INNOVATIVE MATERIALS AND ENGINEERING STRATEGIES IN U.S. CUSTOM VEHICLES

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Abstract. The article is devoted to the analysis of innovative materials and engineering strategies used in the manufacture of customized cars in the USA. Scientific novelty is a comprehensive approach to the design and manufacture of new generation composite components using the precision fiberglass innovation (PFIS) technology. The purpose of the study is to identify modern innovative technologies for the production of fiberglass and fiberglass that have practical application in the automotive industry. During the scientific study, general scientific methods of cognition were used: analysis, synthesis, comparison, systematization, generalization, modeling. The results of the study show that none of the existing industrial technologies for the formation of fiberglass is universal for all types of automotive components. Special attention is paid to the author's PFIS system, which is fundamentally different from classical approaches in that it provides full integration of the design and production stages. Within the framework of PFIS, controlled fiber orientation according to load distribution, adaptive change in part thickness, and rapid change of structures without loss of production efficiency are implemented. The proposed system allows creating complex geometric shapes taking into account local requirements for mechanical properties, which is critically important for engineering solutions in the field of custom automotive manufacturing, electric vehicles, and the defense and aerospace industries. It is shown that thanks to PFIS, it becomes possible to implement high-precision optimization of mass-dimensional characteristics of parts, reduce material consumption, and ensure strategic production efficiency factors: competitiveness, stability of innovations, adaptability to new market challenges. The practical significance of the research lies in the implementation of a flexible high-tech platform for the manufacture of innovative composite parts in modern automotive manufacturing.

Keywords: fiberglass, fiberglass, composites, automotive manufacturing, PFIS, innovations.

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Introduction

Over the past decades, the custom car industry in the United States has demonstrated a steady trend toward reducing vehicle weight and increasing fuel efficiency without sacrificing strength, safety, or performance. A key driver of these changes is the introduction of innovative materials, including high-strength aluminum alloys, carbon composites, multilayer polymer matrices, and additively manufactured metal components. Reducing structural mass directly correlates with reduced energy consumption, improved dynamic performance, and reduced emissions, making such solutions relevant to both individual tuning and broader automotive industry trends.

A study of innovation in the field of American custom cars is revealing, given the high concentration of copyright patents, experimental material processing techniques, and non-standard design solutions that often precede mass production. The analysis of these developments allows not only to assess the current level of technological maturity, but also to identify future development vectors - in particular, the integration of multifunctional materials, topological optimization of load-bearing elements and hybrid production processes. In this context, custom vehicles act as a kind of "laboratories on wheels", where solutions are tested that can determine the further evolution of automotive engineering.

Literature Review

The issue of introducing innovative materials and engineering strategies in the field of creating customized cars in the USA is widely studied in the world scientific literature, given the intensive development of the automotive industry and high competitiveness in the market. The variety of technologies used to optimize the weight, strength and efficiency of components has been reflected in numerous scientific studies and industry reports.

A significant contribution to the development of the topic has been made by authors such as A. Kumar [7], who studied the process of vacuum resin infusion using the Taguchi method for optimization, and N. L. Miazza [8], who presented the potential of pultrusion for mass production of lightweight elements. An overview of modern composite materials, their applications and advantages in the context of automotive engineering is covered in the works of F. Khan et al. [6], as well as in the publication of L. Yan and H. Xu [11], which consider the prospects of lightweight composites in the future. Special attention should also be paid to the study of H. Ning et al. [9], who proposed technological solutions based on long-fiber thermoplastics for highly functional elements.

In addition to scientific research, expert literature was also used for the analysis, in particular industry reports and resources: Solvay [3], Cannon [10], as well as statistical and economic reviews from the Bureau of Transportation Statistics [2] and FRED [4], [5]. These materials made it possible to trace the market dynamics and technological trends in the industry, which directly affect the choice of engineering solutions.

