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PERFORMANCE OPTIMIZATION STRATEGY FOR CARBON FIBER REINFORCED ALUMINUM MATRIX COMPOSITES

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Abstract: Carbon fiber reinforced aluminum matrix composites (Cf/Al) are highly sought after for their exceptional strength, modulus, and light weight, making them ideal for aerospace and automotive applications. However, the inherent differences in physical and chemical properties between carbon fibers and the aluminum matrix present significant challenges for achieving optimal interfacial bonding, ultimately limiting the composite's performance. This paper investigates strategies to enhance the interface in Cf/Al composites, with a particular focus on carbon fiber copper plating and wettability improvement methods. Experimental data analysis demonstrates the effectiveness of these methods in improving interfacial bonding and wettability, leading to enhanced overall mechanical properties, electrical conductivity, and corrosion resistance of the composites. The research underscores the critical role of interface optimization in unlocking the full potential of Cf/Al composites for broader applications in high-performance engineering sectors. Additionally, this paper explores various liquid-phase composite preparation processes, including diffusion bonding, pressure impregnation, and pressure less infiltration, comparing their advantages and limitations in terms of efficiency, cost, and composite properties. This review concludes by emphasizing the significance of interface optimization and highlighting the potential for further research in areas such as mechanism understanding, systematic studies, process optimization, environmental friendliness, and long-term performance stability to advance the field of high-performance composite materials.
Keywords: Electroless plating; Cf/Al; Composite material; Wettability

1 INTRODUCTION

Carbon fiber-reinforced aluminum composites are popular in aerospace and automotive manufacturing. They have excellent mechanical properties and are lightweight. However, issues at the interface between the carbon fiber and aluminum matrix, like low wettability and different thermal expansion coefficients, limit their performance. Researchers have developed many surface treatment techniques and liquid phase composite preparation processes to improve interfacial bonding. These include electroless copper plating and diffusion bonding. This paper will review these strategies, with a focus on carbon fiber copper plating and wettability improvement techniques. The review aims to provide a reference for the research and application of carbon fiber aluminum matrix composites.

Carbon fiber-aluminum matrix composites have great potential for use in many fields. They combine the high strength and modulus of carbon fibers with the light weight and corrosion resistance of aluminum matrices. However, interfacial issues restrict their performance. The carbon fiber has low surface energy, which leads to poor wettability with aluminum. This results in insufficient interfacial bonding strength and affects the overall performance of the composite material. To overcome these challenges, researchers have explored various surface treatment techniques, such as chemical copper plating and composite material addition, to improve the interfacial bonding and wettability of carbon fiber and aluminum matrix. This paper will focus on these optimization strategies to provide a valuable reference for the research and application of carbon fiber aluminum matrix composites. Applying these techniques enhances the mechanical properties of the composite material. Adding carbon fiber increases the hardness of the aluminum matrix composite by 14%–22%. Chemical copper plating increases the hardness by an additional 23%–26%. Copper plating also raises the material's tensile strength by about 15% and its elastic modulus by about 10% [1]. It also improves its electrical conductivity and corrosion resistance. Electroless copper plating treatment increases the interfacial bond strength of a carbon fiber-aluminum matrix composite by about 50% compared to an untreated sample. It also raises the electrical conductivity by about 20% [2]. Current research has made progress in optimizing the interface, improving performance, and expanding applications of carbon fiber-aluminum matrix composites. However, more research is needed in areas such as mechanism understanding, systematic studies, further application expansion, process optimization, environmental friendliness, and long-term performance stability.

2 STRATEGIES FOR ENHANCING CARBON FIBER ALUMINUM COMPOSITES

2.1 Liquid-Solid Preparation Technique

Liquid-solid forming technology is a key process in making carbon fiber-aluminum matrix composites. It is gaining interest for its cost-effectiveness and ability to create parts with complex shapes.

