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RESEARCH ON THE INFLUENCE OF NEW STRUCTURAL MATERIALS AND MANUFACTURING PROCESSES WITH 3D PRINTING ON THE RELIABILITY OF AUTOMOBILE HUBS

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Abstract:
This paper presents the results of modeling and analyzing the influence of new structural materials on the strength and reliability characteristics of automotive chassis hubs using SolidWorks. The possibility of replacing traditional metal materials used in the production of automotive hubs with polymer composite material (PCM) designed with predetermined properties is discussed. During the study, the manufacture of automobile hubs using 3D printing technology was optimized with modern software. The simulation results of three different materials, namely PCM Acrylonitrile Butadiene Styrene / Glass Fiber (ABS/GF), titanium alloy Ti-8Mn and steel C45, using finite element analysis (FEA), showed that the newly developed ABS/GF PCM material based on glass fiber reinforced thermoplastic polymer is more suitable for manufacturing automotive axles than two existing metals, titanium alloy Ti-8Mn and steel C45, thanks to its high strength and being 72.78% lighter than steel C45 and 55.11% lighter than titanium alloy Ti-8Mn. The design of the automobile hubs was optimized using 3D modeling and FEA. Tests demonstrated the high strength and durability of the new material, making it promising for all-weather operation under real road and traffic conditions.

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1. INTRODUCTION

The chassis is designed to ensure safety and comfort when moving the automobile on the road without shaking and vibrations. The mechanisms and parts of the chassis connect the wheels to the body, dampen its vibrations and transmit the forces acting on the car. The study and modeling of the influence of the operational properties of new structural materials of chassis parts on the reliability and safety of ground transport and technological machines is of great importance for science and production [1].

A large number of materials are used in the automotive industry, such as steel, aluminum, iron, glass, composite materials, rubber, copper, and many other materials. In the last few decades, advances in the development of these materials have led to advanced manufacturing and increased car safety. Car manufacturers strive to reduce car weight in order to increase speed and power, and thus improve their performance. Tyre-road friction also plays an important role in vehicle handling performance [2]. In addition, manufacturers aim to enhance traffic safety by selecting materials that are highly durable and can absorb energy during collisions [3]. Simulation can easily reduce the time spent on creating complex 3D models, as well as mitigate risks associated with the design and manufacturing process [4, 5]. In this article [5], the authors used FEA based on ANSYS software to simulate and compare two types of materials: forged steel and aluminum. According to the simulation results, forged steel proved to be a more suitable material for automobile hubs than aluminum, as it can withstand greater loads with less deformation. Thus, FEA allows obtaining

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reliable results that correspond to those obtained during bench tests of hubs under static loads [6–8]. CAD/CAE systems SolidWorks (Simulation) and Compass are environments for 3D modeling, design, analysis, and optimization of design solutions [9, 10]. SolidWorks Simulation is an easy-to-use structural analysis tool that applies FEA to predict the behavior of loaded parts by virtually testing CAD models [10].

In the paper [11], the authors used FEA with SolidWorks software (SolidWorks Simulation) for the design, analysis, and evaluation of PCM. The results showed that the accuracy of calculations for the main physical and mechanical characteristics of reinforced PCM, based on the developed methodology, is sufficiently high, and the overall 3D model of the basic structural cell fully corresponds to the actual reinforced plastic, with an error of no more than approximately 0.01%. On the other hand, in the paper [12], the authors used two types of calculations performed in the Simulation package of SolidWorks software: strength calculations and maximum displacement calculations. The calculations were performed with a given operating temperature of the hub equal to 450°C, for two types of materials: C45 steel and H18 aluminum alloy. The results of modeling and analysis of the strength of two hubs made of different materials: C45 steel and H18 aluminum alloy, using the finite element method, performed using the SolidWorks Simulation system, showed that the automotive hub made of C45 steel has a high load and stress resistance [12]. Therefore, preliminary strength and maximum displacement calculations performed in the Simulation package of SolidWorks software allow for obtaining reliable research results without testing on a test bench.

In research [13], the authors compared the FEA capabilities of the software packages SolidWorks, Ansys, Abaqus and Inventor Nastran. These software packages were chosen because they are popular products on the market today. In the authors' opinion, their capabilities and specific features were compared with each other. The results of the study illustrate that all four software packages have almost the same capabilities, but the most diverse in the list is SolidWorks.

In the article [14], the authors consider the influence of elliptical holes on the stress state of anisotropic (orthotropic) uniaxially reinforced plate subjected to static loading. Holes in machine parts are typical sources of stress concentrations. The stress distribution around holes, which are sources of stress concentrations, is significantly affected not only by the hole size and material but also by its shape and position relative to the direction of external load action. Although in practice, elliptical holes are less common than circular holes. Analytical and numerical methods used to perform stress distribution in a plane isotropic field are weakened by holes. Based on the results obtained in this paper, it can be concluded that by applying the finite element method, the problems of stress-strain conditions of thin plates with different hole shapes can be effectively solved. The authors in the article [15] analyzed the stress distribution in an isotropic plate with rectangular holes subjected to tensile load using the finite element method. The results show that the presence of such hole shapes often has a negative impact on the amplitude and distribution of stresses in the components of mechanical structures, which can affect their safety and reliability, and also negatively affect their service life. The paper [16] examined the impact of square holes, as a source of stress concentration, on the stress distribution in machine and equipment components. The fact is that these forms of the openings occur less in practice, but the knowledge of the influence of the square opening on the stress distribution, from the aspect of its size, the radius of the angles curvature and positions in relation to the attack lines of external loads is important to those designing and constructing parts with such opening shapes. The circular hole shape was chosen for the automobile hubs because of its strength and good load-bearing capacity, which helps to distribute the force evenly and keep the wheel rotating stably. The circular hole was used because its geometry allows the material to withstand compression better than other shapes, while minimizing the stress concentration caused by sharp corners. Furthermore, the circular shape minimizes the contact area, thereby reducing friction, making the vehicle move more smoothly. Using other hole shapes (e.g. rectangular, square, triangular) will not be suitable for wheel axles because these shapes will create stress concentration corner points, resulting in material weakening and easy damage. In addition, it will cause loss of stability because when the vehicle is running, the axle will go up and down, causing imbalance, vibration, and not ensuring safety for the driver. Therefore, from the research articles of the above authors, it can be concluded that round holes have the ideal shape for wheel axles to ensure durability, stability, and smooth operation.

