BIO Web of Conferences **145**, 03048 (2024) https://doi.org/10.1051/bioconf/202414503048
Forestry Forum 2024

Methods of manufacturing long-length power structures made of polymer composite materials

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Abstract. This article compares technologies for manufacturing in the designs of modern structures from PCM and their impact on the structure of the finished product. Various methods are known for manufacturing parts and assemblies from PCM: contact, vacuum, autoclave, winding, press chamber, thermocompression, pressure impregnation, infusion, pultrusion, etc. Assessing the advantages and disadvantages of each method allows the designer and technologist to choose the optimal methods for molding products from PCM, which is an urgent task at the present time, when PCM is increasingly used in the designs of modern structures.

1 Introduction

A wide variety of polymer composite materials (PCMs) and the desire to expand their use in structures for various purposes requires a rational choice of manufacturing technology, taking into account promising methods. The manufacturing method, in turn, directly affects the characteristics and structure of the future PCM product.

The difference between the properties of anisotropic materials and isotropic concepts requires the definition of their properties and taking them into account in calculation and manufacturing methods. This difference makes it possible to regulate the mechanical, dynamic and operational characteristics of structures by changing the composition, concentration and relative position of the reinforcing elements. The mechanical characteristics of structural PCM are continuously improving, which has led to their widespread use in various power structures, which requires further development of methods for their calculation and manufacturing methods [1,2].

The purpose of the study is to compare the characteristics of products obtained as a result of using various methods for their manufacture from PCM and to select the optimal method and mode for manufacturing the spar of a detachable part of an aircraft wing from PCM [3].

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The pressure impregnation method involves the use of a mold and installation to supply the binder under pressure. The gap between the mandrel and the die corresponds to the thickness of the spar. The installation for supplying the binder includes a tank with the binder, a compressor unit for supplying the binder under pressure and a binder supply control system. Carbon fiber joints are laid dry on a mandrel pre-coated with anti-adhesive lubricant. The mandrel with the collected carbon fiber package is placed in the mold and tightly closed with a lid. We connect one line to the installation with a binder, and the second to the vacuum pump. A vacuum is first maintained to remove excess air between the layers of reinforcing material, then the binder is supplied under pressure from 2 to 6 atm and the spar is impregnated. When resin appears in the filter trap, the inlet and outlet holes are closed and the binder is polymerized by heaters mounted in the mold [4]. After removing the products from the mold and cleaning, quality control of gluing, contour and submission for assembly is carried out.

2 Materials and Methods

The advantage of this method is the high quality of the finished product: the thickness is precisely maintained, the product has high physical and mechanical properties.

The disadvantage of this method is the expensive and complex equipment.

The equipment diagram is shown in Figure 1.

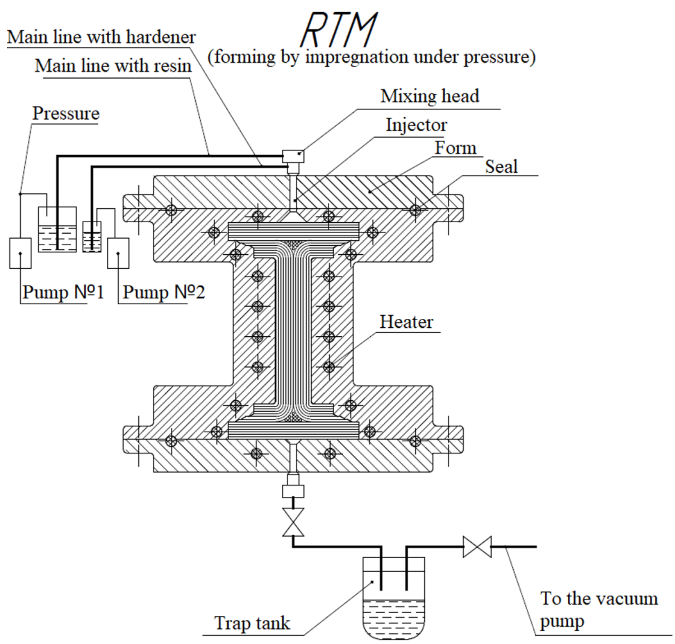

Fig. 1 - Equipment diagram for the RTM method

3 Method of press chamber molding (air compression)

The method is based on creating molding pressure due to air pressure through an elastic diaphragm to the workpiece (air supplied from an air compressor to a rubber bag) [3]. A pre-assembled package of reinforcing material - prepreg - is placed in a rigid mold, pre-coated with an anti-adhesive lubricant, inside of which are placed bags made of rubber type R-181, having plugs with fittings through which pressure from the compressor is applied inside the bag in the range of 3-5 kg /cm2. After closing the sealed mold, its heating is turned on due to electric plate heaters made of stainless steel type X18N9T l0.1mm. The molding pressure is controlled using a pressure gauge. The advantage of this method is the ease of control of the molding pressure, due to control using a pressure gauge and the absence of expensive equipment. The disadvantage of this method is the lack of reusable use of the rubber block due to its low heat resistance [5,6].

