UDC 620.22

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RESEARCH ON THE INFLUENCE OF TECHNOLOGICAL FACTORS ON THE QUALITY OF COMPOSITE MATERIALS

Purpose. *The purpose of this study is to analyze the impact of the main stages of manufacturing composite products on the probability of various defects. Special attention is paid to finding and justifying practical ways to eliminate them at the early stages of the production process. The work is aimed at identifying the relationship between technological parameters, such as temperature, pressure and polymerization time, and the final quality, strength and reliability of the finished product. In addition, the goal is to develop methodological recommendations for manufacturers to minimize defects and increase production efficiency.*

Research methods. *The work uses an analytical method and a detailed consideration of factors that directly affect the quality of composite materials. An analysis of scientific and technical literature was conducted, as well as systematization of production practice data. To detect hidden defects and assess their impact on the structure of the material, modern methods of non-destructive testing were used. This allowed obtaining objective data on the condition of the material without its destruction, which is critically important for preserving the integrity of products.*

Results. *Based on literary data and production practice, attention is paid to the production factors that most affect the quality of manufacturing composite materials and parts made from them. Analysis and comparison of existing destructive testing methods to preserve the structure of products, as well as the use of various control methods to detect defects in the complex structure of composite materials, which can ensure high quality of the manufactured products.*

Practical value. *The work examines the factors that affect the quality of the product during its operation, as well as technological factors and methods of their control. For the study, practical work was carried out to determine the influence of technological factors on the quality of the product, and methods for eliminating defects in ing of the part.*

Key words: *vacuum, grinded fabric, prepreg, polymerization, venture, composite materials.*

Introduction

The modern use of composite materials extends to all fields of engineering, ranging from the most prominent such as aerospace, shipbuilding, mechanical engineering, or other industrial sectors, to our everyday life. The field of synthesized materials offers new solutions to complex engineering problems without the mandatory presence of high-tech equipment or additional mechanical processing for high-quality surface formation.

Composite materials are combined (the combination of the reinforcing component and the matrix is adjusted) to better utilize their advantages while minimizing their disadvantages. This intensification process allows designers to overcome the limitations associated with the selection and manufacture of traditional materials, simultaneously expanding possibilities in selection, as well as reducing unnecessary steps (such as surface oxidation or galvanizing), or reducing the weight of structural elements. It is also possible to use stronger and lighter materials, whose properties are tailored to specific requirements. Thanks to the ease of manufacturing complex shapes and the reusability of existing structures, the use of composites leads to more economical and technological improvements in selected industries.

At the same time, the manufacture of composite materials is a complex process due to the large number of technological factors that affect product quality: the choice of materials, their bonding with each other, temperature regimes, process duration, as well as mechanical and chemical influences. Managing these factors allows for controlling and significantly improving the properties of the final product, obtaining materials with the necessary characteristics for various purposes of their use.

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DOI 10.15588/1607-6885-2025-3-6

Purpose

Investigate the technological modes of manufacturing and various deviations that can lead to serious defects in the composite structure: such as porosity, delamination, uneven distribution of the reinforcing material, which ultimately reduces its mechanical strength, durability, and reliability.

Results and discussion

The main factors affecting the technological process of manufacturing composite materials have been analyzed, their characteristics, conditions, types, and areas of application are presented.

Temperature factor. Temperature is one of the main factors influencing the process of manufacturing composite materials. High temperatures can accelerate the polymerization process, which is important for the production of composites based on thermosetting polymers, such as epoxy resins. At the same time, excessively high temperatures can lead to the decomposition of the material, significantly deteriorating its mechanical properties.

In the process of manufacturing composites based on thermoplastic polymers, the "fusion" of fibers with the matrix is controlled by temperature. The choice of the optimal temperature is critical to ensuring the strength and durability of the composite material. If the temperature is too low, it may lead to insufficient integration of the fibers and matrix, which will affect the material's strength [1].

At every stage of product manufacturing (during cutting of composite material, milling or drilling, or during its polymerization in the oven), temperature can affect the quality of mechanical and chemical factors, the deterioration of which may lead to a reduction in the subsequent service life [2].

