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Review of New Carbon Fiber Composites: Preparation, Advantages and Recommendations

Binhan Wang

New Oriental International Curriculum Centre, Beijing, China
wangbinhan2008@outlook.com

Abstract. Carbon fiber composites are widely used in industries such as aerospace, computers and renewable energy. The author explore several important advances in carbon fiber composites in recent years, including the fusion of two specific carbon materials, the introduction of hybrid fibers, material sustainability, fabrication techniques, and functional enhancement methods. For each of these focuses, preparation methods and their advantages are introduced. By examining the relevant literature, the author also identify some unresolved key issues, such as dispersion and recombination of nanomaterials, optimization of material interactions, consistency of the fabrication process, and stability of the materials. Based on these findings, the author make a number of constructive suggestions. Based on the application of computer-based or mathematical techniques, the author point out that the evaluation of material properties and new approaches can be obtained. Combined with concrete realizations in the future, the author believe that our results will give a great boost to the real-world applications of composite materials.

Keywords: Carbon Fiber Composites, Nanomaterials, Additive Manufacturing

1. Introduction

The history of composites dates back to ancient times. A simple example is that early human civilizations used natural fibers such as straw, clay and animal dung to reinforce building materials. As time progressed, true composites originated in the early 20th century. Researchers, such as Hermann Staudinger and Carl Wagner, did pioneer work in the field of polymers, developing synthetic resin materials [1,2]. The basic research mentioned above laid the foundation for the use of composites in industry. In the ensuing years, there has been a continuous demand for lightthe authoright, durable and high-performance materials in various industries. Consequently, there was rapid development of systematic research and engineering applications of composites. In the mid-tthe authorntieth century, the use of Fiberglass Reinforced Plastics (FRP) in aircraft components made an outstanding contribution to the aerospace industry [3]. The aforementioned composites revolutionized the design and performance of aerospace structures by providing excellent strength, stiffness and lightthe authoright properties. Overall, composites are widely used in the automotive, aerospace, sporting goods and construction industries [4-7].

Composites are composite materials consisting of two or more components that have similar properties, which are usually superior to a single type of material [8]. Consider the example of

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combining high-strength fibers (e.g., carbon, glass, or aramid fibers) with a matrix material (usually a polymer, metal, or ceramic). The author can adjust their heat transfer and electrical conductivity to satisfy specific requirements in industry [3,9,10]. Recent research emphasizes on improving the performance and durability of carbon fiber composites through innovative manufacturing techniques and material modifications. For example, researchers have explored the introduction of nanostructured materials (e.g., carbon nanotubes and graphene) to improve the adhesion and strength of composites [11]. Optimizing the fiber-matrix interface and tuning the microstructure of composites can improve specific properties. With the continuous advancement of composites, sustainable reinforcements and nanocomposites are also recent research hotspots. In addition, mathematical modeling [12] and computer simulation [13] techniques provide new ideas, for example, for the prediction of the behavior of composites under different conditions.

In recent years, carbon fiber reinforced composites have received a lot of attention for their excellent properties, which can significantly reduce industrial production costs. Moreover, by integrating advanced manufacturing technologies, material innovations and computational modeling methods, carbon fiber composites can revolutionize the design and performance of future structural components. Based on the above scenario, the author aim to provide a comprehensive review of the latest research trends and advances in the field of carbon fiber composites. In the following the author highlight some of the major research directions and advances in this field.

Researchers have improved the properties of carbon fiber composites through, for example, optimizing fiber orientation, strengthening the bond betthe authoren fibers and matrix, and introducing nanostructured reinforcements [11, 14, 15]. These efforts have greatly improved the tensile strength, stiffness and impact resistance of carbon fiber composites.

Tailoring the structure of carbon fiber composites is also highly significant for the application of the composites. By adjusting appropriate experimental parameters such as fiber orientation, fiber volume fraction, and matrix morphology, the author can tailor the mechanical, thermal, and electrical properties of carbon fiber composites to meet the needs of specific applications [16, 17].

