ending (Fig. 1)) are made in two transitions: laying out the first layer package (No. 1-11 in Fig. 1) - autoclave molding - first transition; laying of the facing layer (No. 12 in Fig. 1) - autoclave molding - the second transition. Manufacturing for 2 transitions is used to exclude external defects and defects in the form of unformations. All parts of a three-layer construction are made in 2 transitions: laying of the outer (lower) skin (layers No. 1-13 of Fig. 2), installation of honeycomb core - autoclave molding - first transition; honeycomb machining the calculation of the inner (upper) lining (layers No. 14-23 of Fig. 2) - autoclave molding - the second transition.
The manufacture of parts in two transitions is used to fix the honeycomb core on the outer skin at the first transition, for the possibility of its subsequent mechanical processing along the contour: making a bevel (angle 30° Fig. 2).

Consider the nomenclature of parts from adhesive prepregs of a new generation of products manufactured by autoclave molding. Let the total number of parts be 243: 45 parts - honeycomb and 198 - monolithic construction. About 80 positions are made of them in 2 transitions. A full autoclave charge averages 3 parts. That is, for the manufacture of all parts from the adhesive prepregs of an airplane, at least 160 (243/3 +80) energy-intensive molding cycles are required.

According to the above mode, the average power of the heating elements during the operation of autoclave plants is 435 kW. As can be seen from the diagram (Fig. 3), the autoclave tena operate 11 hours before the start of cooling during each molding cycle.

3. Energy consumption

In order to reduce energy consumption in the manufacture of parts from adhesive prepregs, a method was proposed to reduce the time of the main molding mode [11,12].

In the manufacture of parts of a monolithic structure for 2 transitions: at the first molding step, the main shutter speed at a temperature of (180 + 5) °C was reduced from 5 to 3 hours. Complete polymerization of the adhesive binder in the workpiece manufactured at the first transition occurs during the second molding transition with holding for 5 hours at a temperature of (180 + 5) °C. Similar to parts of a monolithic structure, for parts of a three-layer structure, the molding mode in terms of holding at a temperature of (180 + 5) °C was reduced from 5 to 3 hours. The reduction of the molding cycle of parts from adhesive prepregs is shown in Fig. 4, it presents the temperature-time diagrams. The diagram shows, the operating time of the Tens autoclave is reduced from 11 to 9 hours.

![Temperature-time diagram](image)

**Figure 4.** Molding diagrams at 3 and 5 hours exposure at pressure.

In the manufacture of parts of a three-layer structure manufactured in 2 transitions, there was a problem in the quality of the monolithic zone of the part.

According to the technical requirements of the design documentation [7], non-destructive acoustic control methods are used to determine the bonding quality of the PCM part. For the monolithic zone of honeycomb parts, the ultrasonic monitoring method (USC) is used to identify areas of separation between the layers of the material of the part. The delamination areas of more than 3 cm² are a critical defect for the part, since they lead to a decrease in the strength of the part.

During ultrasonic testing of the monolithic zone of honeycomb parts, in addition to bundles, zones of acoustic signal transmission as a result of its attenuation were detected. With the attenuation of the acoustic signal, the zones of the part become unsuitable for non-destructive testing. According to the results of research, these zones are classified as zones of increased porosity of the PCM. In areas of increased signal attenuation, a decrease in strength characteristics by (5-7)% is observed compared to high-quality areas of the part, which is a deviation.

The causes of stratification zones and increased attenuation of the acoustic signal on the details of the honeycomb structure were investigated. As a result of acoustic control, a defect was detected.
“Signal attenuation” is a form of a monolithic zone of honeycomb parts in 2 transitions. The boundary of the transition from the outer to the inner sheathing of the parts through the KMKS adhesive prepreg layer is the boundary of the signal attenuation during acoustic monitoring [13,14].

The presumptive cause of signal attenuation at the casing boundary is an excess of the adhesive binder formed on the molded outer casing during the second molding transition.

In this regard, it became necessary to form a honeycomb structure part (layers Nos. 1-23 of Fig. 4) in one transition.

The complexity of manufacturing honeycomb parts in one autoclave molding is the need to fix the honeycomb core to the outer skin to ensure the bevel of the honeycomb core around the perimeter.