Stir casting is a method for uniformly dispersing carbon fibers in liquid aluminum or its alloys. This is achieved by mechanical stirring. The method includes full liquid, semi-solid, and stir casting. Stir casting has advantages such as simplicity, low cost, and high productivity. It also allows for secondary processing. Experiments have shown that the content of carbon fibers significantly affects the mechanical properties of the composite material. When the content reaches 8wt%, the tensile strength and yield strength reach 219MPa and 171MPa respectively, and the elongation is 9.3%, which is the peak performance. However, beyond a certain threshold, increasing the carbon fiber content to 10wt% leads to a decrease in the material's strength to 209MPa and 189MPa. Additionally, the elongation decreases to 8.2%. [3]. An excessively high carbon fiber content can lead to poor dispersion and affect the material properties. We can improve the dispersion of carbon fibers and interfacial bonding by optimizing parameters. These parameters include stirring speed, time, mold preheating temperature, and pouring temperature.

Squeeze casting is a process where liquid aluminum metal is forced into a pre-heated carbon fiber preform by applying external mechanical pressure. After solidification, a composite material is formed. This method is cost-effective and suitable for mass production. The right pressure improves the wettability between the carbon fiber and aluminum metal. This reduces the interfacial reaction and makes the structure of the composite material more compact and uniform. To obtain the best composite properties, key parameters such as extrusion pressure, holding time, and preform preheating temperature can be optimized. The vacuum hot pressing method involves using a furnace called OTF-1200X-VHP4. This furnace applies high pressure in a vacuum. It allows for precise control of parameters like pressing temperature, pressure, and time. This precision helps create high-quality carbon fiber reinforced aluminum matrix composites. Orthogonal experiments have led to the discovery of the best hot pressing process parameters. These parameters include a hot-pressing temperature of 510°C, a hot-pressing time of 180 minutes, and a hot-pressing pressure of 15 MPa. Under these conditions, the tensile strength and density of the resulting composite reached 286.98 MPa and 99.92%, respectively [4], showing excellent mechanical properties.

The hot pressing and diffusion method is a key solid state forming technology for preparing carbon fiber-aluminum matrix composites. The process utilizes high temperatures and pressures. These conditions create an atomic-level bond between the carbon fiber and the aluminum matrix. This bonding strengthens the interface connection. As a result, the material's strength, corrosion resistance, and wear resistance all improve. The process includes steps such as pretreatment, layering, mixing, hot pressing and post-processing. The pretreatment stage is key for carbon fiber and aluminum matrix bonding. It involves surface treatment and precise control of temperature, pressure, and time. Experiments show that at a 45% carbon fiber volume fraction, the composite's tensile strength is 856MPa at room temperature and 774.7MPa at 350°C. Its tensile modulus is 204.3GPa at room temperature and 197.3GPa at 350°C. The average density is 98.86%, the interface bonding is good, and the Al_4C_3 content, a reaction product at the interface, is low [5]. The data indicate that the hot press diffusion method can enhance the properties of carbon fiber-aluminum matrix composites. This is achieved by optimizing the process parameters. It offers an effective method to produce high-performance, low-cost composites.

Stir casting, squeeze casting, and hot press diffusion are methods for carbon fiber-aluminum composites. Stir casting is cost-effective for mass production but has challenges with dispersion and bonding. Squeeze casting provides a uniform structure with good wettability but requires precise parameter control. Hot pressing and diffusion offer strong interfacial bonding but are energy-intensive and costly. Choosing the right method depends on performance needs, cost, and efficiency.

2.2 Liquid-Phase Composite Preparation Technique

Carbon and aluminum differ significantly in physical and chemical properties like melting points and thermal expansion coefficients. These differences make direct composite challenging and demand special preparation processes. Presently, the liquid phase composite preparation processes for carbon fiber-aluminum matrix composites fall into three categories: diffusion bonding method, pressure impregnation method, and pressure less infiltration method.

Diffusion bonding is a pressurized heating treatment method used in a vacuum environment. It arranges carbon fibers and aluminum foil layer by layer to prevent unwanted interfacial reactions. The heating temperature is controlled below the melting point of the aluminum substrate. Diffusion bonding joins the substrate and carbon fibers, resulting in carbon fiber-aluminum matrix composites. These composites have a controlled reinforcement phase distribution, high density, and excellent mechanical properties. High equipment costs and slow forming speeds restrict mass production. Nevertheless, research demonstrates that adjusting parameters such as hot-pressing temperature, time, and pressure can improve composite performance. The bonding strength of acid- and alkali-treated carbon fibers to the aluminum substrate can exceed 1.5 times that of untreated carbon fibers. Vacuum heating treatment effectively removes gases and impurities at the interface, increasing the interfacial bonding strength to over 1.2 times that of untreated composites. Experiments show that at the optimal hot-pressing temperature of 560°C, with a duration of 35 minutes and a pressure of 30 MPa, the Al_4C_3 content in the prepared composite material is only 1.3%. This further demonstrates that the properties of the composite material can be significantly improved through precise adjustment of the process parameters [6].