The equipment diagram for the pneumocompression method is identical to the equipment diagram for the thermocompression method, except for the presence of silicone mandrels instead of rubber bags, which expand when heated and create a pressure during polymerization in the range of 3-5 kg/cm2. Thus, the equipment diagram is general and is shown in Figure 2.

The difference between our proposed method of heating a sealed mold is that its heating occurs due to the flow of hot oil through special channels in the mold. The silicone rubber mandrel begins to expand. The molding pressure is controlled only by temperature and cannot be changed abruptly. Cooling of the mold occurs by switching the mixer to a tank with cold oil [7].

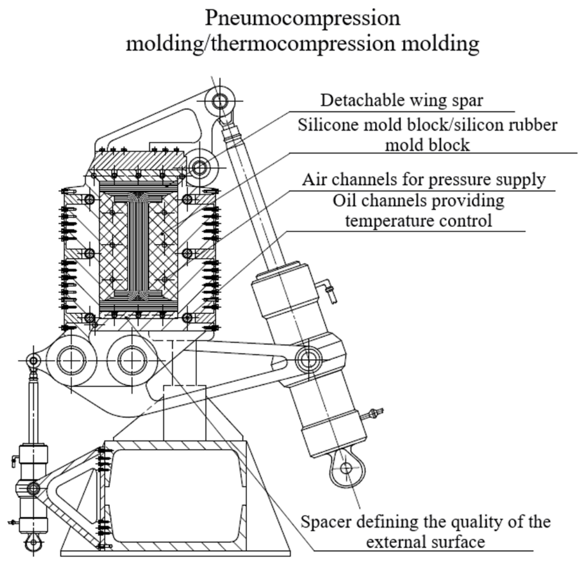

Fig. 2 - Scheme of equipment for pneumocompression and thermocompression molding

The advantage of this method is the relatively high molding pressure, reaching up to 5 atm in the polymerization mode, as well as the reusability of silicone mandrels, since organosilicon rubber allows heating up to 3500C, as well as reduced costs for heating the mold and product [8].

The disadvantages of this method are the following factors:

1. Inability to directly control molding pressure
2. Molding pressure is difficult to maintain constant. There is always a heating zone and a cooling zone, due to which the change in molding pressure occurs smoothly.
3. Molding pressure depends on temperature and sometimes polymerization requires temperatures of 180 degrees or higher, which rubber cannot withstand. As a result, the rubber mold block in the pneumocompression method is practically disposable.
4. Due to the different thickness of the rubber mold block, it expands differently, which creates different pressure, which leads to different volume content of the binder.
5. Excess air is not removed.

Using a combined method - combining pneumocompression and thermocompression allows you to use the advantages of each method. To do this, it is necessary to make silicone bags from special silicone rubber, inside of which adjustable pressure can be applied and they are reusable [9].

The vacuum infusion method is to create a molding pressure by reducing the pressure under the vacuum bag, resulting in a molding pressure close to atmospheric. This method also differs in that prepreg is not used. Impregnation of dry reinforcing material occurs by connecting the mandrel to a container with a binder, which impregnates the product under vacuum. A pre-assembled package of dry pre-cut blanks is placed on a non-hermetic mandrel, which is not heated, but has cavities for impregnating the reinforcing material with a binder, as well as pumping out air. To improve the upper and lower surfaces of the spar flange, additional side mandrels are used. Metal tsulaga, up to 4 mm thick, with drainage holes, is placed on top of the bag. Then a double vacuum bag is assembled. Tsulaga is covered with anti-adhesive grease, a sacrificial layer is placed under it, a release film with micro-perforation is placed on top of it, then a drainage layer, then a reusable silicone film, which completes the vacuum bag No. 1. Vacuum bag No. 2 is installed on top of vacuum bag No. 1, which is sealed using a sealing cord glued around the perimeter. Vacuum bag No. 2 consists of a drainage layer and a reusable silicone vacuum film. To polymerize the binder, a thermal oven is used or the mold must have heaters [10].

The advantages of this method are the simplicity of equipment, it is not expensive. Sealing is carried out using vacuum bags and does not require the creation of sealed molds. Forming pressure is low, which means the mandrels will have less mass.

The disadvantages of this method are the large amount of waste: both the binder and materials, such as the drainage layer, separating film, tubes through which the binder is supplied, silicone film, which, although it can withstand up to 30 manufacturing cycles, can be damaged. Forming pressure depends on the vacuum pump, temperature and humidity in the room. It is necessary to carefully assemble the vacuum bag and control its tightness, as a result of which the quality of the product directly depends on the qualifications of the worker, and even an experienced worker will produce products that will differ in porosity and physical and mechanical properties. The calibrated surface becomes a wall; the shape of the belts is maintained, but can be damaged as a result of improper assembly of the package. Low molding pressure leads to a higher volumetric binder content, which means a higher weight of the final product [11, 12].

The equipment diagram is shown in Figure 3.