According to the normative documentation of the customer [9], fixing the honeycomb core to the outer skin by vacuum molding at a temperature of 80 °C was ineffective. Therefore, the technology of fixing the honeycomb core on the outer skin of the autoclave subform was tested. The following autoclave molding mode of the honeycomb core to the outer skin was successfully tested and implemented:

- heating under vacuum to (100 + 5) °C,
- pressure supply (2 + 0.25) kgf / mm², vacuum shutdown,
- exposure at a temperature of (100 + 5) °C for 1 hour;
- pressure cooling, pressure relief.

The reduction of the molding cycle of parts of the honeycomb structure at the first transition is shown in the temperature-time diagram in Fig. 5.

By increasing the viscosity of the adhesive binder (adhesive matrix), at a molding temperature of (100 + 5) °C in the prepreg under pressure, the lower skin of the part is molded and adhesive bonds (fugs) are formed with the honeycomb core, these bonds are sufficient to perform mechanical processing of the bevels around the honeycomb core. Further, after laying out the inner lining, the final molding (curing) of the part is performed.

Figure 5. Diagrams of molding with a 5-hour exposure and an hour shaping under pressure.

The molding of the monolithic zone of honeycomb parts in one molding cycle, subsequently, eliminated the identification of such unacceptable defects as: “delamination” and “increased attenuation of the ultrasonic signal.” The bonding quality of parts manufactured by this advanced technology is confirmed by the results of acoustic control.

4. Calculating the economic effect
From the diagram (Fig. 5), the operation of the autoclave ten is reduced from 11 to 3 hours, while the energy consumption for heating the part to 100 °C during molding is much less than for heating to 180 °C when fully molded.

In addition, during autoclave molding, compared with the full molding mode, the operating time of the vacuum pump is reduced from 4.5 to 2 hours before applying pressure and the time of operation of the fan from 15.5 to 5.5 hours, it works throughout the cycle.
In the manufacture of 243 parts from adhesive prepregs, it is possible to produce 38 positions of monolithic parts and 43 positions of honeycomb parts according to shortened molding cycles.

Having considered the reduction of the modes of forming parts from adhesive prepregs, it is possible to calculate the economic effect of reducing the consumed electric energy.

\[
E_1 = H \cdot (T_1 - T_2) \cdot K \cdot B_1 \cdot C
\]

where: 
E1 – economic effect while reducing the molding mode of monolithic parts, rub.
H – power autoclave installation, 435 kW,
T1 – operation time of heating elements in full mode, 11 hours.,
T2 – the operating time of the heating elements in the reduced mode, 9 hours,
T3 - the operating time of the heating elements during molding, 3 hours.,
K - coefficient taking into account incomplete loading of equipment power during molding, 0.4,
B1 – number of molding cycles for cast parts, 10.
B2 – number of molding cycles for honeycomb parts, 12.
C - cost 1 kW, 2.15 rub.

\[
E_1 = 435 \cdot (11 - 9) \cdot 0.4 \cdot 10 \cdot 2.15 = 7482 \text{ rub.}
\]

\[
E_2 = H \cdot (T_1 - T_3) \cdot K \cdot B_2 \cdot C
\]

where: 
E2 – economic effect when replacing the molding mode of the honeycomb parts with a subform, rub.

\[
E_2 = 435 \cdot (11 - 3) \cdot 0.4 \cdot 12 \cdot 2.15 = 35913 \text{ rub.}
\]

E = E1 + E2

where E – overall economic effect, rub.

E = 43395 rub.

So, due to the reduction of the modes of forming parts from adhesive prepregs, the overall economic effect on one plane will be 43,395 rubles. This calculation did not take into account: a reduction in the energy consumed by reducing the operating time of the vacuum pump and fan during autoclave molding, reducing the complexity and time of manufacturing parts, and also saving auxiliary materials.

5. Conclusion
Changing the mode and reducing the time of molding monolithic parts in accordance with the consumed electricity during autoclave molding.

Replacing the full cycle of the first transition to the details of the honeycomb structure using autofill allows you to automatically consume electricity during autoclave molding, as well as improve the bonding quality of parts, confirming acoustic control.

Changing the mode of forming parts from glue blanks will reduce the complexity and time of manufacturing parts, save expensive auxiliary materials.

This advanced technology for manufacturing parts of a monolithic and honeycomb structure from glue blanks, aimed at energy saving, coastal production and improving the quality of parts, and has been introduced into the production of aircraft parts from PCM.

The manufacturing technology of parts from PCM allows the manufacture of parts for other aircraft products. Thus, to save resources, it is advisable to unify the range of materials used for the manufacture of PCM parts.

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