Functional enhancement of carbon fibers allows for improved bonding of carbon fibers to the substrate and enhancement of other properties of carbon fibers, such as self-repair, corrosion resistance, and electrical conductivity [18]. For example, techniques such as plasma treatment, chemical vapor deposition, and surface coating can be used to change the chemical properties and morphology of carbon fibers [19].

Utilizing carbon fiber polymers, 3D printing is the capable of creating complex geometries and structures. This technique is fully flexible, reduces material waste, and is suitable for manufacturing lightthe authoright, high-performance components [20, 21]. Multifunctional carbon fiber composites are also kinds of the research priorities. These materials not only have excellent mechanical properties, but also have additional functions such as self-sensing, self-repair and energy harvesting [22]. By integrating functional additives and nanomaterials into the composite matrix, researchers aim to create materials with enhanced capabilities for a variety of application scenarios [23].

Mathematical modeling and computer simulation play a crucial role in predicting the behavior, failure and performance of carbon fiber composites. Taking Finite Element Analysis (FEA), Molecular Dynamics (MD) simulations and multiscale modeling approaches are currently trendy methods. These ways investigate the complex behavior of materials under different conditions and optimize the structural design and basic properties [24, 25].

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2. Preparation methods for novel carbon fiber composite materials

In this chapter, the author will provide a basic introduction to the preparation methods of six types of composites: carbon nanotubes (CNTs), graphene nanoparticles (GNPs), aramid or glass fibers, biobased resins and matrices, carbon-fiber-reinforced polymers, and carbon-fiber surfaces. The relevant experiments are done in a standard laboratory setting, and the chapter is intended to help those who are new to the industry to understand the preparation process.

The specialized steps for reinforcing composites using carbon nanotubes (CNTs) are as follows [26-28]: In the material preparation stage, the author can select and prepare the matrix material based on the polymer, metal or ceramic matrix chosen for the application requirements. Then synthesize or purchase carbon nanotubes with desired properties such as length, diameter and various functional properties. Next, the author need to dispense the carbon nanotubes, a step that can be enhanced by techniques such as sonication, high-shear mixing, or functionalization to disperse the carbon nanotubes in the matrix material. In composite preparation, dispersed carbon nanotubes are mixed with the matrix material using melt mixing, solution mixing, or in situ growth. The composite mixture is processed by compression molding, injection molding, or fiber winding to prepare a block, strip sample, or part. Observations for structural characterization of the composites are carried out using equipment such as scanning electron microscope (SEM), transmission electron microscope (TEM), or atomic force microscope (AFM) to understand the dispersion and arrangement of carbon nanotubes in the matrix. Subsequent evaluations such as mechanical tests (tensile, compression, bending), thermal analyses (DSC, TGA), and conductivity measurements the authorre performed to check the properties of the composites. Processing parameters such as mixing time, temperature and pressure the authorre optimized to achieve the desired dispersion effect and properties. Different carbon nanotube functionalization techniques are also explored to enhance their compatibility with the matrix material and optimize interfacial bonding. Finally, the author evaluate the performance of carbon nanotube-reinforced composites in the direction of the desired application, such as structural components, electronic devices or biomedical implants. Subsequently, long-term durability and reliability tests are performed to assess the stability and other properties of the composites under various environmental conditions.

3. Reinforcing materials

The following are the specific professional steps for incorporating reinforcing materials such as aramid or glass fibers into carbon fiber composites [29, 30]: The author first need to select the appropriate type and size of carbon fiber as the main material, and other reinforcing materials such as aramid or glass fibers. Necessary surface treatments are applied to the aramid or glass fibers to improve their adhesion and compatibility with the carbon fibers and matrix materials. Next, the carbon fibers are mixed with the reinforcing materials such as aramid or glass fibers by dry mixing (e.g., mechanical mixing) or the authort mixing (e.g., impregnation). The ratios and proportions of the various reinforcing materials are adjusted according to the design requirements and performance objectives.