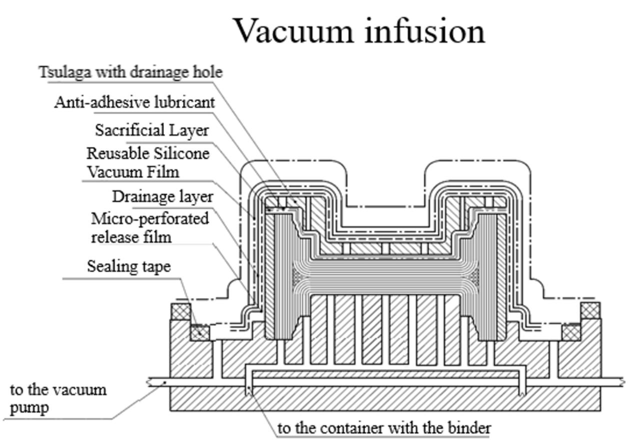

Fig. 3 - Diagram of equipment for the vacuum infusion method

4 Autoclave Molding

The autoclave molding method is based on creating molding pressure in a sealed chamber by supplying compressed air. A pre-assembled prepreg bag is placed into a rigid mandrel, pre-coated with a release agent. The package with the mandrel is fed into the sealed chamber of the autoclave. The air inside the chamber begins to heat up and circulate due to the built-in fan. After the chamber has been warmed up to operating temperature, compressed nitrogen is supplied (at a polymerization temperature of 1800C and above) to prevent bags from burning, etc. Inside the autoclave, thermocouples are installed on the product to control the temperature regime. Safety valves are also installed to relieve pressure [13].

Advantages: the structure of the product is comparable to the pneumocompression method; in addition, the autoclave method is universal for molding products of various configurations.

Disadvantages: high cost of equipment, slow heating due to heat exchange through air in the autoclave. It is necessary to use a mandrel in addition to the autoclave itself. It is almost impossible to use an autoclave for our product, since the length of our product (wing spar) must be 45 meters.

The equipment diagram is shown in Figure 4.

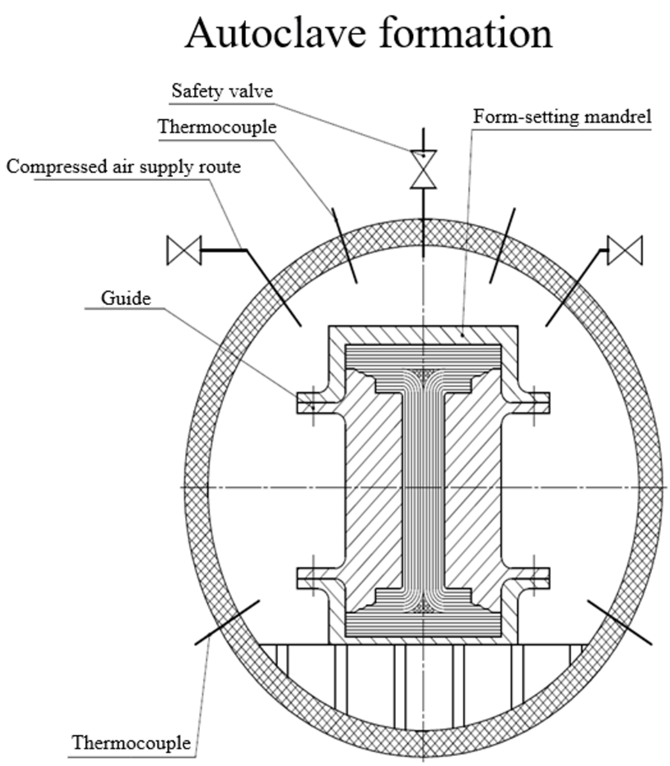

Fig. 4 - Diagram of equipment for the autoclave molding method Development of technological molding modes

The development of technological molding modes is carried out based on the required structure of the future product, as well as on the basis of the binder used. For thermocompression molding, pneumocompression and autoclave - this will be prepreg ASM 1209. For vacuum infusion - EPS-I-108 binder, for the RTM method - T-26 binder.

RTM Method

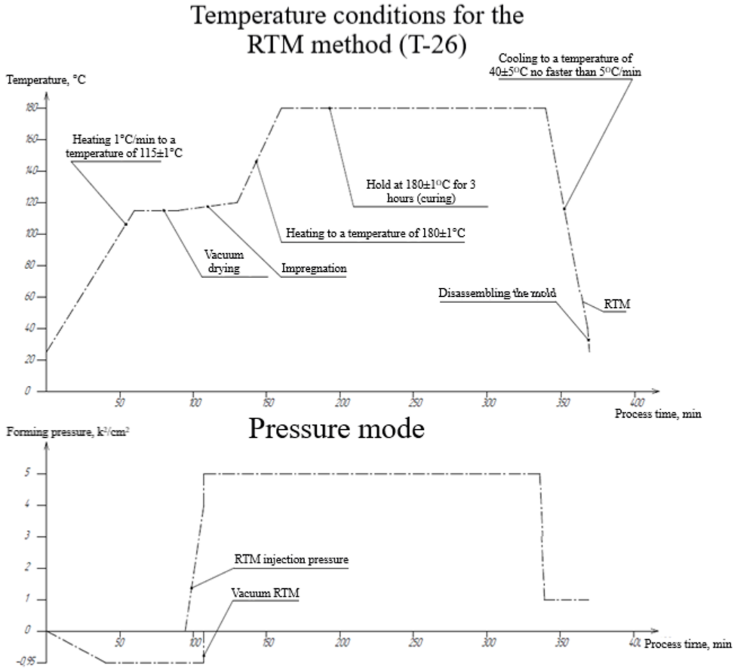

Fig. 5 - Technological mode for manufacturing a spar using the RTM method

Temperature:

