MANUFACTURING OF AUTOMOTIVE PARTS FROM COMPOSITE MATERIALS: RESOURCE SHORTAGES, TECHNOLOGICAL PROCESSES, AND INNOVATIVE SOLUTIONS

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Abstract
This article explores the technological aspects of manufacturing automotive parts and equipment components from composite materials, which are widely used in the modern automotive industry. A significant issue highlighted in the study is the shortage of materials during the production, maintenance, repair, or replacement of these parts. The paper emphasizes the importance of addressing this problem for national industrial sectors and outlines technological processes aimed at efficiently utilizing residual resources. Furthermore, it presents new models and methods for the rapid production of composite-assembled compounds. The study provides insights into innovative approaches that can ensure timely and cost-effective manufacturing, thereby enhancing the sustainability and efficiency of automotive production.

Keywords: Resources, composite compounds, plastic, alloy, blanks, planks, mold, stamp, press, forging, punch, die, non-metal, steel, non-ferrous metal, alloys, elements, residuals, mechanical engineering, physical, chemical, mechanical, mechanisms, instruments, machinery, equipment, hydraulic, pneumatic, operation, technique, technology, shape, assembly, welding, cutting.

Introduction

General Description of Composite Materials and Their Components

The development of all industrial sectors, as well as the improvement of product quality, requires the creation of new structural materials. Industries such as aviation, rocket and space technology, automotive manufacturing, nuclear energy, and many others have a high demand for materials with unique properties, including high strength, heat resistance, thermal stability, low density, and other special characteristics [1].

A composite material is a new, unique material obtained by combining additional materials with significantly different (contrasting) mechanical, physical, and chemical properties that are closely linked to each other. The technology utilizes the quantitative and qualitative characteristics of each component, resulting in an effective combination that differs from the properties of individual components.

Composite materials can be classified into fiber-reinforced, layered, layered-fiber, and powder composites.

The production of composite materials can be achieved through reinforcement, which involves incorporating high-strength and high-modulus components into a matrix. This process significantly increases the operating temperature limit of the material. Additionally, coating methods are used to create an optimal layer within the material, enhancing the structural reliability of both the material and the final product [2].

The first group of "matrix-type" materials typically consists of fiber composites, where the reinforcing elements are connected by a component of variously arranged reinforcing particles or binding mixtures. These materials include compositions reinforced by dispersed particles or randomly distributed individual crystals within the matrix.

There are various hardening mechanisms for layered, fiber-reinforced, and dispersion-strengthened materials. Composite materials represent a new class of structural materials created by combining dissimilar materials while maintaining the interface between them. This combination yields qualitatively new properties not inherent to the original components [3].

Composite materials possess a unique set of characteristics not found in conventional metallic and polymer materials. These properties include exceptional strength and rigidity, fatigue resistance, heat resistance, and superior performance in various physical and specialized applications. The technology of composite materials is being widely adopted across nearly all industrial sectors. In many cases, the production process of composite materials is integrated with the manufacturing process of semi-finished products or parts designed to meet predefined specifications [4-6]. The primary groups of composite materials are fiber-reinforced and dispersion-strengthened composites.