Pressure impregnation is a method for preparing composites. It is used for items like sheets, rods, and tubes in various sizes. Aluminum is pressed into preheated carbon fiber preforms using hydraulic pressure. This method controls the density and volume fraction of the reinforcement phase to optimize properties. However, high pressure can damage the carbon fibers and impact the mechanical properties. Preheating and lubrication can be used to prevent damage. Preheating makes the carbon fibers softer, while lubrication reduces friction. Experiments show that adjusting process parameters and pre-treatment measures can enhance composite performance. For instance, preheating the carbon fiber preform at 600°C, infiltrating at 780°C, and infiltrating at a pressure of 1.5MPa followed by rapid cooling with water led to the best properties in the carbon fiber-aluminum matrix composite. The material showed no defects like porosity. The flexural strength exceeded 1400 MPa, the specific strength and specific are 667 (MPa·cm^3/g) and 110 (GPa·cm^3/g), respectively. The longitudinal thermal expansion coefficient is (0–2) × 10^{-6}/°C, and the transverse thermal expansion coefficient is (17–20) × 10^{-6}/°C [7].

The twin-roll casting process is a new method for preparing carbon fiber-aluminum matrix composites. It has the advantages of being continuous and efficient, and is expected to enable mass production. By reasonably selecting process parameters such as the casting speed and pouring temperature, the thickness, density and wettability of the composite material can be controlled. At a volume fraction of 6.8% carbon fiber, the composite material achieved a tensile strength of 137.1MPa. This is a 182% increase from the matrix's tensile strength. Furthermore, it was found that the composite material's interface structure could be improved by heat treating it in a vacuum atmosphere, which may further enhance its performance. After interface optimization, the tensile strength of the composite material reached 155.6MPa [7]. The process parameters of this technology are complex to control and require further research and optimization to achieve more efficient mass production.

Diffusion bonding, pressure impregnation, and double roll casting are primary methods for fabricating carbon fiber-aluminum composites, each with unique traits and uses. Diffusion bonding, in a vacuum, bonds the materials through controlled heating and time, resulting in high-density, mechanically strong composites, but it's costly and slow. Pressure infiltration uses external pressure to push aluminum into preheated carbon fiber preforms. It can fit various sizes but may damage fibers with excessive pressure. Double roll casting is a new and efficient method for mass production. However, it requires precise parameter control. Choosing the right method involves considering factors such as efficiency, cost, and composite properties.

3 INTERFACE OPTIMIZATION FOR CARBON FIBER ALUMINUM COMPOSITES

3.1 Carbon Fiber-Reinforced Aluminum with Copper Plating

Copper plating causes solid solution strengthening and second phase strengthening. Cu-Cf/Al composite with 1% carbon content is harder and more ductile than Cf-Al material. The copper-carbon fiber composite has high hardness due to the SPS sintering process. Copper atoms from the carbon fiber's copper plating can diffuse into the aluminum matrix during this process. This diffusion leads to solid solution strengthening, which significantly increases the composite's hardness. Intermetallic compounds such as AlCu and Al_2Cu may also form at the carbon fiber interface. These compounds contribute to a second-phase strengthening effect in the composite material. As the carbon fiber content increases, the strengthening effect becomes more pronounced [8]. As shown in Table 1. Intermetallic compounds such as AlCu and Al_2Cu are formed in Cu-Cf/Al composites. These compounds are distributed as fine particles. They are positioned between the carbon fibers and the aluminum matrix. Their presence strengthens the composite. Additionally, they increase the hardness of the composite material [8].