Next, the substrate pretreatment stage is entered, in which suitable substrates such as polymers are prepared and subjected to necessary pre-treatments such as surface activation or addition of binders to enhance their adhesion to the reinforcing materials. Subsequently, the blended reinforcing material is mixed with the pretreated matrix material to ensure uniform dispersion. The mixed materials are then molded into composite samples of the desired shape and size using methods such as compression molding, injection molding, or lamination. The molded composite samples are then

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heat cured to ensure adequate bonding betthe authoren the reinforcement and matrix materials. Surface coating or functionalization is also applied to improve the performance and durability of the composites, as needed. Finally, the author enter the evaluation and optimization stage, where the prepared composite samples are tested for mechanical properties (e.g., tensile, flexural, and impact tests), thermal properties (e.g., thermal conductivity rate and heat loss), and interfacial bonding properties. And based on the test results, the preparation process and material formulation are optimized to achieve the desired performance requirements.

The following are the specialized steps for the use of bio-based resins and matrices in the preparation of sustainable carbon fiber composites with reduced environmental impact [31, 32]: In the first stage, the author select renewable raw materials suitable for bio-based resins, such as vegetable oils, biomass or degradable polymers. And the author select environmentally friendly materials suitable for the matrix such as renewable plastics or environmentally friendly polymers. According to the properties of renewable raw materials, the author select suitable production processes for bio-based resins, such as biomass conversion, biopolymerization, or biosynthesis, and carry out the necessary treatments and functionalization of bio-based resins in order to improve their compatibility and adhesion with carbon fibers and other reinforcing materials. In the matrix pre-treatment stage, the author need to prepare selected environmentally friendly matrix materials to ensure that they meet environmental standards and sustainability requirements. The matrix material is then subjected to necessary surface treatment or addition of appropriate reinforcement to enhance its bonding with the bio-based resin and carbon fibers. Next, the bio-based resin and carbon fiber are mixed the authorll to ensure that the bio-based resin and carbon fiber can be the authorll dispersed. The mixed bio-based resin and carbon fiber material is then molded, typically using extrusion, compression molding, or injection molding, into strips or blocks. The molded composite is then cured to ensure adequate bonding betthe authoren the bio-based resin, the matrix material and the carbon fibers. Post-treatment steps such as surface coating or addition of functional additives are continued to improve the performance and environmental adaptability of the composites. Finally, the author enter the system evaluation and optimization stage, where the prepared bio-based resin composites are subjected to performance tests, including mechanical properties, thermal properties and environmental impact assessment. And based on the test results, the preparation process and material formulation the authorre optimized to improve the performance and environmental friendliness of the composites.

The specialized steps of additive manufacturing technology for complex geometries and structures using carbon fiber reinforced polymers are as follows [33, 34]: This type of composite material is slightly different from others, starting with the design and modeling phase. More complex geometries and structures can be created using computer-aided design software, such as CAD. The next step is conventional material preparation, selecting carbon fiber reinforced polymer materials suitable for additive manufacturing, e.g. resin, rubber. Determine the type of carbon fiber, resin system, and reinforcement needed to meet design requirements and performance goals. Next, the author build the designed geometry and structure layer by layer using additive manufacturing techniques such as 3D printing, laser sintering or composite additive manufacturing. And the appropriate additive manufacturing process is selected according to the design requirements, such as light curing, fused deposition, and hot melt jetting. First, the necessary pre-treatment of carbon fiber reinforced polymers, such as surface activation or addition of adhesives, is required to enhance interlayer bonding and structural stability. Next, complex structures are prepared, i.e., layers of carbon fiber reinforced polymers are stacked and cured using additive manufacturing techniques to create complex geometries and structures. Consideration is given to the type of support structure or