MATERIALS AND METHODS

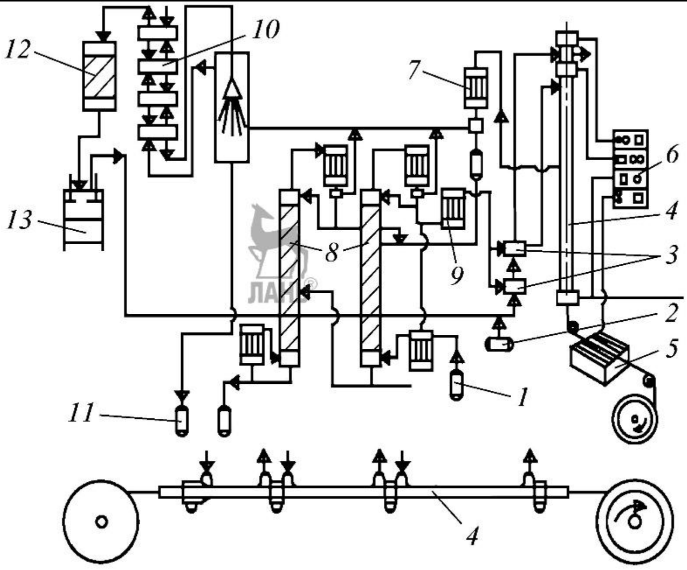
Fiber-Reinforced Composite Materials

The creation and application of fiber-reinforced composite materials represent one of the most critical challenges of modern technology. The processes involved in addressing this challenge include reducing the structure's weight to improve material weight efficiency and increasing its strength and rigidity. The typical properties of primary reinforcing materials for low-density fiber-reinforced composites are presented in Table 1.

Table 1. Properties of reinforcing materials

Material	Density, kg/m^3	Strength, N/mm^2	Pressure, GPa	Stretching, km
Fiber				
Boron	2630	2500…3800	380…448	95,144
Carbon	1600	2500…3500	250…300	156,218
Wire				
Steel	7800	3600…4000	200	45,51
Filamentous crystals				
Silicon carbide	3210	37000	580	1150

Note: UU is the breaking length, that is, the greatest length of a string (fibers, fabrics, etc.) hanging freely at one end, at which it still does not break under its own weight.



1, 2 - initial boron trichloride and hydrogen; 3 - mixture preparation system; 4 - reactor; 5 - fiber diameter measurement sensor; 6 - automatic control sensor; 7 - condensation of boron trichloride; 8 - condensate rectification; 9 - evaporation of boron trichloride; 10 - absorption of hydrogen chloride; 11 - collection of hydrochloric acid; 12 - hydrogen drying; 13 - hydrogen compression

Fig. 1. Scheme of obtaining boron fibers

Boron Fibers

Boron fibers are widely used for reinforcing metal and polymer matrices due to their high strength, stiffness, and low density. The strength properties of the fibers can be enhanced through surface treatment (chemical polishing), which eliminates or reduces surface defects. The decrease in density occurs as the fiber diameter increases because the relative content of the tungsten core within the fiber decreases, with boron accumulating during the fiber production process. Increasing the diameter reduces the fiber's cost and simplifies the manufacturing process of composite materials.

The main technological process for obtaining boron fibers involves the gas-phase deposition of boron from a mixture of hydrogen and boron trichloride onto a heated tungsten or carbon substrate. In industrial conditions, this process is performed continuously (Figure 1). To prevent interaction between boron fibers and metals (such as aluminum and titanium alloys) during the manufacturing or application of composite materials, various barrier coatings are applied to the fibers.

On an industrial scale, boron fibers are produced with silicon carbide (SiC) and boron carbide (B4C) coatings.

Coreless Silicon Carbide Fibers

Coreless fibers are produced in three stages: preparation of the initial mass, fiber formation, and fiber oxidation and carburization. The starting material for fiber production is dichlorodimethylsilane $[(CH_3)_2SiCl_2]$, which, in the presence of molten sodium, transforms into

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dimethylpolysilane. Afterward, it is polymerized in an autoclave at 450–470°C and 100 kPa pressure under an argon atmosphere for 8–14 hours, resulting in polycarbosilane.
Following vacuum distillation at 280°C and thermal processing, polycarbosilane transforms into a polymer with an average molecular weight of 1500 and a chain-like molecular structure.

Silicon Carbide Fibers on Substrates

The technology for producing silicon carbide fibers through vapor-phase deposition on superconducting substrates is similar to the process used for boron fibers. Tungsten or carbon filaments serve as the substrate. The installation used for fiber production closely resembles reactors employed for boron fiber manufacturing.
The application of protective coatings (SiC, B4C, BN) on the fibers prevents interaction with the matrix material. These coatings enhance the thermal stability of the fibers, making them more promising for reinforcing metallic matrices.