This paper focuses on studying the influence of composite materials made from ABS plastic and glass fiber filler (ABS/GF) in comparison with two metal materials, titanium alloy and steel. It analyzes and evaluates the advantages and disadvantages of composite materials relative to traditional metal materials. Based on a new composite-material design, which was studied and compared with two existing metal materials—titanium alloy Ti-8Mn and steel C45 (parameters according to GOST SolidWorks). Simulation results in the SolidWorks environment showed that ABS/GF composite material has the highest safety factor and better performance than the other two materials, titanium alloy Ti-8Mn and steel C45. The article then discusses optimizing the 3D printing process to manufacture car hubs from the new ABS/GF composite material, using modern software such as Ultimaker Cura.

2. RESEARCH PROBLEM

The paper discusses the possibilities of manufacturing automotive hubs from PCM. An analysis of the advantages and disadvantages of hubs made from PCM was conducted.

Main advantages of replacing metal materials with PCM:

• Reduction of mass by 2-3 times compared to metal discs [1];

• Low noise level during braking;

• Increased wear resistance compared to metal hubs;

• Improved corrosion resistance of the brake disc made from PCM.

Disadvantages:

• High manufacturing cost of hubs from PCM before mass production;

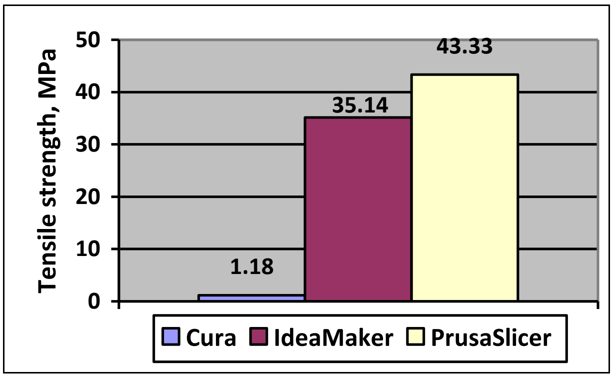
• Need for designing a new PCM with specified properties;

• Requirement to develop new technological processes and justify manufacturing equipment for producing hubs from PCM.

The application of PCM in the production of automobile hubs opens up opportunities for using additive manufacturing techniques to create three-dimensional objects through layer-by-layer material addition. The implementation of additive technologies is carried out with the help of 3D printers, ensuring nearly waste-free production.

Additive technological methods allow for reducing labor intensity, production time, and cost. The use of PCM in combination with additive technologies significantly improves the characteristics of products [17, 18].

A comparative analysis of the results of the conducted studies on printing duration and extruder head movement using Cura (39 min), IdeaMaker (43 min), and PrusaSlicer (47 min) showed a significant difference in the manufacturing time of test samples with the same set of parameters. The tensile strength and elastic modulus of the samples also differ considerably (see Fig. 1) [1, 18].



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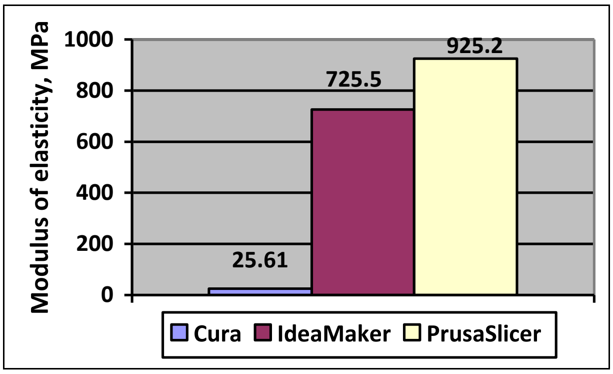


b)

Fig. 1. Test results of ABS plastic: a) Tensile strength (MPa), b) Modulus of elasticity (MPa)

The results of the studies allow for justifying the choice of software for printing the most critical parts of transport and technological machines.

3. MATERIALS FOR AUTOMOBILE HUBS

Modern structural materials such as carbon fiber composites, aluminum alloys, and alloyed steels have a high strength-to-weight ratio, making them ideal for use in automotive manufacturing. Research shows that the application of such materials can reduce part weight, improve durability, and lower fuel consumption [19].

Currently, in modern automotive design, ferrous metals account for about 60-70%; non-ferrous metals – 5-7%; PCM – 9-13%; textiles – 4%; glass – 3% [20-22].