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support material to be used to support or reinforce the manufacturing process of the complex part. Subsequently, the necessary post-processing steps, such as heat treatment, surface coating, or surface polishing, are performed to improve the surface quality and performance of the manufactured part. And quality control and inspection are performed to ensure that the fabricated part meets the design specifications and requirements. Finally, the author need to perform performance tests on the fabricated complex geometries, including mechanical properties, heat resistance, and corrosion resistance. Finally, the test results are analyzed and optimized and improved as needed. The professional steps for functionalizing carbon fiber surfaces are as follows [35, 36]: First, the author need to thoroughly clean the carbon fiber surface using solvents or surfactants to remove grease, dirt and impurities from the surface to ensure a clean surface. Next, the carbon fiber surface is activated using techniques such as chemical methods or plasma treatment to increase the content of reactive groups and improve surface energy and reactivity. This is follothe authord by the functional activation stage, where functional groups or surface modifiers are formed on the carbon fiber surface using methods such as chemical coating, solution impregnation, or vapor phase deposition. Appropriate functionalizing agents, such as silane coupling agents, organic acids, surfactants, etc., are selected according to the nature and requirements of the substrate material. The functionalizing agent solution or gas is covered onto the surface of the carbon fiber, and interacts with the active sites on the surface of the carbon fiber through a chemical reaction to form a chemical bond or cross-linking structure. The functionalized carbon fibers are then cured to ensure that the functionalizer is firmly attached to the carbon fiber surface and forms a stable bond at the interface with the base material. This is follothe authord by two evaluation stages, where the surface of the functionalized carbon fiber is first characterized and analyzed using surface analysis techniques such as scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), or infrared spectroscopy (FTIR). Subsequently, interfacial bond strength tests, such as shear tests or tensile tests, are performed to assess the effect of the functionalization treatment on interfacial adhesion. Finally, the performance is evaluated, that is, the composites composed of functionalized carbon fibers and matrix materials are evaluated in terms of mechanical properties, interfacial properties and durability. Finally, the test results are used to optimize the functionalization treatment process and material combinations to improve the performance and stability of the composites.

4. Advantages and principles of diverse novel carbon fiber composite materials

In recent years, in the field of composite materials, scholars have made significant breakthroughs in new materials related to carbon fiber. Based on the experimental method statement above, the author give the properties and advantages of different carbon fiber composites in this chapter: for example, carbon nanotubes reinforced composites, which can improve mechanical properties and electrical conductivity. Modification of carbon fiber composites using graphene nanosheets improves fracture toughness and fatigue resistance. Hybrid carbon fiber composites incorporating reinforcements such as aramid or glass fibers can help experimenters achieve customized properties. Bio-based resins and matrices can be used to prepare sustainable carbon fiber composites with reduced environmental impact. Additive manufacturing techniques using carbon fiber reinforced polymers for complex geometries and structures can effectively improve material utilization, stiffness and toughness. Researchers can functionalize carbon fiber surfaces to improve interfacial adhesion and compatibility with matrix materials. These latest developments in carbon fiber composites have been widely used in industries such as aerospace, automotive, sporting goods and renewable energy. Next, the author introduce each of these various carbon fiber-related composites separately.

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Carbon Nanotubes (CNTs) are nanostructures composed of carbon atoms that have very high strength and stiffness, as the authorll as excellent electrical and thermal conductivity [37]. There are several reasons why adding carbon nanotubes to composites can improve their mechanical properties and electrical conductivity [38]: Carbon nanotubes have strength and stiffness greater than steel, making them excellent reinforcing materials. When carbon nanotubes are incorporated into the composite matrix in a uniformly dispersed manner, they effectively prevent crack extension, thereby increasing the strength and toughness of the composite.

Since the size of carbon nanotubes is only at the nanometer level, they can form a layer of dense reinforcing network structure in the composite material. This network structure can effectively transfer loads and improve the overall performance of the composite material.

Carbon nanotubes have good interfacial compatibility with a wide range of matrix materials (e.g., polymers, metals, or ceramics), which allows them to be effectively bonded to the matrix, thus enhancing the physical properties of the composites. In addition, the high surface area of carbon nanotubes enables them to effectively adsorb matrix materials, further enhancing the interfacial bonding strength.

Carbon nanotubes themselves have excellent electrical conductivity, so adding them to composites can effectively increase the electrical conductivity of the composites. This is especially important for applications that require electrical conductivity (e.g., electronic devices, sensors, etc.).

5. Graphene nanosheets (GNPs)

Graphene nanosheets (GNPs) are two-dimensional carbon nanomaterials with unique mechanical, electrical and thermal properties [39]. When nanosheets are added to carbon fiber composites, fracture toughness and fatigue resistance can be improved through several mechanisms [40,41]: Graphene nanosheets have high aspect ratios and excellent mechanical properties, including high tensile strength and modulus. When graphene nanosheets are dispersed in the matrix of the carbon fiber composites, they can act as a support, enabling effective connection of cracks and resistance to crack extension. This reinforcing effect increases the energy required for crack initiation and extension, thereby improving the fracture toughness of the composite.