Carbon Fibers

Carbon fibers, primarily derived from the decomposition of viscose and polyacrylonitrile (PAN) fibers, exhibit a wide range of properties. The production technology for carbon fibers involves thermal treatment of various organic fibers, among which PAN and pitch-based fibers stand out for their optimal technological, economic, and operational characteristics.
The conversion of viscose and PAN fibers into carbon fibers involves three stages: stabilization, carbonization, and graphitization.

- **Stabilization:** Conducted to retain the preferential orientation of macromolecules.
- **Carbonization:** Pyrolysis of stabilized viscose and PAN fibers, during which they transform into carbon fibers.
- **Graphitization:** Carried out to enhance the elastic modulus of the fibers, performed in an inert gas atmosphere at temperatures between 1800–3000°C.

As a result of carbonization and graphitization, the diameter of the original viscose and PAN fibers decreases by approximately twofold, reaching 7–10 μm, while their density increases from 1.2 to 1.7–2.7 g/cm^3.
In polymer composite materials (carbon plastics), carbon fiber-matrix bonding strength is improved through fiber matrix viscerization, where crystallized particles (Si, SiC, Si_3N_4, TiO_2) form on the fiber surface.

Other Reinforcing Fibers

- **Corrosion-Resistant Steel Wires:** Offer the most cost-effective and technologically durable solution for reinforcing metal matrices. High-temperature-resistant steel wires, such as VNS-9 (18Kh15N5AM3), provide good performance but have relatively high density.
- **Beryllium Wires:** Notable for their low density, with strength primarily depending on their diameter.
- **Fibers from Refractory Compounds (SiC, Al_2O_3):** These fibers have low density, high specific strength and stiffness, and excellent thermal stability, maintaining high strength

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up to 1000–1100°C. However, they have low flexibility, are brittle, and their properties heavily depend on surface conditions.

- **Glass Fibers:** Widely used for reinforcing non-metallic matrices due to their high strength, heat and corrosion resistance, low thermal conductivity, and dielectric properties. Various glass fiber profiles are produced, aiding in denser fiber packing in composites. Hollow-profile fibers reduce density, improve bending stiffness, and enhance insulation properties. Compared to other reinforcing materials, glass fibers have a relatively low elastic modulus.
- **Organic Fibers:** Employed to reinforce non-metallic polymer matrices. They have lower density than glass fibers and an elastic modulus 2.5–3 times higher. PAN fibers used for metal matrices offer superior strength, stiffness, flexibility, impact resistance, temperature variation tolerance, and surface defect insensitivity.

Metal Matrices

Light metals (Al, Mg, Ti) and their alloys are used as metal matrices for high-specific-strength composite materials. To improve the strength properties of matrix materials, hardening through thermal treatment can be applied.

The mechanical properties of viscose and PAN fibers based on metal matrices, promising for practical applications, are provided in Table 2.

Table 2. Properties of uniaxially reinforced metal matrix composite materials

Material			Power, P, kg/m^3	Pressure %, N/mm	E, GPa	T, N/mm
Type	Matrix	Fiber				
VKA-1	AD-1	Borley, Q_z=2500 N/mm^2	2650	1000 … 1200	250	60
VKU-1	Al-Si	Carbon, E=450 GPa	2400	1000	270	40
KAS-1	AD-1	Steel VNS-9, Q_z=3600 N/mm^2	4520	1300 … 1450	110	60

Note: Tv is shear stress, Iv sh is compressive strength.

Boron-Aluminum Composite Material (VKA-1)

VKA-1 is a boron-aluminum composite material obtained by hot pressing a package consisting of alternating layers of aluminum alloy foil and unidirectional boron fibers, with a fiber volume fraction of 40–50%. The strength of this material along the reinforcement direction is twice as high as that of high-strength aluminum alloys, and its elastic modulus is three times greater.