3.1. Composite Material Automobile Hubs

In modern mechanical engineering, the economic efficiency of plastics implementation is demonstrated by significant weight reduction of mechanisms, improved operational characteristics, and resource savings, especially of non-ferrous metals and steel. Replacing metal materials with PCM reduces labor intensity and production costs of mechanical products. Replacing ferrous metals with polymers can reduce manufacturing labor by an average of 5-6 times and reduce costs by 2-6 times [23]. When replacing non-ferrous metals with composites, costs decrease by 4-10 times [23].

PCM are developed by combining two or more components with different physical and chemical properties. When these components are combined, a new composite material is created that surpasses the individual components in properties, often exhibiting higher strength, lightness, or environmental resistance [21, 22].

Modern PCM typically consist of two main components: reinforcing fibers and a matrix. Common fiber materials include carbon fiber, high-strength glass, organic fibers, boron fibers, and others. The matrix can include thermoplastic polymers (e.g., polyamide, polyethylene, polystyrene) and thermosetting resins (phenolic, epoxy, polyester, etc.) [24]. Meanwhile, the operational properties and energy absorption capacity of PCMs provide a unique combination of weight reduction and increased impact resistance of transport structures.

Continuous Fiber Reinforced Polymer Composites (CFRPC) are actively used in automotive, aerospace, and astronautics due to their lightness and high strength. In modern aircraft such as the A350XWB, composites constitute over 50% of the materials, enabling weight reduction of the structure by up to 60% compared to conventional steel [25]. However, their cost is higher than traditional metals due to raw material, manufacturing, and processing expenses. Thermosetting composites are widely used but cannot be recycled without losing properties. Thermoplastic composites, known for their high durability and recyclability, are becoming promising for "green" technologies. However, their shaping, for example, by injection molding, complicates the creation of complex structures. Additive manufacturing, also known as 3D printing, represents a new method of part formation based on a layer-by-layer principle, allowing for rapid fabrication of structural elements of any complexity [25]. The development of fiber materials for Fused Deposition Modeling (FDM) technology from these raw materials has attracted interest due to their light weight and high strength-to-weight ratio [25, 26].

ABS plastic, whose full name is acrylonitrile butadiene styrene, is widely used as a material for FDM printing. This petroleum-based plastic has relatively good characteristics in terms of durability and strength, such as impact resistance, tensile strength, as well as moderate resistance to heat and chemicals. The ability to print at lower nozzle temperatures compared to other materials ensures high precision. ABS plastic is widely used in the automotive industry, household appliance manufacturing, and product design. Among the materials suitable for composite reinforcement in 3D printing, the best are carbon fiber and fiberglass. However, the cost of carbon fiber is significantly higher than that of fiberglass. Therefore, fiberglass will be chosen as the filler in the development of new composite materials for 3D printing.

3.2 Titanium Alloy Automobile Hubs

Titanium alloys have very high tensile strength and are lightweight, corrosion-resistant, strong at higher temperatures, and thermally stable. Compared to aluminum, titanium alloys are inferior in processing and design, and they have a higher cost. Although they are still in the development stage, titanium alloys have already found applications in the racing industry [27]. Machining titanium is more difficult than other materials. It is difficult to cast compared to steel, so titanium is often machined and shaped from the forging process. This is costly for the manufacturer.

3.3 Steel Automobile Hubs

For steel wheels, the choice of suitable material depends largely on the technical parameters related to operational durability and weight [28]. The main advantages of steel automobile hubs are low cost, flexibility, good shock absorption, deformation protection, and simple and inexpensive repair in case of bending. The main disadvantages are weight and poor corrosion resistance.

4. RESULTS AND DISCUSSION

To analyze the safety factor of different automotive hub materials, the methodological approach of this study consists of two parts. First, the design drawing is converted from 2D to 3D for the automotive hub using SolidWorks software. This allows simulation of the influence of three different materials, including a composite material developed by the author, which will be compared with two available materials under identical constraint conditions. The required parameter calculations of the three materials included in the simulation are applied in a hypothetical force and stress action to be performed. Subsequently, static analysis is conducted using the FEA method. SolidWorks software was chosen for this study due to its comprehensive features, including design validation and reverse engineering tools. It is widely used in the industry for manufacturing detailed and realistic models of industrial parts [29].

The electronic model of the hub is created using SolidWorks software for three-dimensional modeling of the “Hub” in Fig. 2.

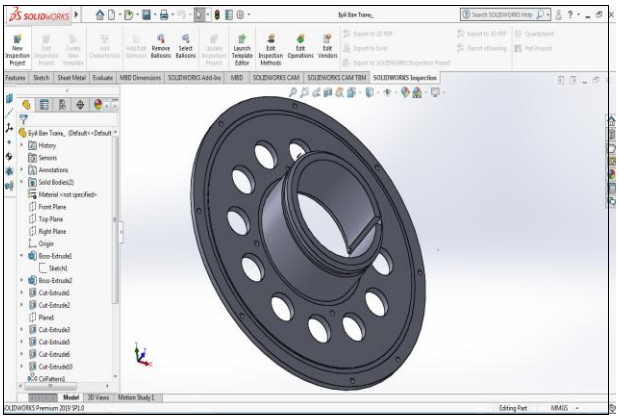
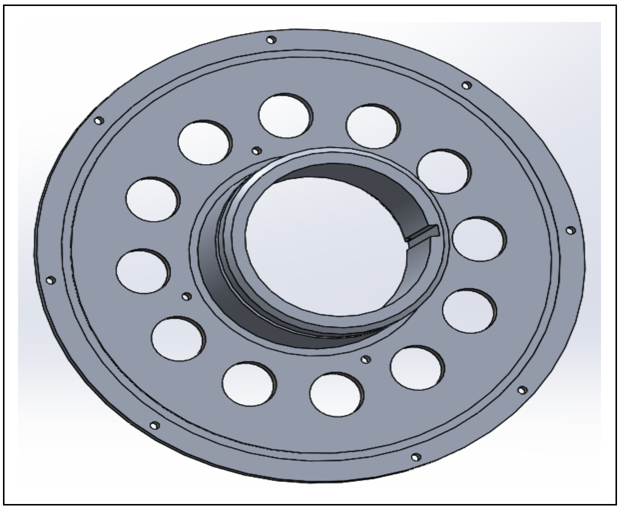