Effect of pressure. Pressure is a factor that influences the quality of composite materials, especially during the forming process: vacuuming (compression and removal of excess air) or pressing in a mold in thermal presses. Increased pressure helps achieve better impregnation of the fibers by the matrix, which improves the mechanical properties of the composite. High pressure also allows the creation of a denser structure, reducing the number of pores or voids, which enhances the tensile strength of the material.

In vacuum composite manufacturing processes, where low pressure is used to remove air from the interfiber space, the pressure is controlled to ensure uniform distribution of the matrix and to achieve the required material consistency, thickness, and surface replication of the mold or mandrel (it is possible to use a repair-type forming where this product will be applied, on the surface of which the composite material will be laid).

Pressure should be monitored periodically and possibly more regularly than temperature, due to the presence of “cold polymerization” (without high temperatures, properly selected pressure ensures the quality of the formation and bonding of composite layers or parts).

There are several types and modes of pressure in the manufacturing of these parts:

- pressing, used for creating composites from thermoplastic materials, especially in the manufacture of structures in the form of plates, pipes, blades, spars, and skins, where there are certain requirements and the need to control pressure;
- autoclave method, this method is important in the production of critical components where it is necessary to achieve a minimum of pores and defects. During the autoclave forming process, composites are subjected to high pressure and temperature in a sealed environment, which ensures thorough impregnation of the fibers with the matrix and minimizes air pores. Thanks to a reliable pressure and temperature control system, this method guarantees excellent quality of the final material with high mechanical and physical properties. Compared to pressing, the autoclave method allows working with large sizes and complex parts, making it versatile for the manufacture of high-precision, reliable, and durable products;
- the vacuum forming method is one of the simplest and most effective methods for manufacturing composites, widely used for creating products from thermoplastic materials, particularly in small-batch and medium-batch production. This method is based on the use of vacuum to deform the material on a mold, or as previously mentioned, it is possible to use existing parts or products as a form. Vacuum forming is used for manufacturing lightweight or combined structures, such as components for the automotive industry, household appliances, decorative elements, or ship hulls (side, bottom, keel hull), which are assembled in large facilities (hangars) and consist of a frame covered with prepreg shaped according to a specified form and assembled from a large number of vacuum bags, as well as a large number of vacuum pumps [3]. That is, the method is limited by the pressure conditions in the system, as well as the cleanliness and quality of the manufactured products when increasing the vacuum size. There may also be a deterioration in the quality of the prepreg, such as wrinkles when there is a large bend in the part, where the angle between two vacuumed surfaces becomes more acute than obtuse;
- the hydrostatic pressure method allows for an even distribution of pressure from all sides, which is especially important for complex shapes or large products that require high precision and density. It helps to avoid local defects and ensures uniformity of the structure, having a significant difference from its counterpart (vacuum method) - the possibility of using higher pressure on the part.

Effect of time. Time is an important factor in the processes of polymerization and material curing, as all changes in the structure can only be recorded with the presence of time variation and its control.

Insufficient polymerization time can lead to the material not gaining sufficient strength, while excessively long time can result in the loss of properties such as elasticity. When manufacturing certain composites, materials for the mold are used in which the operating temperature

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DOI 10.15588/1607-6885-2025-3-6

is lower than the polymerization temperature of the binder in the composite; therefore, preliminary polymerization is performed at lower settings (then the part is removed and final polymerization is carried out without the mold) or with increased time but reduced temperature.

The time required for the curing of composite materials also depends on temperature and pressure, as they can accelerate or slow down the processes of polymerization and curing. Considering and regulating these factors helps maintain the quality of the material and its stability at all stages of manufacturing depending on various factors [4–6].

The influence of moisture and other extraneous inclusions. Moisture is another important factor that can affect the quality of composite materials, especially during the stages of fiber storage and processing. High humidity can lead to water penetration into the material's structure, which worsens its physicochemical properties. This can cause corrosion or degradation of the material, as well as reduce its strength and resistance to loads.

Moisture control is an important stage at all phases of composite production, particularly during fiber storage, matrix processing, as well as during material forming and curing. Accordingly, air cleanliness is regulated by the state standard ДСТУ ISO 14644-1:2009, there are 4 classes of cleanliness and more, but under more responsible production conditions or the creation of composite material itself, it is necessary to use a higher cleanliness class due to the need to meet high quality requirements, as well as safety in production, where the air may contain ether, formaldehyde, and other resins and substances.