Thus, the work summarized five key technologies presented in the aforementioned studies and presented them in comparison with the author's technology, which is currently being implemented in the automotive market in the USA. Despite a sufficient number of sources on this topic, there is a lack of a systematic approach to the analysis of innovative solutions, therefore, using various methods of scientific knowledge, the information was analyzed, grouped, systematized and presented in the light of the research topic.

The purpose of the article is to identify modern innovative technologies for the production of fiberglass and fiberglass that have practical use in the automotive industry.

Research Results

The automotive manufacturing market in the United States is one of the key sectors of industry and makes a significant contribution to the country's gross domestic product. In monetary terms, the amount of added value in the production of automobiles and components amounted to 142.7 billion dollars. in 2020, 185.9 billion dollars. in 2024, which indicates a steady growth in the economic role of the industry [4]. If this rate of development is maintained, the amount of added value in automobile manufacturing may reach approximately 270–280 billion dollars. by 2030, which reflects the market's orientation towards products with higher technological and material complexity, and not only on an increase in the number of vehicles produced.

If we turn to production volumes, the picture here is more uneven. In 2019, the United States produced about 10.9 million vehicles, in 2020 the volume fell to 8.8 million, that is, by almost a fifth, and in 2021 production increased to 9.2 million units [2]. At the same time, domestic sales remained higher than production volumes: 13.7 million in 2019, 11.6 million in 2020 and 11.8 million in 2021 [2]. This indicates a stable demand for cars and the partial dependence of the market on imported supplies. Provided that the moderate pace of recovery is maintained and restrictions in supply chains are gradually lifted, production volumes by 2030 may approach the level of 11–12 million vehicles per year, however, the main contribution to the development of the industry will be formed not by quantitative growth, but by increasing the cost and complexity of each individual unit of production [5].

Over the past six years, the market has gone through a phase of sharp decline, slow recovery, and transition to more cautious growth, with the emphasis shifting from quantity to technological complexity of products. At this stage, innovative materials and modern production technologies begin to play a key role. Manufacturers are increasingly using light and high-strength alloys, polymer composite materials, and multilayer body structures, which allow them to reduce the mass of the vehicle and increase energy efficiency. This is especially important for electric and hybrid models, where heat transfer, battery safety, and structural durability are critical [11].

Modern automotive industry is in a phase of profound material science transformation, driven by the requirements for reducing the mass of vehicles, increasing energy efficiency, and meeting environmental standards. A key development direction is the transition from traditional metal structures to lightweight composite materials, which provide a high strength-to-weight ratio and allow reducing the total weight of the vehicle by up to 50% compared to individual metal components [11]. This has a direct impact on:

1) reducing fuel consumption in cars with internal combustion engines;

2) increasing the range of electric vehicles;

3) reducing the number of components and simplifying assembly by combining several functions in one part.

The second important trend is the development of multi-material structures and the combination of different types of composites within a single body or power frame. Polymer composites remain dominant due to their good processability and the possibility of mass production, but hybrid structures that combine the properties of metals, polymers and ceramic phases to achieve locally optimal characteristics of strength, stiffness and heat resistance are increasingly used [6]. In parallel, technologies for forming parts with fast-curing resins, automated pressing and thermoplastic molding are developing, which makes it possible to use composites in serial production, and not only in sports or small-scale models [3]. The third strategic direction is related to the sustainability and functional integration of materials. Bio-oriented and recycled composites are actively researched, which reduce the carbon footprint of production and simplify disposal at the end of the vehicle's life cycle [6]. Special attention is paid to multifunctional materials with sensory, self-healing and electromagnetic properties, which allows combining structural and intellectual functions in one material layer. For electric vehicles, this is of additional importance due to the need for thermal insulation of batteries and protection against electromagnetic interference [11]. Thus, innovations in composites form not only new structures, but also a new logic of vehicle design.

Let us consider the key future trends in innovative technologies for the use of composite materials in the automotive industry in Table 1.