In the temperature range of up to 2400°C, the strength of boron-aluminum composite materials surpasses that of high-strength and heat-resistant aluminum alloys. Additionally, these composites exhibit high long-term strength at 400°C and 500°C.

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Carbon Fiber-Reinforced Aluminum Composite Material (VKU-1)

VKU-1 is a composite material reinforced with carbon fibers based on aluminum. It demonstrates high values of specific strength and stiffness, making it suitable for applications requiring lightweight yet robust materials.

Steel-Aluminum Composite Material (KAS-1)

KAS-1 consists of a steel-aluminum composition reinforced with non-brittle metal wires. The volume fraction of wire in the composite is 25–30%. The reinforcement significantly enhances the specific strength and creep resistance of the material.

Magnesium-Boron Fiber Composite Material (BKM-I)

BKM-I is a composite material based on the magnesium-boron fiber system. Magnesium-based composite materials exhibit properties comparable to, and in some aspects superior to, boron-aluminum composites, especially in terms of specific characteristics.

Titanium-Based Composite Materials

Titanium and its alloys are considered highly promising matrix materials for composites. The reinforcements typically include boron fibers coated with silicon carbide (SiC), aluminum oxide (Al_2O_3), molybdenum, and beryllium wires. In this case, the stiffness of the titanium matrix increases by more than twofold, density decreases, and high-temperature performance improves.

Non-Metallic Fiber-Reinforced Polymer Composite Materials

The second group of composite materials with low density and high specific strength consists of fiber fillers—non-metallic, polymer-based composite materials.

However, polymer composite materials are characterized by relatively low heat resistance. As the temperature increases, the strength and elastic properties of reinforced polymers, as well as their adhesion to the fibers, decrease. Epoxy binder-based composites are used for products operating at temperatures up to 200°C, while polyamide matrices are applied at higher temperatures.

Classification of Polymer Composite Materials by Filler Type

Based on the type of filler (reinforcement), several groups of polymer composite materials exist. Some polymer matrix composites exhibit uniaxial reinforcement properties. A distinctive feature of carbon fiber-reinforced composites (carbon plastics) is their high vibration resistance, which is attributed to fatigue resistance and excellent damping capacity.

Organoplastics

Organoplastics are materials filled with organic fibers. Despite their relatively low density, these materials demonstrate sufficiently high specific stiffness and strength and perform well under variable loads. Organoplastics possess high tensile strength along the fiber direction, withstand impact loads, and are resistant to long-term static loads. However, they exhibit lower performance under compression.

Methods for Producing Composite Material Blanks

Layered composites are systems consisting of alternating two-dimensional reinforcing components, such as castings, plates, and sheet materials, rigidly bonded across the entire surface. Depending on the type of reinforcing element and hardening mechanism, the following types are distinguished:

- Three-dimensional reinforcing elements (particles)
- Powder composite materials (PCM)
- Two-dimensional reinforcing elements (sheets, planks) – layered composite materials (LCM)
- One-dimensional reinforcing elements (fibers, wires) – fiber-reinforced composite materials

Manufacturing Methods for Composite Materials

Various manufacturing methods are employed for composite materials, including:

- Sheet coating
- Diffusion welding
- Electroslag welding
- Explosive welding and other welding techniques
- Casting and coating through melting
- Electric conduction methods
- Thermomechanical coating
- Vapor deposition
- Glazing
- Liquid metal impregnation
- Detonation coating
- Vacuum coating
- Gas-thermal methods
- Winding
- Expansion for multi-layer pipes
- Pressing
- Extrusion
- Eutectic crystallization, among others

Key Considerations in the Technological Process

Developing the technological process for manufacturing products from composite materials involves addressing numerous challenges, including:

- Selection of reinforcing and matrix materials
- Analysis of their chemical interactions
- Optimization of wetting processes
- Methods for orienting reinforcing fibers