Fig. 2. Digital model of a “Hub” type part created using the 3D program SolidWorks

The 3D model images of the three different materials were used as input for the testing phase in SolidWorks simulation, which included finite element analysis to simulate material loading and deformation. Rendered models for three different materials, PCM ABS/GF, titanium alloy, and steel, are shown in Fig. 3.



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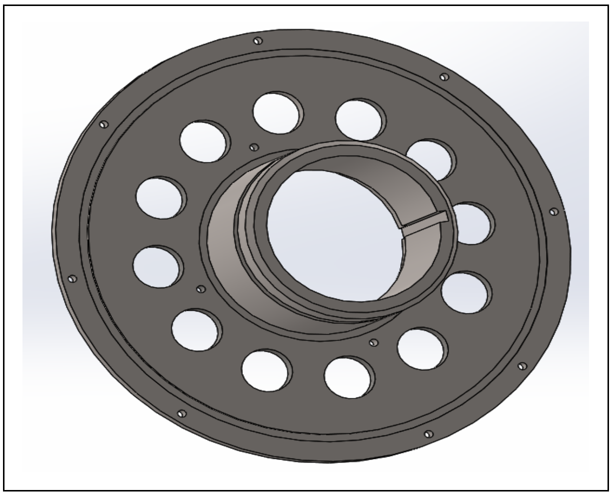

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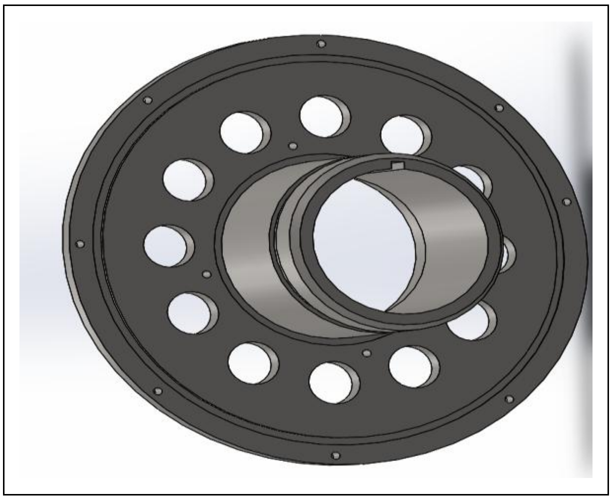


c)

Fig. 3. 3D model of the automobile hubs for three different materials: a) PCM ABS/GF, b) titanium alloy, c) steel

4.1. Methodology of Static Analysis Using FEA

In the paper, a simulation of the effect of axial force acting on automobile hubs made of three different materials: steel, titanium alloy and composite, was carried out. The conditions related to the dimensions of the hubs and the applied forces were identical for all tested materials. For the study, a static finite element analysis was performed using SolidWorks.

Regarding the application of FEA in the design of automobile wheels, many studies have been proposed so far. Desnica et al. [30] for static analysis and determination of safety factor of wheel rims, this study considered steel, aluminum, magnesium and carbon fiber rims using finite element analysis (FEA) in SolidWorks. The results obtained for the safety factor of carbon fiber wheel rims are the most suitable alternative for static operating conditions. Kader et al. [31] used SolidWorks Simulation 22 Mechanical software FEA of the composite material, and ANSYS 2022 R1 was used to study the mechanical properties of the leaf spring model fabricated from the proposed composite material. The FEA results showed a significant reduction in the weight of leaf springs, with very good mechanical properties, including the tensile and impact strength, hardness, and damping ratio, when using the proposed copolymer-reinforced composite material. The article by author Aslam [32] presented the model characteristics of the go-kart chassis calculated by FEA in NASTRAN software and empirical model analysis (EMA) using ME'ScopeVES software. The results of the study showed that the FEA method was validated with EMA with errors below 10% at least for the first five modes. The authors in the paper [33] used SolidWorks to model standard automotive wheel rims and ABAQUS software for static load analysis using the FEA method by considering four different materials of wheel rims, namely aluminum, steel alloy, forged steel and magnesium. The results of the study showed that the displacements occurring on the rim made of steel alloy material were the smallest compared to the other three materials.

4.2. Methodology of the Automobile Hubs Calculation

For the simulation, two types of calculations were used, performed in the Simulation package of SolidWorks software: factor of safety and maximum displacement analyses. The calculations were performed with an axial force acting on the hubs equal to 2000 N, for three types of materials: steel C45, titanium alloy Ti-8Mn and PCM ABS/GF. The material properties are given in Table 1.