1. Heating to 115°C at 2°C/min. (60 min)
2. Vacuum drying of the mold for 30 minutes.
3. Impregnation of the product with a binder under a pressure of 5 atm. (40 min)
4. Heating to 180°C at 2°C/min (30 min)
5. Polymerize at 180°C for 3 hours.
6. Cooling to 40°C at 5°C/min.
7. Disassembling the mold

Pressure mode:

1. Creating a vacuum with a vacuum pump to a level of -0.95 kg/cm^2
2. Vacuum drying of the mold for 30 minutes.
3. Turning off the vacuum pump while simultaneously supplying the binder with the supply unit under a pressure of 5 kg/cm^2
4. Relieving pressure due to depressurization of the mold

AIR COMPRESSION MOLDING

Temperature:

1. Heating to 120°C at 1°C/min. (95 min)
2. Hold for 15 minutes at a temperature of 120 °C - gelation.
3. Heating to 140°C at 1°C/min (20 min)
4. Curing at 140°C for 3 hours.
5. Cooling to 40°C at 5°C/min.
6. Disassembling the mold

Pressure mode:

1. Creating a pressure of 5 kg/cm^2 (10 min)
2. Maintaining the set pressure until the mold cools (325 min)
3. Pressure relief

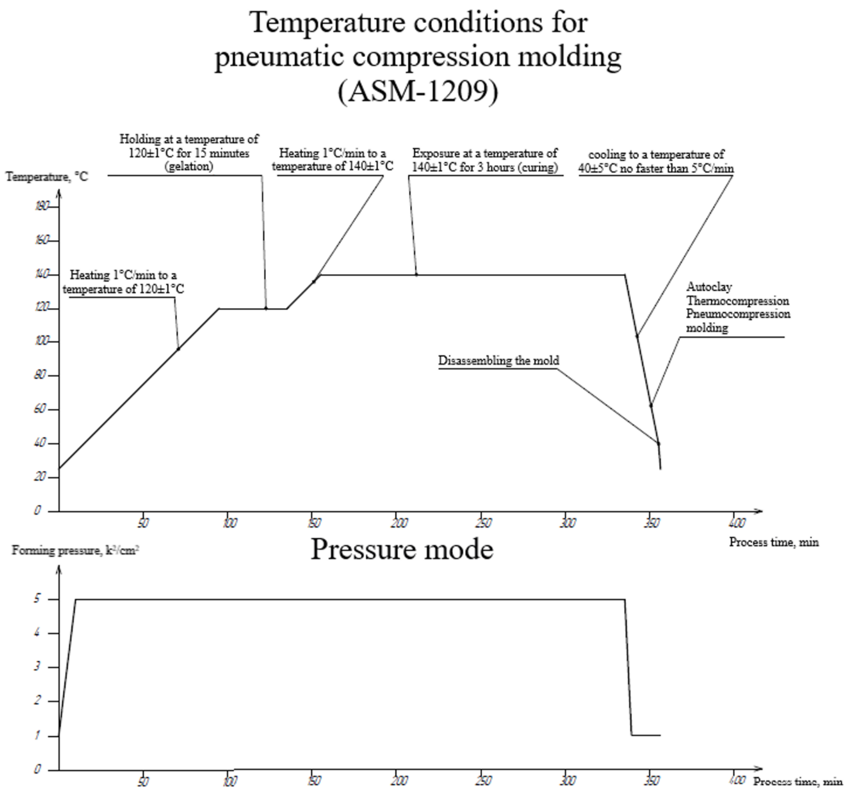

Fig. 6 - Technological regime for manufacturing a spar using pneumatic compression molding

THERMAL COMPRESSION MOLDING

Temperature:
1. Heating to 120℃ at 1℃/min. (95 min)
2. Hold for 15 minutes at a temperature of 120 ℃ - gelation.
3. Heating to 140℃ at 1℃/min (20 min)
4. Curing at 140℃ for 3 hours.
5. Cooling to 40℃ at 5℃/min.
6. Disassembling the mold

Pressure mode:

It is obtained automatically due to the thermal expansion of silicone rubber and looks like this:
1. Pressure increase up to 3 kg/cm^2
2. Maintain pressure at 3 kg/cm^2 for 15 minutes
3. Increase in pressure up to 5 kg/cm^2
4. Pressure holding 5 kg/cm^2 for 3 hours
5. Gradual decrease in pressure