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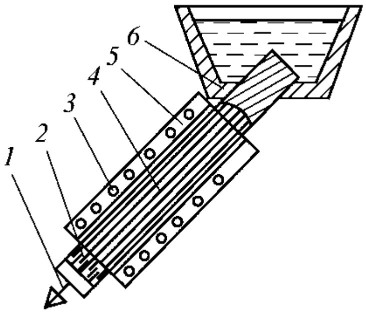
- Techniques for final bonding of fibers and matrices into a unified product
- Selection of optimal technological regimes

Industrial Application of Impregnation Methods

Impregnation is one of the most effective and widely adopted industrial methods for producing composite materials. This process has several advantages over solid-phase techniques for manufacturing ceramic-metal composite materials (CMCM):

- High productivity
- Minimal mechanical stress on components, enabling the production of large and complex-shaped products
- Continuity of the impregnation process
- High potential for mechanization and automation of the technological process



1 - supply to the vacuum pump; 2 - cork stoppers; 3 - resistance furnace; 4 - fibers; 5 - mold; 6 - crucible with a solution of matrix material

Figure 2. Vacuum impregnation scheme.

Filling Holes with Molten Metal

The process of filling holes with molten metal (see Figure 2) is driven by the pressure difference between the atmospheric pressure and the pressure created within the holes during vacuum application. The vertical positioning of the crucible ensures an additional pressure from the molten mass, which accelerates the flow process.

A variation of pressure-assisted impregnation involves creating excess pressure in the molten metal bath by introducing compressed gas. This method enhances the infiltration of molten metal into the holes, ensuring uniform filling.

Furthermore, the efficiency of the impregnation process can be significantly improved by applying ultrasonic vibrations. Ultrasonic treatment reduces surface tension, promotes better wetting of the material, and ensures more complete filling of microvoids, thereby improving the overall quality and structural integrity of the composite material.

Conclusions

This study has examined the technological aspects and properties of composite materials used in various industrial sectors, with a particular focus on the automotive industry. The following key conclusions can be drawn:

1. **Diverse Composite Material Types:** Composite materials such as boron-aluminum (VKA-1), carbon fiber-reinforced aluminum (VKU-1), steel-aluminum (KAS-1), magnesium-boron (BKM-I), and titanium-based composites each exhibit unique mechanical and thermal properties that make them suitable for specialized applications. These materials demonstrate superior strength, stiffness, and thermal resistance compared to conventional alloys.
2. **Fiber Reinforcement Significance:** The reinforcement of metal and polymer matrices with various fibers (boron, carbon, silicon carbide, glass, and organic fibers) significantly enhances mechanical properties such as strength, elasticity, and thermal stability. The choice of fiber type and its interaction with the matrix material is crucial in determining the final performance of the composite.
3. **Advanced Manufacturing Techniques:** Composite material production employs diverse methods, including hot pressing, diffusion welding, explosive welding, vapor deposition, and liquid metal impregnation. Impregnation, particularly when aided by ultrasonic vibrations, stands out due to its high productivity, the ability to produce large and complex components, and improved process continuity.
4. **Ultrasonic-Assisted Impregnation Efficiency:** The application of ultrasonic vibrations during the impregnation process significantly enhances material quality by reducing surface tension, improving wetting, and ensuring the complete filling of microvoids. This results in composites with superior mechanical integrity and fewer defects.
5. **Tailored Properties for Industrial Applications:** Composite materials can be engineered to exhibit specific properties such as high strength-to-weight ratios, corrosion resistance, and fatigue durability. This customization makes them ideal for use in demanding industries like aerospace, automotive, and energy.
6. **Challenges and Future Perspectives:** Despite their advantages, challenges remain, including material costs, complex manufacturing processes, and limited heat resistance in certain polymer composites. Future developments should focus on improving cost-effectiveness, enhancing heat resistance, and further automating manufacturing processes.

In conclusion, composite materials represent a vital class of materials for modern industry due to their ability to combine desirable properties that surpass those of traditional materials. Continued research and technological advancements will further expand their applications and improve their performance, leading to more efficient, lightweight, and durable solutions across various industries.

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