Moisture can occur as condensation when storing prepreg at subzero temperatures in freezers, or in the binder mixture and other consumables, as well as in cut pieces before the next molding of the material on mandrels or layups on the mold. Moisture also appears on glass fiber rovings stored in rooms near resin impregnation areas or layup workstations. In the case of mass production and the inability to store materials elsewhere, the aforementioned materials should be placed in foam inserts or cores that simulate voids and lighten the subsequent structure, due to their high porosity and good ability to absorb moisture and other unwanted substances.

To ensure product quality and avoid further defects related to poor storage and storage conditions, drying of the products is carried out, which depends on their type, structure, and accordingly volume, since in addition to moisture, there may be wax present in fiberglass fabrics or possible gasoline or acetylene inclusions on parts during storage or manufacturing.

Manufacturers producing fiberglass fabric impregnate it with paraffin emulsion or other types of oil for preservation purposes, but the presence of such components in the fabric composition can significantly affect the subsequent quality of the manufactured prepreg, so it is necessary to perform an annealing operation. It is simultaneously used as a substitute for drying for fabrics that have been oiled, but it should be taken into account that not all fabrics have prior impregnation.

Drying from moisture has better performance in process technology due to lower requirements for time and temperature, as well as necessary equipment, so it is better to use fiberglass without adding various preservatives, which will save time and energy, which will increase hundreds of times with large production volumes. It is recommended to perform drying and annealing for as large volumes of fabric as possible to save resources and necessary time [7].

Influence of chemical additives. Chemical additives, such as plasticizers, stabilizers, polymerization accelerators, and other modifying agents, are important components of the composite material manufacturing process. They are used to improve the properties of the material, particularly strength, flexibility, load resistance, and thermal stability. However, unlike the effects of moisture or other unwanted inclusions, additives are controlled elements of the technological process, and their impact directly depends on the accuracy of dosing and usage conditions.

One of the key problems is that incorrect selection or overdosing of chemical additives can cause defects in the material, such as reduced stability, formation of pores, cracks, or uneven polymerization of the binder, which can lead to defects in parts of the component or product in critical areas or where a continuous surface is required. As a result, the part will be defective without any possibility of repair. For example, using plasticizers in excessive amounts can reduce the stiffness of the composite, and stabilizers in high concentrations can worsen its adhesive properties, affecting the delamination of prepreg layers or detachment from the bonded part.

Additional risks are associated with the use of additives prone to the release of volatile substances, such as ethers or formaldehyde resins. This requires adherence to strict cleanliness standards in production. To prevent the release of chemical residues into the air of production premises, especially in cases of mass production, it is necessary to use exhaust systems and regular cleaning of work areas, which should be monitored by recorders and other control devices.

Chemical additives also affect the storage of materials. For example, polymerization accelerators included in prepregs, binders, or other pre-treated materials can change their properties under improper storage conditions. High humidity or inappropriate temperature can cause undesirable chemical reactions, leading to a deterioration in the quality of the finished product. During the manufacturing of products, it is necessary to control the conditions of forming, creating, and processing composites at all stages to avoid the formation of unwanted inclusions or residual stresses, as is the case with extraneous inclusions (humidity, dust, oily materials). Implementing these measures will help preserve the mechanical and physicochemical properties of the composite material and ensure the stability of its operational characteristics [8, 9].

Preparation of the binder (matrix). The process of manufacturing composite materials begins with the

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DOI 10.15588/1607-6885-2025-3-6

preparation of raw materials. This aspect includes the preparation of epoxy resin, which is the main protective component of the reinforcing element and the "form holder", since in the production of prepregs, the binder is responsible for maintaining the shape of the fabric. These include many types of adhesives with various physical and chemical characteristics, as well as different modes and components.