Table 1 – Key future trends and innovative technologies for the use of composite materials in the automotive industry

Direction of innovation	Essence of the trend	Technological significance for the industry
Lightweight structures [11]	Replacement of metal components with composites featuring a high strength-to-weight ratio	reduction of vehicle mass; improved energy efficiency; increased driving range of electric vehicles
Multimaterial structures [6]	Combination of different types of materials within a single structure	optimization of local properties; reduction of overall mass without loss of stiffness
Automated forming [3]	Rapid pressing; thermoplastic forming; automated fiber placement	feasibility of serial production of composite components
Part consolidation [11]	Integration of several components into a single composite part	simplification of assembly; reduction in the number of joints; increased reliability
Bio-based and recycled composites [6]	Use of natural fibers and recycled raw materials	reduction of environmental impact; compliance with principles of the circular economy
Multifunctional materials [6,11]	Embedded sensors; self-healing capabilities; electromagnetic shielding	integration of structural and intelligent functions
Materials for electric vehicles [11]	Composites with enhanced thermal insulation and battery protection	improved safety and durability of battery systems
Fast-curing resins [3]	Reduction of the production cycle time	lower costs; increased scalability of manufacturing

Note: systematized by the author based on sources [3; 6; 11]

In the production of automotive parts from fiberglass and fiberglass, various technological approaches are used, which differ in molding speed, cost, level of automation and stability of the properties of finished products. The most common are pressing sheet molding materials, vacuum resin infusion, high-pressure resin casting, molding from long-fiber thermoplastic composites and continuous production of profiles by pultrusion. Each of these technologies is focused on different types of parts and different production scales, so they do not compete directly, but complement each other within the framework of modern automotive engineering.

One of the most common technologies is the pressing process of sheet molding materials, which is described in detail in the work of G. Alnersson and M. Norrby [1]. In this case, sheets are used that already contain resin and crushed fiberglass, which are placed in a mold and compressed under the influence of temperature and pressure until the cavity is completely filled. The advantage of this approach is a short production cycle and relatively low cost of both materials and molds. This makes the technology attractive for mass production of body panels. At the same time, the random orientation of the fibers leads to uneven strength in different directions, and the quality of the parts strongly depends on the molding modes, which makes it difficult to consistently reproduce the properties.

Another approach is associated with the impregnation of dry reinforcement with resin under the influence of vacuum, which is typical of the vacuum infusion technology. A. Kumar et al. [7] showed that the pressure, viscosity of the resin and the number of layers of reinforcement play a decisive role here, since they determine the permeability of the structure and the uniformity of fiber saturation. This technology allows you to obtain parts with high quality internal structure and a minimum number of pores, which is important for loaded elements. However, the process itself remains relatively slow, and the complexity of controlling the resin flow limits the use of the technology in large-scale production.

To increase productivity in mass production, high-pressure resin molding is increasingly being used, which combines the injection of resin under pressure with the evacuation of the mold. After the formation of the fibrous blank, the resin quickly fills the mold, which allows significantly reducing the cycle time and ensuring high repeatability of the results [10]. This process is well suited for complex thin-walled parts with high requirements for surface quality. The main limiting factor remains the high cost of equipment and the need for precise control of molding parameters. A separate group consists of technologies related to the use of long-fiber thermoplastic composites, which combine good mechanical properties with the possibility of processing. In the work of H. Ning et al. [9] it is shown that the length of the fibers in such materials allows achieving significant stiffness and impact resistance while maintaining suitability for molding parts of complex geometry. An important advantage is the possibility of reprocessing and stability of properties in mass production. That is why such materials are widely used for semi-supporting elements of the interior, floor panels and functional module housings, where a combination of strength and manufacturability is required [9].