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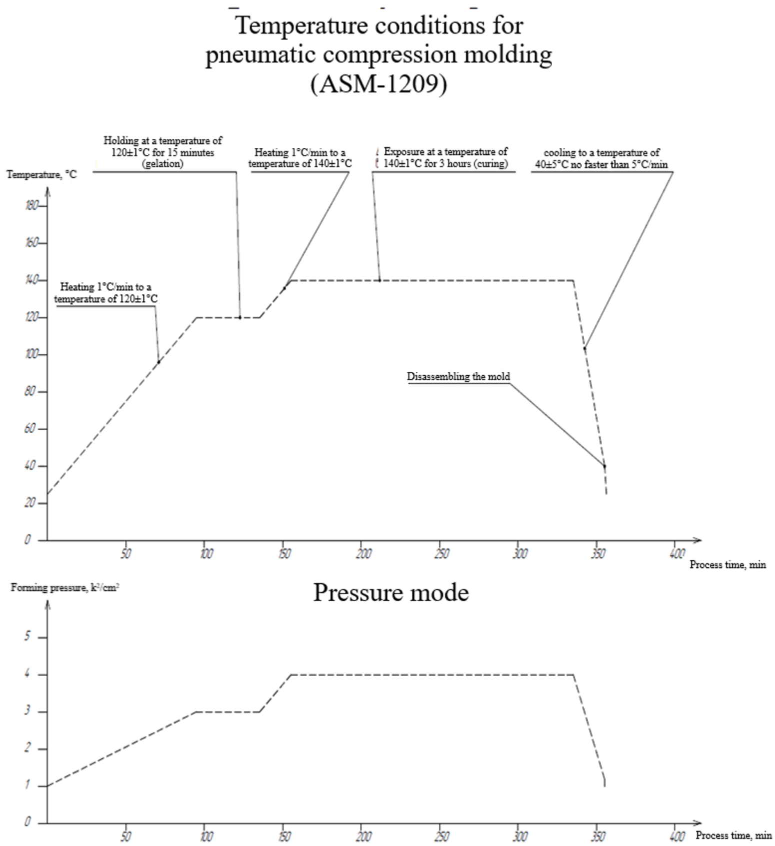

Fig. 7 - Technological mode for manufacturing a spar using thermocompression molding

VACUUM INFUSION

Temperature:

1. The area is not heated, at this time vacuum bags are collected and their tightness is checked
2. Heating to 35°C at 5°C/min (10 min)
3. Maintain a temperature of 35°C for the duration of impregnation with the binder
4. Cooling to 40°C at 5°C/min.
5. holding the bag at a temperature of 25°C for 24 hours (pre-curing)

Additional hardening by heat treatment in steps

6. Heating to 70°C at 5°C/min (45 min)
7. Temperature holding 70°C 4 hours
8. Heating to 90°C at 5°C/min (20 min)
9. Temperature holding 90°C 3 hours
10. Heating to 120°C at 5°C/min (30 min)
11. Temperature holding 120°C 3 hours
12. Disassembling the package.

Pressure mode:

Consists of two modes, individual for each package.

Package № 1 (internal)

1. Vacuum to a level of -0.95 kg / cm^2
2. Pressure holding for 1440 min

3. Gradual pressure release during stepwise heat treatment
Package № 2 (external)
1. Vacuum to a level of -0.85 kg/cm^2
2. Pressure holding for 2140 minutes before cooling begins
3. Gradual release of pressure.

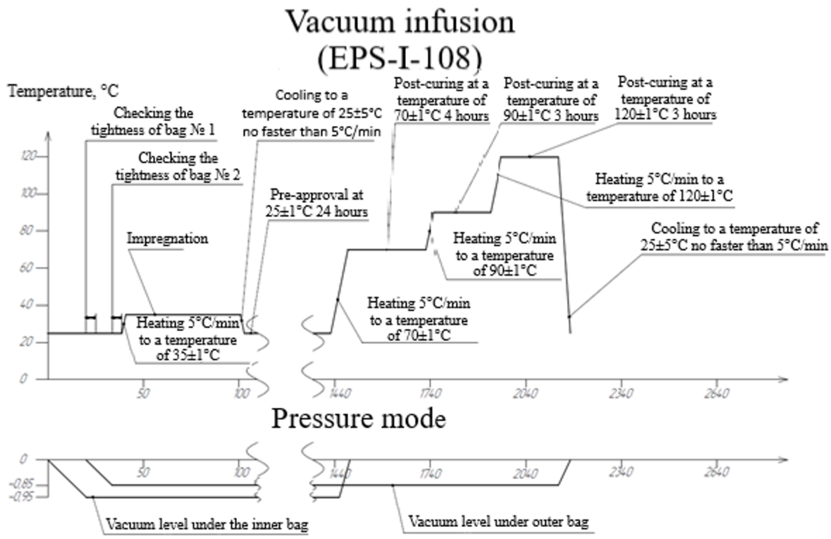

Fig. 8 - Technological mode for manufacturing a spar using the vacuum infusion method