For example, polyurethane adhesives can be either cold-curing or hot-curing. Their composition includes polyesters, polyisocyanates, and fillers (including cement). The chemical reaction that occurs when the components are mixed ensures the adhesive hardens. They have universal adhesion due to polar groups (NHCO), good vibration resistance, strength under uneven tearing, and resistance to the effects of petroleum fuels and lubricants. Well-known brands of such adhesives – ПУ-2, ВК-5, ВК-П, leukonate. It is important to note the toxicity of adhesives and their various fields of application, where in one case they may serve as a sublayer for laying impregnated fabric, and in another – for bonding composite-metal, metal-metal.

Also, adhesives modified with carbon-containing compounds are characterized by high heat resistance. For example, the ВК-20 adhesive can withstand prolonged heating up to 350–400°C and short-term heating up to 800°C, maintaining high strength or altering adhesion with small doses of "alloying".

Cyanoacrylate-based adhesives, including brands ЕО №87 і ЕО №170, are not prone to aging, and their strength increases during storage.

To improve the adhesive properties, silicone adhesives are often combined with other resins. Many adhesives also use mineral fillers to improve the properties [10, 11].

Fabric preparation (reinforcing component). When preparing fabric for impregnation, it is recommended to use methods or instructions for the production of composites, in accordance with the materials used in their manufacture, due to the structurally different processing and operating modes.

Fabric treatment involves annealing, or drying. Annealing may involve higher temperatures than drying, and may require more space to remove wax or oils. Drying has a simpler purpose - it is used to remove moisture, volatile compounds, oils, and wax from the fabric.

Cleaning the fabric is necessary before applying the resin to the fiberglass and impregnating it to remove preservatives or moisture. If more specific components such as dirt or grease are present, the fabric should be cut and excluded from further use, especially when making critical structures. This will ensure better adhesion between the fibers and the resin.

Pre-cutting is performed after heat treatment or after, depending on the technological process. The fiberglass should be cut into blanks of the required shape and size, with minimal material consumption. This is done both manually and with the use of special equipment. It is important to avoid twisting or pulling the fibers when cutting. But it is not possible to completely avoid this due to the fact that often reinforcing materials have a high threshold for shear and tension. In such cases, a larger specified allowance for this material or preliminary impregnation is used, when it already becomes a prepreg.

When cutting is performed manually, the quality and accuracy of the manufactured blanks, and accordingly their subsequent efficiency in the layout, are worse. There is an imposition of one tolerance on another, especially when the cutting was designed for a high material consumption coefficient, as well as a large number of threads and delamination of the fabric blank layer. This phenomenon occurs more often with dense material and small blanks. Material stretching is also possible.

Cutting using special equipment (plotters and their various types) is more aimed at optimizing production, improving the quality of cutting, its accuracy, high material consumption coefficient and the need for only one person when performing large volumes of production. This method allows you to ensure high requirements for cutting with an accuracy of up to 0.1 mm, strong pressing, and technological efficiency.

Impregnation with a binder (resin) must be carried out in designated areas (equipped areas or rooms). The binder must be applied evenly to ensure complete impregnation of the fabric, the cleanliness of its application and the avoidance of dirt or unnecessary impurities. Particular attention must be paid to various degreasing agents or oils. For impregnation, the method of manual application, vacuum infusion, as well as equipment in the form of impregnation machines is used, which allow removing part of the air and achieving the required ratio of fiber to resin. Rollers or spatulas are used to evenly distribute the resin and remove air pockets during the manual method and vacuum infusion. One of the impregnation machines is shown in Figure 1.

Figure 1. Modular impregnation line for the production of fabric or tow prepregs

On one line, solvents from hot-melt resins (binders) are used, as well as reverse roller coating for the production of polymer film using hot-melt resins, which will improve the quality of the applied resin layer and ensure the proper condition after rolling with rollers.

In such machines, there is precise control of the thermal process: the speed of heating and cooling, which will increase the quality of the manufactured products and reduce the number of scrap with the number of

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DOI 10.15588/1607-6885-2025-3-6

unimpregnated zones.

Improving the quality of polymerization, which determines the mechanical strength, chemical resistance and durability of future structures and products.

It is necessary to control the temperature and ensure uniform heating throughout the product. Insufficient heating can lead to incomplete polymerization, while overheating can lead to thermal degradation of the resin. It is also necessary to take into account the materials and volumes of the matrices and mandrels on which the prepreg was laid out.