Table 1. Characteristics of the analysed materials

Properties	Steel C45	Titanium alloy Ti-8Mn	PCM ABS/CF
Density (kg/m^3)	7800	4730	2123
Young's modulus of elasticity - E (N/mm^2)	210.10^3	115.10^3	68025
Poisson's ratio (-)	0.28	0.33	0.28
Critical stress (N/mm^2)	580	810	3298

The mesh of the automobile hub is created using SolidWorks software, as shown in Figs. 4 and 5, which shows the procedure for installing the fixed bracket in the open position for attachment to the wheel, and Fig. 6 shows how the load F is entered into the 3D model of the automobile hub.

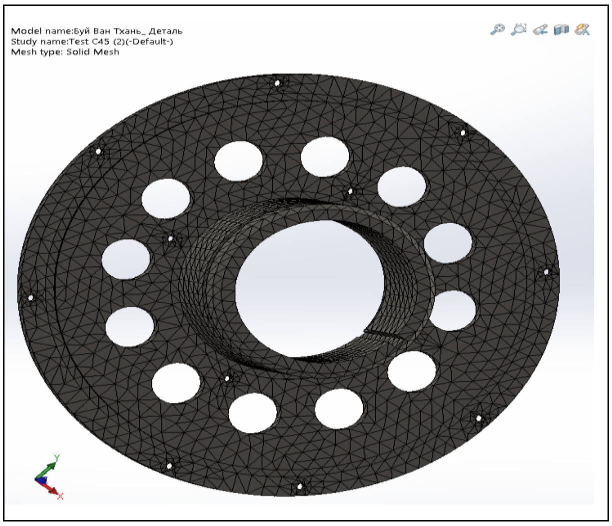


Fig. 4. Creating the mesh of the automobile hub design

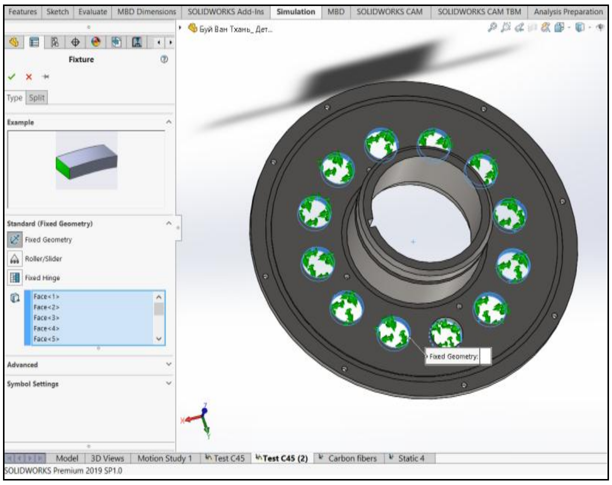


Fig. 5. Fixed support placement at the screw hole

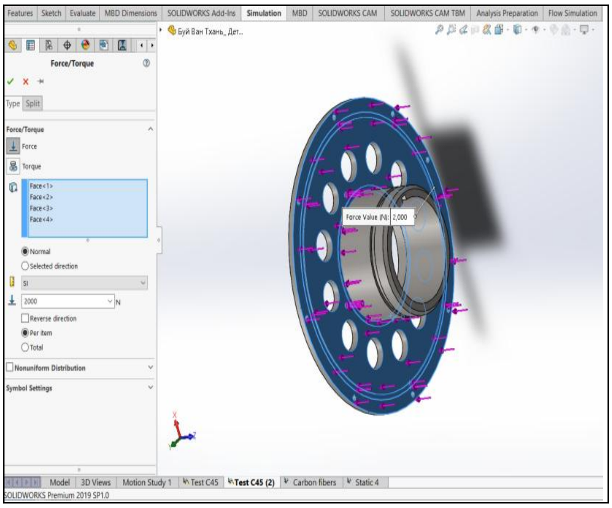
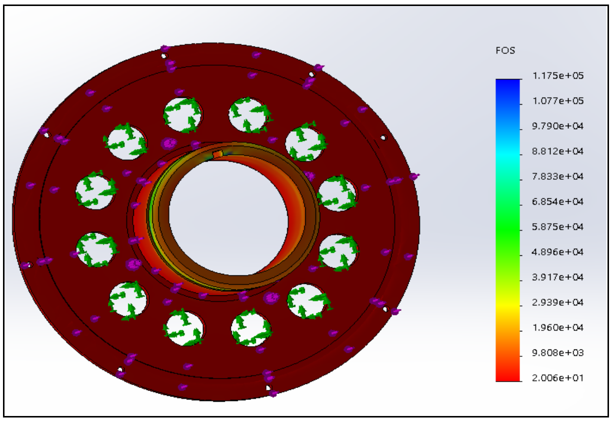


Fig. 6. Applying the load Fz to the 3D model

The results of the factor of safety and maximum displacement analyses of the automobile hub made of composite materials ABS/GF, obtained using FEA, are shown in Fig. 7.