Another direction is focused on the manufacture of long profiles with a constant cross-section, which is implemented by the pultrusion method. This technology, according to N. Miazza [8], is one of the most cost-effective for large volumes of production, since the process is continuous and lends itself well to automation. In the automotive industry, bumper beams, door stiffeners and body strength profiles are manufactured in this way. An additional advantage is the ability to combine different types of fibers within one profile. The limitation remains the complexity of manufacturing parts with a variable cross-section, although modern developments in curvilinear pultrusion are gradually expanding the design capabilities of this technology [8]. Let us consider the advantages and disadvantages of each of the described technologies in Table 2.

Table 2 – Advantages and disadvantages of fiberglass technologies used in the automotive industry

Technology	Advantages	Limitations
Sheet molding compound compression molding (SMC) [1]	fast cycle; low cost of materials and tooling; suitability for mass production	non-uniform mechanical properties; high sensitivity to process parameters
Vacuum-assisted resin transfer molding (VARTM) [7]	high impregnation quality; homogeneous structure; suitability for large components	long cycle time; difficulty of scaling for large production series
High-pressure resin transfer molding (HP-	short cycle; high repeatability; good surface quality; potential	high equipment cost; complexity of process control

RTM) [10]	for automation	
Long fiber thermoplastic composites (LFT) [9]	high strength; impact resistance; recyclability; capability to form complex geometries	limitations in maximum stiffness compared with continuous fiber composites
Pultrusion [8]	very high productivity; low unit cost at large volumes; stable properties	predominantly constant cross-section; limited geometric complexity

Note: systematized by the author based on sources [1, 7, 8, 9, 10]

It can be noted that none of the technologies is universal for all types of automotive parts. Pressing of sheet materials and high-pressure resin casting are most suitable for serial production of body elements, vacuum infusion provides high quality for complex structures, long-fiber thermoplastic composites are optimal for functional and semi-load-bearing parts, while pultrusion is effective for the manufacture of power profiles. It is the combination of these approaches that forms the modern technological basis for the use of fiberglass and fiberglass in automotive engineering.

Along with industrially standardized fiberglass molding technologies, such as sheet molding, vacuum resin infusion, high-pressure resin casting, long-fiber thermoplastic composite molding, and pultrusion, the industry is also developing proprietary patented approaches focused on a high level of customization and system integration of engineering and manufacturing solutions. One such technology is the Precision Fiberglass Innovation System (PFIS), developed by Alexei Maksimov, which is positioned not as a separate method of material molding, but as a comprehensive production and engineering methodology for managing the full cycle of creating composite components for critical segments, including automotive design, electric mobility, aerospace applications, the marine sector, and defense infrastructure. Unlike classical technologies, in which the key properties of the part are determined by the type of semi-finished product and rigidly specified molding modes, in precision fiberglass, the optimization of geometry, fiber architecture and local mechanical characteristics is carried out at the level of an integrated design and production process (Table 3).

Table 3 – Main technological characteristics of the precision fiberglass technology system in comparison with classical approaches

Characteristic	Description of PFIS properties	Difference from classical technologies
Fiber architecture formation	controlled orientation of fibers in accordance with load distribution	in SMC and VARTM, orientation is predominantly predefined by the semi-finished material
Local thickness adaptation	variable thickness within a single component	in most RTM and LFT processes, thickness is defined by mold geometry
Integration of design and manufacturing	digital modeling directly influences technological parameters	in standard processes, these stages are often separated
Flexibility in design changes	rapid adaptation to new models and configurations	molds and tooling in HP-RTM and pultrusion are less flexible
Customization	focus on unique and small-series solutions	classical technologies are optimized for large-scale production
Strategic KPIs	evaluation of effectiveness through weight reduction; export competitiveness; innovation stability	in industrial processes, assessment is usually limited to production metrics