AUTOCLAVE MOLDING

Temperature:
1. Heating to 120°C at 1°C/min. (95 min)
2. Hold for 15 minutes at a temperature of 120 °C - gelation.
3. Heating to 140°C at 1°C/min (20 min)
4. Curing at 140°C for 3 hours.
5. Cooling to 40°C at 5°C/min.
6. Opening the autoclave

Pressure mode
1. Creating a pressure of 5 kg/cm^2 (40 min)
2. Maintaining the set pressure until the mold cools (295 min)
3. Pressure relief

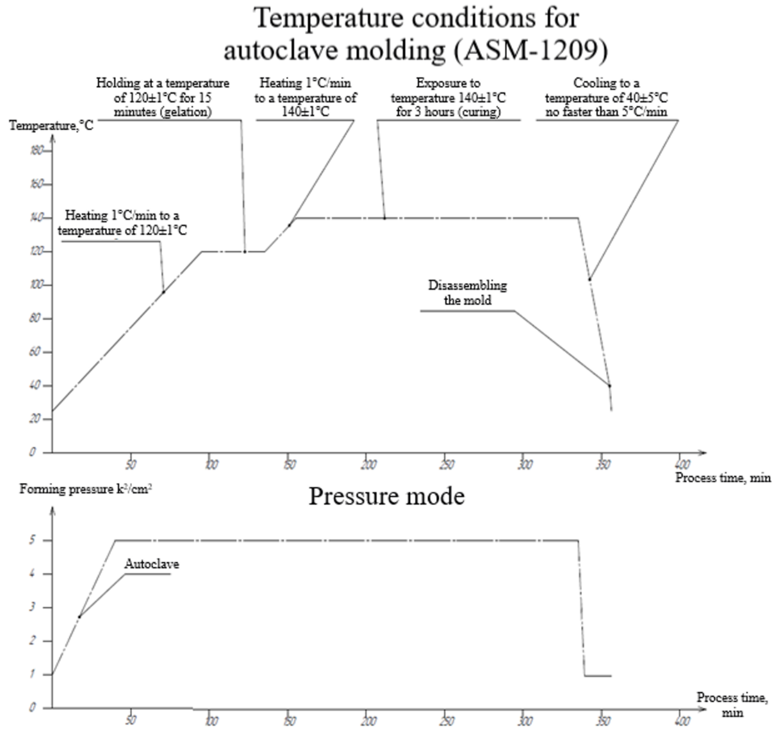

Fig. 9 - Technological mode for manufacturing a spar using autoclave molding

5 Research and results

A comparative analysis of manufacturing methods based on the obtained technological modes is presented in Table 1.

Table 1 - Comparative analysis of technological modes

№	Molding method	Total production time, hour	Number of temperature operations	Number of pressure mode operations	Forming pressure, kg/cm^2
1	RTM	6,2	7	4	5
2	Pneumocompression	6	6	3	5
3	Thermocompression	6	6	0 (automatically according to heating mode)	3-5
4	Vacuum infusion	36,3	12	6	-0,85-0,95
5	Autoclave	6	6	3	5

FibArm 530/300 tape – reinforcing material (unidirectional carbon tape). Used for the manufacture of spar for the detachable part of the wing. We will analyze the free volume, as well as the thickness of the layer, after crimping statistically. To do this, let's take the known data for two carbon unidirectional tapes, build a trend line and determine the curve for our reinforcing material. The calculation will be qualitatively correct [14, 15].

To construct the curves, we take the data of crimping and free volume for carbon fabric UL-300-12K-230 and Sva-11123 “Prepreg-SKM”, then we apply the trend line with the greatest convergence and construct the required curves according to the law.

Table 2 - Data for constructing crimping curves

UL-300-12K-230		FibArm tape 530/300		Sva-11123 «Prepreg-SKM»	
Crimping pressure, kg/cm^2	Monolayer thickness, mm	Crimping pressure, kg/cm^2	Monolayer thickness, mm	Crimping pressure, kg/cm^2	Monolayer thickness, mm
0,5	0,246	0,5	0,220	0,5	0,135
1	0,235	1	0,209	1	0,128
2	0,228	2	0,202	2	0,122
3	0,223	3	0,197	3	0,118
4	0,218	4	0,193	4	0,116
5	0,216	5	0,19	5	0,115

Table 3 - Data for plotting the dependence of free volume on molding pressure

UL-300-12K-230		FibArm tape 530/300		Sva-11123 «Prepreg-SKM»	
Crimping pressure, kg/cm^2	Free volume, %	Crimping pressure, kg/cm^2	Free volume, %	Crimping pressure, kg/cm^2	Free volume, %
0,5	45,7	**0,5**	45,5	**0,5**	45,6
1	43,0	**1**	43,4	**1**	42,6
2	41,4	**2**	41,4	**2**	39,8
3	41,0	**3**	40,3	**3**	37,7
4	39,0	**4**	39,5	**4**	36,6
5	38,9	**5**	38,9	**5**	36,2

Let's determine the minimum required binder application. To do this, we multiply the free volume by the density of the binder and refer it to a unit area. We will obtain a linear characteristic that will correspond to the mass of the finished product, since this value will determine the required application of binder per square meter of fabric.