Table 1 Vickers Hardness of The Sample (HV)

Sample	Vickers hardness (HV)
AL	41.03
0.5%Wt C_f/Al	47.24
1.0%Wt C_f/Al	50.18
0.5%Wt Cu-C_f /Al	58.35
1.0%Wt Cu-C_f /Al	63.12

Copper plating strengthens the interface bonding by completely surrounding the carbon fiber. This enhances the bond between the matrix and the carbon fiber and improves wettability. After copper plating, the carbon fiber surface is covered with a copper layer, preventing chemical reactions with the aluminum substrate. This reduces contact between them, leading to improved bonding between the reinforcement and the matrix metal. The result is a high-quality interface structure and bonding strength. The original carbon fiber surface is smooth, but copper plating forms a uniform and dense copper layer on it. This prevents direct contact between the carbon fiber and the aluminum substrate, avoiding interface reactions. Copper plating significantly improves interfacial bonding by creating a copper layer on the carbon fiber surface. The copper layer enhances wettability and promotes bonding between the carbon fiber and the aluminum substrate. A tight interface bond, such as the one shown in Figure 1, is beneficial. It allows for the effective transfer of loads. These loads are between the carbon fiber and aluminum matrix. This transfer improves the overall performance of the composite [9].

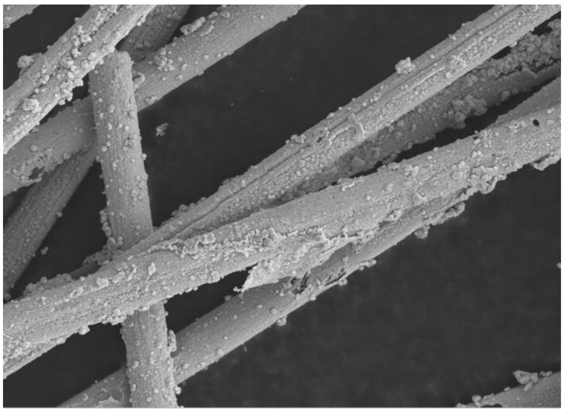

Figure 1 Microstructure of Carbon Fiber Coated with Copper

Carbon fiber copper plating technology is a reinforcement phase modification method that significantly impacts the mechanical properties of composite materials. Studies show that copper plating on carbon fiber surfaces improves the interfacial bonding between fibers and the resin matrix. This, in turn, enhances the overall performance of the composite material. The copper plating layer optimizes the interfacial structure and reduces defects, thereby increasing bond strength. This stronger bond allows for more effective load transfer, maximizing the reinforcing effect of carbon fibers. As a result, the composite material's ductility, fatigue resistance, and impact resistance improve. In the composite material, carbon fibers are evenly dispersed within the resin matrix, creating a strong interfacial bond. The addition of copper-plated carbon fibers helps to effectively distribute external loads throughout the composite material, preventing stress concentration. When an external force acts on the composite material, the copper-plated carbon fibers can withstand some of the load. They then transfer this load to the resin matrix via the interface. This mechanism of load distribution not only enhances the ductility of the composite material but also improves its fatigue resistance and impact resistance. Figure 2 shows the fracture morphology of C_f-Cu/Al with a carbon content of 1%. Pull-out phenomena in fracture morphology are relatively rare. This indicates that the carbon fiber can effectively bear and disperse the load. This prevents material damage under external forces when the composite material is subjected to tensile load. The load dispersion mechanism improves the ductility of the composite material. It also enhances its fatigue resistance and impact resistance [10].