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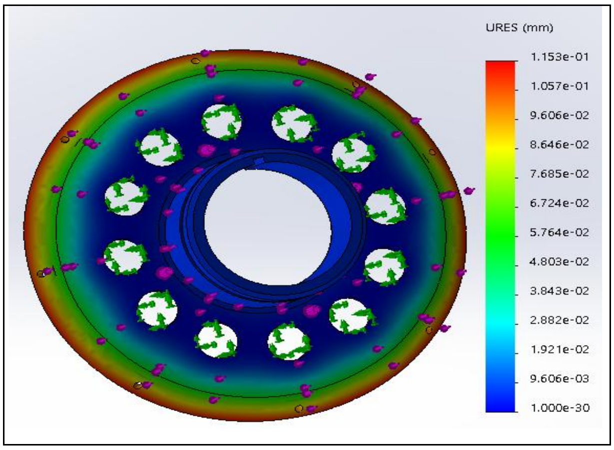

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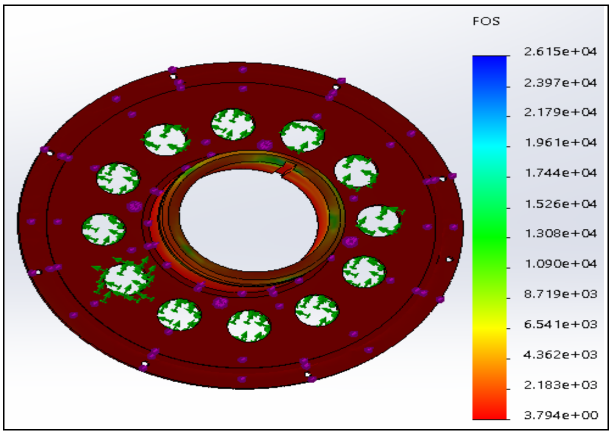
Fig. 7. The results of the factor of safety and maximum displacement analyses of the automobile hub made of composite materials ABS/GF: a) factor of safety, b) maximum displacement

The results of the factor of safety and maximum displacement analyses of the automobile hub made of material Titanium alloy Ti-8Mn, obtained using FEA, are shown in Fig. 8.



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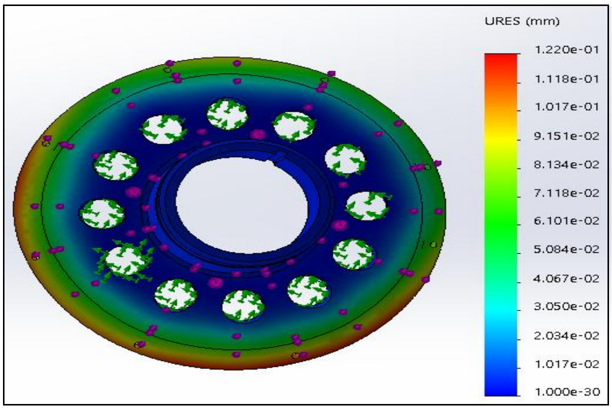

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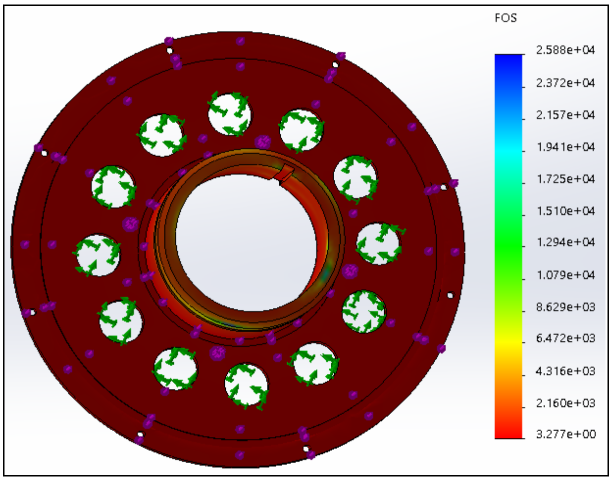
Fig. 8. The results of the factor of safety and maximum displacement analyses of the automobile hub made of material Titanium alloy Ti-8Mn: a) factor of safety, b) maximum displacement

The results of the factor of safety and maximum displacement analyses of the automobile hub made of material steel C45, obtained using FEA, are shown in Fig. 9.

The results of the material comparison are presented in Table 2.



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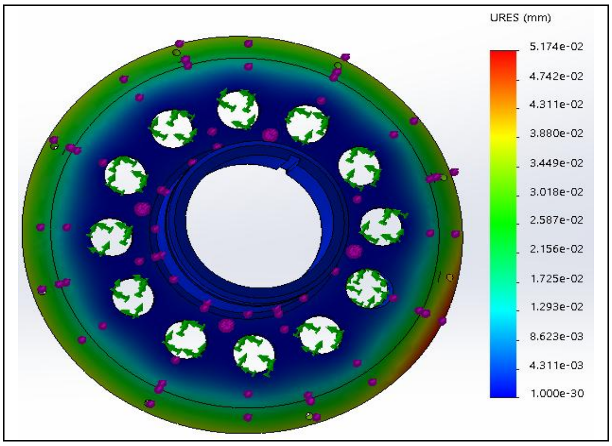

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Fig. 9. The results of the factor of safety and maximum displacement analyses of the automobile hub made of material steel C45: a) factor of safety, b) maximum displacement

By comparing the obtained results, it can be concluded that the composite material used for manufacturing automotive hubs is superior to the other two materials, which are the Titanium Ti-8Mn alloy and C45 steel. Because the safety margin of the composite automotive hub under a load of 2000 N reaches a maximum value of 1.175e+05, which is 4.49 times higher than that of the titanium alloy (2.615e+04) and 4.54 times higher than that of steel (2.588e+04).

The maximum displacement of the hub made from ABS/GF composite under a load of 2000 N is 0.1153 mm, which is less than that of the titanium alloy (0.1220 mm) and greater than that of steel C45 (0.05174 mm).