Note: compiled by the author

The fundamental difference between this technology and the pressing of sheet molding materials, as can be seen in Table 3, is the controllability of the reinforcement structure. In SMC-type technologies, the orientation of the fibers is mainly random and is only partially corrected during the flow of the material in the mold, which causes anisotropy of properties and limits the possibilities of local strengthening of load zones. In contrast, PFIS provides for the purposeful formation of the fiber structure in accordance with the stress distribution, which allows achieving increased stiffness in critical areas without an overall increase in the mass of the part. Compared to vacuum infusion, where the main emphasis is on the quality of impregnation and minimizing porosity, PFIS shifts the focus to the structural adaptation of the material to functional requirements, and not only to ensuring the homogeneity of the matrix. As for high-pressure resin molding, which is focused on cycle reduction and repeatability of serial production, PFIS is less dependent on rigidly standardized molds and allows for faster changes in design parameters when switching between models or modifications of parts. Compared to long-fiber thermoplastic composites, where the advantage is manufacturability and processability, PFIS provides greater flexibility in forming complex aerodynamic surfaces and power elements with zonally variable properties. Finally, unlike pultrusion, which is effective for profiles of constant cross-section, PFIS is focused on three-dimensional geometrically complex structures characteristic of body, aerodynamic and integrated structures.

This author's technology is based on a combination of several conceptual levels: digital analytics of materials and design, controlled formation of fiber architecture, phased integration of production operations and a strategic efficiency assessment system. The use of engineering tools, in particular parametric modeling, stress-strain simulations and load flow analysis, allows you to identify zones where traditional materials or standard composite schemes are ineffective. Then the principle of zonal design is implemented, when different areas of one part receive different thicknesses, reinforcement orientations and the degree of material compaction. The production process is organized according to the logic of a phased funnel "concept – prototype – integration – finalization", which reduces the number of iterations between design and manufacturing and reduces the risks of loss of productivity during scaling.

PFIS technology does not replace industrial methods of forming composites, but complements them at the level of high-tech and strategically important applications, where the key are the flexibility of design solutions, the speed of the innovation cycle and the adaptation of the material to specific operating conditions. By integrating digital design with controlled formation of the material structure, PFIS allows you to reduce the mass of components without reducing strength, increase the aerodynamic and energy efficiency of transport systems and reduce the time of transition from prototype to serial product. On the scale of the US national market, this creates the prerequisites for the development of localized production competencies in the field of high-tech composites, reducing dependence on imported solutions, and increasing competitiveness in industries related to electromobility, renewable energy, aerospace systems, and defense infrastructure.

Conclusions

The US automotive market is in a phase of qualitative growth, when the key drivers of development are not production volumes, but the technological complexity of products, the level of materials science solutions and the speed of the innovation cycle. Under these conditions, innovative composite materials and integrated engineering methods play a decisive role in increasing energy efficiency, functional integration and competitiveness of transport systems. Compared to the author's method "Innovative Precision Fiberglass System", pressing sheet molding materials is inferior due to random or poorly controlled fiber orientation, which limits the possibilities of local strengthening of load zones and leads to anisotropy of properties. Vacuum resin infusion, in turn, although it provides high structural uniformity, is characterized by long cycles and an orientation mainly on the quality of impregnation, rather than on the constructive adaptation of the material to functional requirements. High-pressure resin molding provides repeatability and speed of mass production, but requires rigidly fixed molds and has limited flexibility when changing geometry and fiber architecture, and long-fiber thermoplastic composites are technological and suitable for processing, but are inferior in the ability to form zonally variable properties and maximum stiffness, characteristic of controlled continuous reinforcement. The pultrusion method provides high productivity and stability of parameters, but is fundamentally limited by a constant cross-section and is not suitable for complex three-dimensional body and aerodynamic elements, which are the basic objects of optimization within the PFIS.

Thus, the author's PFIS technology forms a transition from standardized materials science production to intelligently controlled composite systems, in which the design, material and manufacturing process are optimized as a single whole, which creates long-term prerequisites for increasing the technological independence of the automotive industry.

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