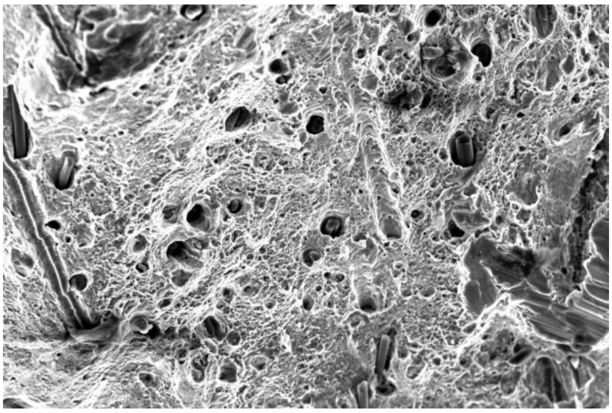

Figure 2 C_f-Cu/Al with 1% Carbon Content

3.2 Improve Wettability of Composite Materials

Wettability is the ability of a liquid to spread over a solid surface and form a stable contact angle. It is an important parameter for evaluating the interaction between a liquid and a solid interface. In carbon fiber reinforced aluminum matrix composites, wettability is a key factor determining the interfacial bond strength and the overall material performance. Good wettability helps the liquid form a uniform and dense coverage on the solid surface. This enhances the interfacial bond. It also improves the mechanical and durability properties of the material. The contact angle is an important parameter for measuring wettability. The smaller the value, the better the wettability of the liquid on the solid and the stronger the interaction between the two. Contact angle measurement can be used to evaluate the free energy of a solid surface. It can also assess the interaction between a liquid and a solid. This provides a basis for optimizing the properties of composite materials. In practice, a contact angle meter can be used to measure the contact angle of a liquid on a solid surface. The instrument usually consists of a micro-syringe, a high-precision stage and a high-resolution camera. The liquid is dropped onto the solid surface using the micro-syringe, and the shape of the drop is captured using the camera. The contact angle is calculated using image analysis software. During the preparation of carbon fiber aluminum matrix composites, the wettability between the carbon fiber and aluminum matrix can be improved. This can be done by optimizing the surface treatment of the carbon fiber and the pre-treatment of the aluminum matrix. By doing so, the interfacial bond strength and overall performance of the composite can be improved. [11].

Wettability is crucial for interfacial bonding in carbon fiber-aluminum matrix composites. Interfacial bonding involves the adhesive strength between the carbon fiber and the aluminum matrix. This strength directly impacts the overall performance of the composite material. It includes mechanical properties, thermal properties, and corrosion resistance. Good wettability allows the aluminum matrix to cover and penetrate the carbon fiber surface effectively. This creates a uniform and compact interface layer. The uniform interface layer provides strong mechanical interlocking and chemical bonding. It enhances the interaction between the carbon fiber and the aluminum matrix. As a result, it improves the interfacial bonding strength of the composite material. If the wettability is poor, the aluminum matrix cannot fully cover the surface of the carbon fiber. This results in voids and defects at the interface. These voids and defects weaken the interfacial bonding and reduce the performance of the composite material. In practical applications, the surface energy of the carbon fibers can be improved. Their wettability with the aluminum matrix can be enhanced by surface treatment techniques. These techniques include chemical treatment, plasma treatment, or coating technology. In addition, the wettability of the aluminum matrix with the carbon fibers can be optimized. This can be done by selecting suitable parameters for the melt infiltration process. These parameters include temperature, pressure, and time. By doing so, the quality of the interfacial bond can be improved. Wettability is a key factor affecting the interfacial bond of carbon fiber-aluminum matrix composites. By optimizing wettability, the interfacial bond strength of the composite material can be significantly improved, thereby improving its overall performance [12].

Chemical plating, plasma treatment, or coating technology can increase the surface energy of carbon fibers. These methods can also improve the wettability of the aluminum substrate to the carbon fibers. Using chemical copper plating can improve the bonding strength of the interface between the substrate and the plating and improve wettability, as shown in Figure 3 (a). For the fusion impregnation process, the wettability of the aluminum substrate to the carbon fibers can be improved. This can be done by adjusting the temperature, pressure, and time during the fusion impregnation process. A moderate increase in temperature and pressure can reduce the surface tension of the molten aluminum. This reduction promotes its spreading and penetration on the surface of the carbon fiber, as shown in Figure 3 (b). Add a small amount of surfactant or wetting agent to the aluminum matrix. This will reduce the surface tension of the molten aluminum. This can improve its wetting ability on the carbon fiber. These additives can form an intermediate layer between the molten aluminum and the carbon fiber to promote good contact between the two. Interface modification can improve the wettability and interfacial strength of the interface. This can be achieved by introducing an interface modification layer. Examples of such layers include a ceramic coating or an intermetallic compound layer. These layers are placed between the carbon fiber and the aluminum substrate. These modification layers can provide mechanical and chemical bonding to enhance the interfacial bonding. Figure 3 (c) shows the surface of the carbon fiber grafted with graphene oxide. Through the above strategies, we can effectively improve the wettability of carbon fiber aluminum matrix composites. This improvement enhances the interfacial bond strength and overall performance. The enhancement is of great significance for the application of carbon fiber aluminum matrix composites in high-end engineering fields [13].