Table 4 - Calculation of mass characteristics of the product

Molding method	Forming pressure, kg/cm^2	Free volume,, %	Binder density, g/cm^3	Linear weight g/1m^2
RTM	5,00	38,9	1,17	45,513
Pneumocompression	5,00	38,9	1,2	46,680
Thermocompression	4,00	39,5	1,2	47,400
Vacuum infusion	-0,95	43,4	1,137	49,346
Autoclaved	5,00	38,9	1,2	46,680

As a result of the analysis, the main characteristics of materials obtained using various molding methods were determined.

To assess porosity we will use statistical data.

With the RTM method, porosity will be near zero, due to pre-evacuation and then very high molding pressure. Any remaining air bubbles will be compressed by the molding pressure[16].

With the pneumatic compression molding method, the expected porosity will be at the level of 2-3% and depends on the quality of the prepreg used, the same will happen when using the autoclave method.

With thermocompression molding, the expected porosity will be at the level of 3-4%, since on average the molding pressure will be slightly lower than with the pneumatic compression method, due to the inertia of heating the rubber [17, 18].

With vacuum infusion, porosity is expected to be 2-4%. Depends on the correct assembly of the vacuum bag and the quality of impregnation. The expected porosity may be at the level of thermocompression molding, since the vacuum is created at -0.95 kg/cm2, which means that some air will still remain under the bag, and the molding pressure is relatively low, which will lead to porosity.

To estimate the cost of tooling and equipment, and the labor intensity of manufacturing, we will use the work [19, 20].

We will evaluate the physical and mechanical properties qualitatively, based on the expected level of porosity.

Table 5 - Study results

Method for forming a long carbon fiber spar	Forming pressure, kg/cm^2	Free volume, %	Monolayer thickness, mm	Expected porosity, %	Binder density, g/cm^3	Linear weight, g/m^2
RTM	5	38,9	0,190	<1	1,17	45,513
Pneumocompression	5	38,9	0,190	2_3	1,2	46,680
Thermocompression	4	39,5	0,193	3_4	1,2	47,400
Vacuum infusion	-0,95	43,4	0,209	2_4	1,137	49,346
Autoclaved	5	38,9	0,190	2_3	1,2	46,680

Method for forming a long carbon fiber spar	Cost price		Labor intensity	The total number of operations to maintain the technological regime		Estimated production time, hour
RTM	200	140	167	7	4	6,2
Pneumocompression	140	260	167	6	3	6
Thermocompression	140	260	160	6	0	6
Vacuum infusion	100	100	100	12	6	36,3
Autoclaved	120	300	140	6	3	6

6 Conclusion

Based on the results of studying the issue of choosing the optimal method for molding a long spar from a composite material, 5 methods were compared: the pressure impregnation method (RTM), pneumatic compression molding, thermocompression molding, vacuum infusion, autoclave molding. The resulting characteristics of the finished product were analyzed, such as: porosity, volumetric content of the binder, linear mass of the binder, the production time of the finished product was assessed, as well as the cost of tooling and equipment. Based on the results of the work, it was decided that the optimal method for manufacturing a long spar from carbon fabric FibArm TAPE 530/300 is the pneumatic compression molding method, for the following reasons:

1. Relatively low porosity.
2. High precision calibrated surface due to form-setting spacers. During the molding process, the spar is pressed against the forming mandrels.
3. Relative simplicity of control of the technological regime.
4. Possibility of reusable silicone mold blocks.
5. Collapsible mold, the length of which can be increased or decreased by changing the number of sections. Easy to transport to the enterprise.
6. Short manufacturing process: about 6 hours.
7. Relatively simple equipment.
8. Possibility of setting pressure and temperature modes for different types of prepregs.