Table 2. Results of the comparison of materials

Material type	Maximum displacement (mm)		Factor of Safety (-)	
	Min.	Max.	Min.	Max.
PCM ABS/GF	1.000e-30	1.153e-01	2.006e+01	1.175e+05
Titanium alloy Ti-8Mn	1.000e-30	1.220e-01	3.794e+00	2.615+04
Steel C45	1.000e-30	5.174e-02	3.277e+00	2.588+04

However, the specific weight of the composite is 2123 kg/m³ (which is only one-third of the density of steel C45, at 7800 kg/m³, and half of the density of titanium alloy, at 4730 kg/m³), helping to reduce the vehicle's weight and fuel consumption.

The hub is planned to be manufactured using 3D printing based on Ultimaker Cura software, from ABS plastic with fillers. The results of the study on printing time and material consumption for printing the hub with fill densities from 40% to 100% are presented in Table 3.

Table 3. Results of printing time and material consumption for producing the hub with fill densities from 40% to 100% [1]

Model filling, %	Material consumption, m	Print time
40	14.56	4 hours 28 min
60	15.54	4 hours 44 min
80	16.54	4 hours 55 min
100	17.27	6 hours 13 min

(Note: m in 3D Printing = meter length of filament consumed)

When filling with material from 40% to 100%, the printing time increases from 4 hours 28 minutes to 6 hours 13 minutes (by 28%).

At the same time, material consumption increases by 1.2 times (from 14.56 m to 17.27 m).

5. CONCLUSION

The results of modeling and analyzing the durability of hubs made from three different materials—PCM ABS/GF, titanium alloy Ti-8Mn, and steel C45—using the FEA method with the SolidWorks simulation system show that the automotive hub made from PCM ABS/GF has the highest durability because it has a maximum safety margin (FOS) of 1.175×10^5, which is 4.49 times higher than that of the titanium alloy (FOS = 2.615×10^4) and 4.54 times higher than that of steel (FOS = 2.588×10^4). This ensures reliability and safety for the vehicle during operation. The simulation results from FEA also indicate that the newly developed PCM ABS/GF material (density of 2123 kg/m³)—a thermoplastic polymer reinforced with glass fibers—is more suitable for the production of automobile axles than the two existing metals, Ti-8Mn titanium alloy and steel C45, due to its high strength and because it is 72.78% lighter than steel C45 (7800 kg/m³) and 55.11% lighter than Ti-8Mn (4730 kg/m³).

Optimizing the 3D printing process of automotive parts in additive manufacturing allows for optimizing production times, ensuring the required quality level and increasing production efficiency based on modern software.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] V. A. Zorin, B. V. Thanh, Study of the influence of new structural materials and hub assembly manufacturing processes on the reliability and safety of the automobile. *VIII International scientific conference (FRITME-2024) - ”Fundamental research and innovative technologies in mechanical engineering”,* 19-20 November 2024, Moscow, pp.83-85.

[2] A. Maknickas, O. Ardatov, M. Bogdevičius, R. Kačianauskas, Modelling the Interaction Between a Laterally Deflected Car Tyre and a Road Surface. *Applied Sciences*, 12(22), 2022: 11332. https://doi.org/10.3390/app122211332

[3] Digital notes ‘CAD/CAM’ R15A0331. *Department of Mechanical Engineering, Malla Reddy college of Engineering & Technology (MRCET)*, India, 2015.

[4] S.S. Panda, J. Gurung, U.K. Chatterjee, S. Sahoo, Modeling and fatigue analysis of automotive wheel rim. *International Journal of Engineering Sciences & Research Technology*, 5(4), 2016: 428-435. https://doi.org/10.5281/zenodo.49728

[5] B. Abhiman, M.Y. Kumar, Optimization of car rim using design and analysis softwares. *International Journal of Research in Aeronautical and Mechanical*, 9(8), 2021: 01-06. https://doi.org/10.5281/ZENODO.5270315

[6] R. Kumbhar, S. Pawar, D. Jadhav, N. Dhanrale, Disc Wheel Rim: CAD Modeling and Correlation between FEA and Experimental Analysis. *International Journal of Engineering Research & Technology*, 3(7), 2014: 1316-1321.

[7] U.S. Maiya, M. Manjunath, S.H. Balakrishna, R.K. Billady, CAD Modelling and Fatigue Analysis of a Wheel Rim Incorporating Finite Element Approach. *Universal Journal of Mechanical Engineering*, 11(2), 2023: 36-45. https://doi.org/10.13189/ujme.2023.110202

[8] M.V. Chugunov, I.N. Polunina, Optimum design of the metal bellows on the SolidWorks platform. *Bulletin of the Mordovian University,* 27(2), 2017: 169-177. https://doi.org/10.15507/0236-2910.027.201702.169-177

[9] КОМПАС-3D. *АСКОН.* (In Russian) https://ascon.ru/products/kompas-3d/ (Accessed: 9 March 2024).

[10] SOLIDWORKS Simulation. *Dassault Systèmes - SolidWorks Corporation.* https://www.solidworks.com/product/solidworks-simulation (Accessed: 9 June 2025).

[11] S.I. Shalgunov, D.A. Trofimov, V I. Sokolov, I.D. Simonov-Emelyanov, Model, analysis of 3D structure and method for calculating the physical and mechanical characteristics of reinforced polymer composite materials. *VI-Russian Scientific and Technical Conference - "Polymer Composite Materials and New Generation Production Technologies"*, 18 November 2022, Moscow, pp.6-19. (In Russian)

[12] V.A. Zorin, B.V. Thanh, Research of the influence of new structural materials and manufacturing processes on the reliability of the automobile hubs. *Bulletin of the Moscow State Automobile and Road Technical University (MADI)*, 2(81), 2025: 34-42.