Graphene nanosheets have a large surface area and can form a dense network structure within the composite matrix. This network structure helps in deflecting and absorbing the energy for crack propagation, thereby depleting the fracture energy and slowing down the rate of crack generation. As a result, the composites exhibit higher fracture resistance and enhanced toughness.

The high surface area and unique surface chemistry of graphene nanosheets help establish strong interactions with the matrix material and carbon fibers. This improved interfacial bonding enhances the load transfer betthe authoren the matrix and fibers, reduces the stress concentration at the interface, and improves the overall mechanical properties of the composite.

The two-dimensional structure and high aspect ratio of graphene nanosheets enable them to effectively block the advancement of microcracks within the composite. This barrier effect contributes to the fatigue resistance of the composites by retarding crack generation and slowing down the growth of cracks under cyclic loading conditions.

The addition of graphene nanosheets to the composite matrix helps to reduce pores and defects in the material. Graphene nanosheets can fill the gaps betthe authoren the carbon fibers and increase the filling density of the matrix, resulting in a more uniform and dense microstructure of the material. This effect helps to improve the mechanical integrity and fatigue resistance of the composites. Hybrid carbon fiber composites incorporating reinforcing materials such as aramid or glass fibers offer several advantages [42,43]: By combining carbon fibers with other types of fibers,

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such as aramid or glass fibers, a synergistic reinforcement effect can be obtained in the composite. This is because each type of fiber has unique mechanical properties such as strength, stiffness and impact resistance. So when these fibers are combined, the overall mechanical properties of the composite are improved beyond what can be achieved with a single fiber type.

Composites allow the proportions of material components to be adjusted to meet specific performance requirements. For example, aramid fibers are known for their excellent impact resistance and energy absorption, while glass fibers have high tensile strength and stiffness. Combining these two components with carbon fibers in various proportions allows for the design of balanced performance combinations for a variety of applications.

Cost-effective solutions can be provided by optimizing the use of materials and taking advantage of the unique strengths of different fiber types. While carbon fibers are known for their high strength and quality, they are more expensive. By incorporating less expensive fibers, such as aramid or glass, into composites, manufacturers can achieve the desired performance characteristics at a lothe authorr cost without sacrificing mechanical properties.

Incorporating aramid or glass fibers into hybrid composites can improve damage tolerance and durability. Aramid fibers excel at absorbing impact energy and resisting delamination, while glass fibers increase resistance to microcracking. The increased damage tolerance results in a composite structure that is more resilient to harsh operating conditions and has a longer service life.

This hybrid composite can also improve fatigue performance by diversifying load paths and mitigating damage mechanisms. By distributing loads efficiently and providing alternative paths for crack propagation, hybrid composites can be more resistant to fatigue damage than single fiber composites. This advantage is particularly beneficial in applications where cyclic loading or dynamic stress conditions exist.

The use of bio-based resins and matrices for the preparation of sustainable carbon fiber composites offers the following benefits [44-46]: Bio-based resins are usually derived from renewable resources, such as vegetable oils or cellulose, and their production process generates lothe authorr carbon emissions compared to traditional petroleum-based resins. Therefore, the use of bio-based resins reduces the environmental impact of the composite preparation process.

Compared with petroleum-based resins, bio-based resins have sustainable utilization properties and are less dependent on non-renewable resources, helping to conserve limited natural resources. For example, conventional carbon fiber composites typically use petroleum-based resins as the matrix, while introducing bio-based resins into the composite preparation process can reduce the need for limited petroleum resources.

Improved material recyclability: Bio-based resins and matrices typically have better degradability and recyclability. This means that composites can be more easily recycled and reused at the end of their useful life, helping to reduce waste generation and promote a circular economy.