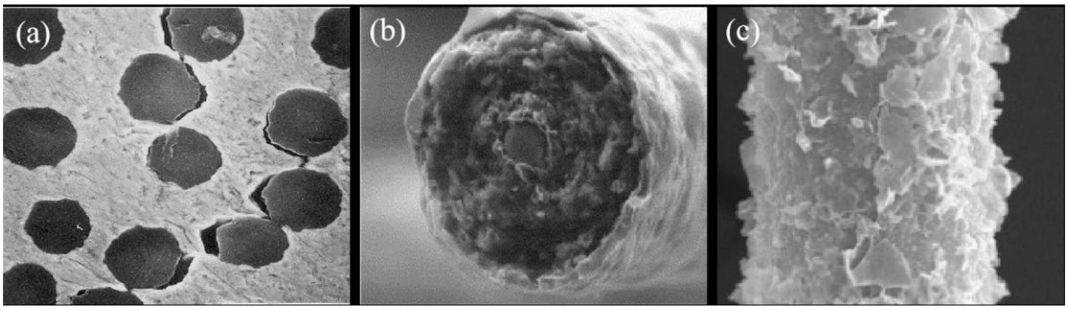

Figure 3 The Form of Carbon Fibers under Different Surface Treatments: (a) Interface between Copper-Plated Carbon Fiber and Copper Matrix; (b) Nickel-Plated Carbon Fiber 800°C Heat Treatment; (c) Graphene Oxide Grafted on a Carbon Fiber Surface

Improving wettability is a key step for optimizing material properties comprehensively. Wettability in materials science is the ability of a liquid to form a stable contact on a solid surface. It directly affects the bond strength and overall performance at the material interface. By optimizing wettability, you can significantly improve the mechanical, thermal, and chemical stability of materials. For example, in composite materials, improving fiber and substrate wettability through surface treatment technology enhances interface bonding. This improves the tensile strength and toughness of the composite material. In metal coating applications, optimizing the wettability of the coating material ensures good adhesion between the coating and the substrate. This enhances corrosion and wear resistance. In electronic materials, improving the wettability of conductive paste to the substrate can improve the conductivity and reliability of the printed circuit. In biomaterial applications, optimizing the wettability of biocompatible materials can enhance their affinity with biological tissues. This improves the biocompatibility and functionality of implantable materials. Improving wettability is an important strategy for optimizing material properties comprehensively. By precisely controlling wettability, we can effectively improve the performance of materials. This improvement applies to various application fields. It promotes progress and innovation in materials science [14-15].

4 CONCLUSIONS

Carbon fiber reinforced aluminum matrix composites are ideal for aerospace and automotive applications. They offer high strength, modulus, and light weight. These properties are complemented by aluminum's electrical conductivity. However, there is a stark contrast in physical and chemical properties between carbon and aluminum. This includes melting points and thermal expansion coefficients. Because of this contrast, specialized preparation methods are necessary for effective compounding. Liquid-phase preparation methods are used for these composites. These methods include diffusion bonding, pressure impregnation, and pressure less infiltration. Each method has its own benefits and drawbacks. The choice of method depends on application needs and cost considerations. Improving the interface between the carbon fiber and the aluminum matrix is crucial for enhancing composite performance. Strategies like copper plating on carbon fibers and enhancing wettability can effectively increase interfacial bond strength and overall composite performance. After copper plating, the composite material shows significantly improved interfacial bond strength and fewer pull-out phenomena in fracture morphology. Techniques such as stir casting, squeeze casting, and hot-pressing diffusion are used for liquid-solid preparation. Diffusion bonding, pressure impregnation, and two-roll casting are used for liquid-phase preparation. These techniques can significantly enhance composite wettability and interfacial bonding. Advances in preparation and interface optimization are expected to expand the use of carbon fiber aluminum composites. This expansion is expected across various industries.

CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

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