[13] I.A. Magomedov, Z.S. Sebaeva, Comparative study of finite element analysis software packages. *Journal of Physics Conference Series*, 1515(3), 2020: 032073. https://doi.org/10.1088/1742-6596/1515/3/032073

[14] V. Nikolić, Ć. Dolićanin, M. Radojković, E. Dolićanin, Stress distribution in an anisotropy plane field weakened by an elliptical hole. *Tehnički Vjesnik*, 22(2), 2015: 329-335. https://doi.org/10.17559/TV-20131102132713

[15] M. Radojković, I. Čamagić, Ž. Šarkočević, P. Živković, Z. Golubović, Stress distribution on an isotropic plate with a rectangular opening under biaxial tension load. *Structural Integrity and Life,* 21(1), 2021: 91-94.

[16] M. Radojković, B. Stoạnović, S. Milojević, D. Marić, S. Savić, A. Skulić, B. Krítić, Square Openings as Sources of Stress Concentration in Parts of Machines and Devices. *Tehnički Vjesnik*, 30(2), 2023: 474-480. https://doi.org/10.17559/TV-20220603080026

[17] A. Jadhav, V.S. Jadhav, A review on 3D printing: An additive manufacturing technology. *Materials Today: Proceedings*, 62(4), 2022: 2094-2099. https://doi.org/10.1016/j.matpr.2022.02.558

[18] D.A. Varakin, V.A. Zorin, I.S. Nefelov, The influence of slicer program parameters on the quality of machine parts manufactured using additive technologies, *High Technologies in the Construction Complex*, 1, 2024: 42-47. (In Russian)

[19] Under The Hood: Exploring Automotive Components and Materials. *Ochre Media*. https://www.automotive-technology.com/articles/exploring-automotive-components-and-materials (Accessed: 9 June 2025).

[20] V.A. Zorin, Engineering Technology, Production and Repair of Lifting, Construction, and Road Machines. *Academy*, Moscow, 2010.

[21] S.L. Bazhenov, Mechanics and Technology of Composite Materials. *Intellect*, Dolgoprudny, 2014.

[22] N.I. Baurova, V.A. Zorin, Use of Polymer Composite Materials in Manufacturing and Repair of Machines. *MADI*, Moscow, 2016.

[23] I.M. Morozov, Fundamentals of Assembly Technology in Mechanical Engineering. *Publishing House of Bauman Moscow State Technical University*, Moscow, 2006.

[24] Composites of the 21st Century: Opportunities and Reality. *Neftegaz.RU*. https://magazine.neftegaz.ru/articles/pererabotka/504745-kompozity-21-veka-vozmozhnosti-i-realnost/ (Accessed: 20 July 2024).

[25] X. Tian, A. Todoroki, T. Liu, L. Wu, Z. Hou, M. Ueda, Y. Hirano, R. Matsuzaki, K. Mizukami, K. Iizuka, A.V. Malakhov, A.N. Polilov, D. Li, B. Lu, 3D printing of continuous fiber reinforced polymer composites: development, application, and prospective. *Chinese Journal of Mechanical Engineering: Additive Manufacturing*, 1(1), 2022: 100016. https://doi.org/10.1016/j.cjmeam.2022.100016

[26] F. Ning, W. Cong, J. Qiu, J. Wei, S. Wang Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modelling. *Composites Part B: Engineering*, 8, 2015: 369-378. https://doi.org/10.1016/j.compositesb.2015.06.013

[27] L. Sannihith, J.K. Babu, B. Rakesh, M.S. Reddy, S. Sripathy, Design and Analysis of Two-Wheeler Wheel Rim with Different Alloy Materials and Loading Conditions. *International Research Journal of Engineering and Technology*, 9(4), 2022: 112-118.

[28] T.C. Chi, Modeling Static analysis Wheel rim Automobile Using FEA. *TNU Journal of Science and Technology*, 229(10), 2024: 100-106. https://doi.org/10.34238/tnu-jst.9952

[29] D.C. Planchard, Engineering Design with SOLIDWORKS 2020. *SDC Publications*, 2020.

[30] E. Desnica, M. Đurđev, B. Vaščić, R. Turmanidze, P. Dašić, Determination of a Safety Factor of a Car Wheel Rim Using Finite Element Analysis in Solidworks. *Applied Engineering Letters,* 7(4), 2022: 163-171. https://doi.org/10.18485/aeletters.2022.7.4.4

[31] E.E. Kader, A.M. Abed, M. Radojković, S. Savić, S. Milojević, B. Stojanović, Design of a Copolymer-Reinforced Composite Material for Leaf Springs Inside the Elastic Suspension Systems of Light-Duty Trucks. *Journal of Composites Science*, 9(5), 2025: 227. https://doi.org/10.3390/jcs9050227

[32] M.F. Aslam, A study of correlation between finite element analysis and experimental modal analysis in structural dynamic analysis. *Technical Report*, 2018. https://doi.org/10.13140/RG.2.2.28632.60162

[33] B. Bastin, S. Adars, A. Madhu, A. Krishnan, B. Jose, P. Raj, Finite Element Analysis of Wheel Rim Using Abaqus Software. *International Journal of Engineering Research and Applications*, 7(2), 2017: 31-34. https://doi.org/10.9790/9622-0702013034