The polymerization time must be optimized and adjusted according to the temperature, as an excessively short cycle can leave the resin uncured, while too long a time can affect the mechanical properties of the composite material, or damage the matrix or mandrel.

It is also necessary to use vacuuming, which allows you to remove air and minimize the formation of pores in the material structure, reducing the possibility of delamination. The use of pressing for critical and especially critical parts and assemblies performs better compared to vacuuming, but reduces the amount of resin. This is especially important when manufacturing large parts, such as ship hulls or aircraft or aerospace components.

Ensuring uniform impregnation of the fibers with resin is important to avoid local defects and weak zones in the material. The use of infusion methods, such as vacuum infusion or the use of pre-impregnated prepregs on rolling machines, can significantly improve the quality of impregnation and save time.

Modern monitoring systems, such as fiber optic sensors, thermal sensors, recorders and others, allow you to monitor the polymerization process in real time and adjust parameters in case of deviations [12-15].

It is also necessary to avoid critical moments such as:

- overheating of the material during molding. The exothermic reaction of the resin can cause local overheating, especially with large masses. This can cause cracks or changes in physicochemical properties;

- poor compaction during pressing or incorrect vacuum mode can leave free zones that will be filled with binder and crumpled fabric, causing defects in the structure;

- improper preparation of the surface of the matrix or mandrel, or preparation of the reinforcing part (fiberglass, carbon fiber) can lead to reduced adhesion between components and cause delamination of the material.

Forming is carried out by various methods, depending on the size, shape and functional requirements of the product. As the material is laid out in layers on the mold (matrix) manually or automatically, the orientation of the fibers is controlled to achieve the required mechanical properties, depending on the inclination: 45°, 90°, 45°×45°, 90°×90° (most frequent).

Conclusions

An analysis of technological factors that affect the quality of the manufactured composite material and parts has been conducted. The possibility of the occurrence and detection of defects in the complex structure of composite materials, cost reduction with appropriate selection of the necessary control methods, has been considered.

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Received 14.08.2025

ДОСЛІДЖЕННЯ ВПЛИВУ ТЕХНОЛОГІЧНИХ ФАКТОРІВ НА ЯКІСТЬ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ

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Мета роботи. *Метою даного дослідження є аналіз впливу основних етапів виготовлення композитних виробів на ймовірність виникнення різноманітних дефектів. Особлива увага приділяється пошуку та обґрунтуванню практичних шляхів їх усунення на ранніх стадіях виробничого процесу. Робота спрямована на виявлення взаємозв'язку між технологічними параметрами, такими як температура, тиск та час полімеризації, і кінцевою якістю, міцністю та надійністю готової продукції. Окрім того, метою є розробка методичних рекомендацій для виробників з метою мінімізації браку та підвищення ефективності виробництва.*

Методи дослідження. *У роботі використано аналітичний метод та детальний розгляд факторів, які безпосередньо впливають на якість композитних матеріалів. Проведено аналіз наукової та технічної літератури, а також систематизація даних виробничої практики. Для виявлення прихованих дефектів та оцінки їхнього впливу на структуру матеріалу застосовано сучасні методи неруйнівного контролю. Це дозволило отримати об'єктивні дані про стан матеріалу без його руйнування, що є критично важливим для збереження цілісності виробів.*

Отримані результати. *На підставі літературних даних і виробничої практики приділено увагу факторам виробництва, які найбільше впливають на якість виготовлення композиційних матеріалів та деталей із них. Аналіз та порівняння наявних методів неруйнівного контролю для збереження структури виробів, а також використання різних методів контролю для виявлення дефектів у складній структурі композиційних матеріалів, що може забезпечити високу якість виготовленої продукції.*

Практична цінність. *В роботі розглянуті чинники, які впливають на якість виробу при його експлуатації, а також технологічні фактори і методи їх контролю. Для дослідження було виконано практичну роботу по визначенню впливу технологічних факторів на якість виробу, і методи усунення дефектів при виготовлені деталі.*

Ключові слова: *вакуум, склотканина, препрег, полімерізація, зв'язувальне, композиційні матеріали.*

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DOI 10.15588/1607-6885-2025-3-6