References

1. Golovin D., Deniskin Y., Sklyarov K., Vasilyeva O., Development of a technology design model for a science-intensive product, E3S Web of ConferencesЭта ссылка отключена., 2022, 363, 04002
2. Kravchenko G., Deniskina A., Durov D., Chulenyov A., Ensuring interchangeability in aircraft production using cutting stands, E3S Web of Conferences, 2023, 458, 03030
3. Pashkov, V.S. & Zhuleva, A.D. & Tikhtey, Yu.N. & Shavelkin, D.S. & Popov, Yu.I.. (2023). Evaluation of the possibility of developing and manufacturing integral composite structures for airframe elements. E3S Web of Conferences. 383. 05007. DOI:10.1051/e3sconf/202338305007.
4. Kriven, G. & Shavelkin, D.. (2024). On Local Stability Loss of Modified Composites with Whiskerized Fibers. Uchenye Zapiski Kazanskogo Universiteta. Seriya Fiziko-Matematicheskie Nauki. 165. 344-360. DOI:10.26907/2541-7746.2023.4.344-360.
5. Protsenko, A. & Safoklov, Boris & Petrov, V. & Dolgov, O. (2023). The Assessment of the Prospects of Composite Materials Manufactured by Vacuum Infusion (VaRTM). DOI:10.1007/978-981-16-8154-7_35.
6. Yurov V.M., Goncharenko V.I., Vasiliev S.L., Dmitriev S.A., Yurgenson S.A. (2019). Experimental study of changes in the structure of polymer composite material by computational x-ray tomography. Eurasian Physical Technical Journal. 16. 26-30. DOI:10.31489/2019No2/26-30.
7. Yurov V.M., Goncharenko V.I., Vasiliev S.L. , Dmitriev S.A. , Yurgenson S.A. (2019). X-ray computed tomography-based analysis of impact damage propagation in composite materials. Eurasian Physical Technical Journal. 16. 31-35. DOI:10.31489/2019No2/31-35
8. Deniskina G.Y., Deniskin Y.I., Bityukov Y.I., About Biortogonal Wavelets, Created on the Basis of Scheme of Increasing of Lazy Wavelets, Lecture Notes in Electrical Engineering, 2021, 729 LNEE, 173–181
9. Prokudin, O. & Solyaev, Y. & Babaytsev, Arseniy & Artemyev, A. & Korobkov, Maksim. (2020). Dynamic characteristics of three-layer beams with load-bearing layers made of alumino-glass plastic. PNRPU Mechanics Bulletin. 2020. 260-270. DOI:10.15593/perm.mech/2020.4.22.
10. Lomakin, E. & Yurgenson, S. & Fedulov, Boris & Fedorenko, Alexey. (2021). MECHANICAL CHARACTERISTICS OF REINFORCED AND THREE-LAYER SHELLS BASED ON METAMATERIALS, TAKING INTO ACCOUNT OPERATIONAL DAMAGE. Mechanics of Solids. 56. 922-929. DOI:10.3103/S0025654421060091.

11. Gurov, Viktor & Deniskina, Antonina & Pocebneva, Irina & Politi, Violetta. (2023). Quality management integration in the functionality of product lifecycle management in energy-effective production. E3S Web of Conferences. 460. DOI:10.1051/e3sconf/202346010034
12. Kravchenko, G. & Popov, Yu & Kolosov, A. & Smolyaninov, A. & Pocebneva, I.. (2022). Method of Design Calculation for Strength of Structures Made of Metal and Polymer Composite. DOI: 10.1007/978-3-031-14125-6_54.
13. Gurov, Viktor & Deniskina, Antonina & Kudryavtseva, Irina & Kostyshak, Mikhail. (2023). Description of the modules of an optimal requirements management system for working with aviation projects. E3S Web of Conferences. 383. 05011. DOI:10.1051/e3sconf/202338305011.
14. Golovin, Dmitry & Samotin, Ivan & Pocebneva, Irina & Vasilyeva, Olga. (2023). Dialogue system for designing technological processes. E3S Web of Conferences. 376. DOI: 10.1051/e3sconf/202337601094
15. Bekhmetiev, Vyacheslav & Kolosov, Aleksandr & Vasilyeva, Olga. (2023). The study of the use of polymer composite materials in the mass and eco-friendly production of aircraft structural elements. E3S Web of Conferences. 460. DOI:10.1051/e3sconf/202346010033.
16. Moskvicheva, E.D., Reznichenko, V.I. (2021). The Use of Basalt Plastic for the Manufacture of Sound Insulation Panels of an Aircraft Engine. In: Jing, Z., Zhan, X. (eds) Proceedings of the International Conference on Aerospace System Science and Engineering 2020. ICASSE 2020. Lecture Notes in Electrical Engineering, vol 680. Springer, Singapore. DOI:10.1007/978-981-33-6060-0_8
17. Bekhmetiev, Vyacheslav & Safoklov, Boris & Gusev, Pavel & Aleksandrovskiy, Maxim. (2023). Possibilities of information technologies in the processes of designing efficient processes for the production of aircraft structures. E3S Web of Conferences. 376. DOI:10.1051/e3sconf/202337601092.
18. Mitrofanov, Oleg & Toropylina, Ekaterina & Smolyaninov, Andrey & Lukmanova, Inessa. (2023). Design of z-shaped reinforced panels of composite materials under compression and shear. E3S Web of Conferences. 383. 05015. DOI: 10.1051/e3sconf/202338305015
19. Kuznetsov, M. & Gusev, Pavel & Bredihin, A. & Chizhov, M.. (2021). Simulation modeling of the automated system tasks of production technical preparation. AIP Conference Proceedings. 2402. 050029. DOI:10.1063/5.0071461.
20. Babaytsev, A.V., Rabinskiy, L.N. & Shavelkin, D.S. Improving Tests of Composites by Fiber Extraction from the Matrix. Russ. Engin. Res. 43, 1465–1468 (2023). DOI:10.3103/S1068798X23110059