Preparing sustainable carbon fiber composites helps companies build an environmentally friendly image and meet the growing consumer demand for environmentally friendly products. Therefore, the use of bio-based resins and matrices for the preparation of composites can improve the brand image and market competitiveness of enterprises. Additive manufacturing techniques for complex geometries and structures using Carbon Fiber Reinforced Polymers (CFRP) offer the following advantages [47,48]: CFRP materials are known for their excellent strength-to-lightthe authoright ratio, making them ideal for parts that require lightthe authoright but superior strength. Additive manufacturing techniques can create complex geometries and maximize the strength to lightthe authoright ratio of the end product while using a minimum amount of material.

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Additive manufacturing technologies, such as 3D printing, provide a high degree of design freedom to create custom components with highly complex shapes and optimized performance that are difficult or impossible to produce using traditional manufacturing methods.

The additive manufacturing process is more resource efficient than traditional subtractive manufacturing methods because it deposits material layer by layer only where the author need it. This greatly reduces material waste and makes materials such as CFRP the prime choice for manufacturing complex components.

Additive manufacturing techniques can create homogeneous structures with precise fiber orientation, giving components enhanced structural integrity and mechanical properties. cfrp materials can be structurally supported in critical areas, improving overall component performance and reliability. Additive manufacturing has a shorter lead time than traditional manufacturing methods because it eliminates the step of mold making and reduces lead time. This enables rapid prototyping and an iterative design process that helps accelerate the development cycle and time-to-market of CFRP-based products.

CFRP components can be integrated directly during the manufacturing process, including incorporating, embedding structural health-monitoring sensors or designing complex internal geometries in fluid flow channels.

Functionalizing the surface of carbon fibers to improve interfacial adhesion and compatibility with the matrix material has the following benefits [36]: Functionalization improves the adhesion betthe authoren the carbon fibers and the matrix material, allowing them to bond more firmly together. This helps to reduce the shear stress at the interface and prevent peeling or delamination betthe authoren material layers, thus improving the overall mechanical properties and durability of the composite material.

The treated carbon fiber surface is more compatible with the matrix material, reducing the interfacial energy and surface tension and promoting a better bond betthe authoren the two. This helps to reduce the residual stress and strain concentration at the interface and improve the fatigue and impact resistance of the composite material.

By improving interfacial adhesion and compatibility betthe authoren carbon fibers and matrix materials, functionalization treatments can optimize the properties of composites. This includes improving strength, stiffness, heat resistance, chemical resistance and other aspects of the performance, so that the composite material in a wider range of applications.

Functionalization treatments can also improve the processability of carbon fibers, making them easier to blend, mold and process with matrix materials. This helps to reduce manufacturing costs, increase productivity, and expand the range of applications for carbon fiber composites.

Reduced energy consumption and environmental impact: Since functionalized carbon fiber surfaces can improve the performance and durability of composites, the amount and frequency of materials used can be reduced, thereby reducing energy consumption and environmental impact.

6. Conclusion

This review has comprehensively explored the significant advancements in carbon fiber composites, highlighting their increasing importance across diverse industries such as aerospace, computing, and renewable energy. The author have delved into key innovations, including the synergistic fusion of distinct carbon materials, the strategic integration of hybrid fibers, and the critical emphasis on material sustainability. Furthermore, the author examined sophisticated fabrication techniques and novel functional enhancement methods that are collectively pushing the boundaries of composite material science. For each area of focus, the author detailed the preparation methodologies and

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elucidated their inherent advantages, providing a holistic understanding of the current state-ofthe-art. Through a thorough examination of the relevant literature, the author identified several persistent challenges that warrant further investigation. These include the complexities associated with the dispersion and recombination of nanomaterials, the intricate optimization of material interactions at various scales, ensuring consistency in fabrication processes, and enhancing the long-term stability of these advanced materials. In light of these findings, the author propose several constructive avenues for future research and development. A particularly promising direction involves the expanded application of computer-based and mathematical techniques for the comprehensive evaluation of material properties and the discovery of novel approaches. The author firmly believe that the continued integration of computational modeling, alongside concrete experimental realizations, will significantly accelerate the real-world applications and transformative potential of carbon fiber composite materials. This ongoing evolution promises to deliver materials with unprecedented performance characteristics, driving innovation and sustainability in numerous technological domains.

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