Short Communication

Resistance Welding of CF/PEI Composites by a Novel Implant of Flame-grown Carbon Nanotubes Grafted Carbon Fibers

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Abstract

Objective: Interface enhancement between resin and fiber has been a longstanding goal for manufacturing composite material. Using carbon nanomaterials in combination with macro-materials for composite materials is an important application of advanced manufacturing technology.

Methods: This study examined the use of carbon nanotubes (CNTs) wrapped carbon fibers (CFs) (CFs@CNT), a cross-scale composite component incorporating CNTs and CFs, as an implant for resistance welding of composites containing carbon-fiber-reinforced polyetherimide (CF/PEI).

Results: The correlation of growth time ($t_g$) on growth morphology of CNTs on implant and strengths of joints were studied. The surface of CF was gradually covered by CNTs and finally completely wrapped, and CNTs appeared as multi-walled CNTs. The interface structure of resistance welded joints and their mechanical properties were evaluated. The PEI resin was sufficiently melted and obtained a perfect bonding joint with stronger mechanical properties when $t_g$ was 2min and 3min. The cracks were found at the edge of the bonding interface and a collapse first appeared in joint when $t_g$ was 4min and 5min, respectively. The defects were caused by the accumulation of amorphous carbon at the top of the CNTs. The strength of joint welded by CFs@CNT implant increased to 37.8MPa compared with the joint obtained by pure CFs implant alone only 24.2MPa when $t_g$ was 3min.

Conclusion: The purpose of strengthening the joint was achieved by improving the wettability of PEI resin on CFs@CNT lead to the CFs was fully wrapped by molten resin during welding process.

Keywords: resistance welding, implant, CFs@CNT, CF/PEI composite, mechanical property
1 INTRODUCTION

Due to its low cost and ease of operation, resistance welding has shown great potential for joining and repairing resin matrix composites [2-5]. Common resin matrix composites include carbon-fiber-reinforced polyetherimide (CF/PEI) or glass-fiber-reinforced polyetherimide (GF/PEI), carbon-fiber-reinforced polyphenylene sulfide (CF/PPS) and carbon-fiber-reinforced epoxy (CF/epoxy) [6-9].

During resistance welding, heating implant is necessary to melt the thermoplastic resin, which usually including carbon fiber (CF) bundle, metal mesh and carbon nanomaterials [10]. Stainless steel (SS) mesh can alleviate the above problems due to its regular structure and high mechanical properties. The GF/PEI welded joint manufactured by SS mesh implant usually was close to 35MPa [7]. To further improving the surface wetting and interface bonding strength of the resin on SS, several surface treatments were implemented and compared. Surface modification of SS mesh implant by an easy etched treatment can obtain a GF/PEI welding joint with 35.44MPa, and had a 27.7% increase than that of the welding joints with untreated SS mesh implant [8]. Three kinds of surface treatments were adopted on SS mesh surfaces and compared the carbon fiber reinforced polyetheretherketone (CF/PEEK) welded jointed, including sandblasting, aryl diazonium grafting and silane grafting [10]. Compared to other surface modifications, silane grafting worked best for resistance welding CF/PEEK joints. A bivalent molecule was applied to prepare an organic coating on the SS mesh surface form a study by Rohart et al. [11], and then evaluated mechanical property of resistance welded CF/PPS joints. An improvement of 32% of joint strength was found with the treated SS mesh relative to the joints with untreated SS mesh.

According to above researches, the bonding interface of the resin and SS surface is a key problem for a reliable welding joint. Compared with surface treatment, surface grafting is a more promising method because it does not require damage the SS surface. The carbon nanomaterial shows potential to improve the strength of the fiber/resin interface by grafting nanomaterial on fiber [11-13]. For the resistance welding, the carbon nanotubes (CNTs) and graphene were used as interface intensifier grafted on SS surface. To improve the bonding interfacial strength between SS wire and PEI resin, the CNT-modified SS mesh was created as a heating implant to apply in the resistance welding of GF/PEI composites. The maximum shear strength of the welded joint reached to 39.2MPa [14]. The graphene oxide nanosheets were introduced on the surface of the heating element and uniform distribution, the welded joints obtained a best lap shear strength (LSS) about 39.5MPa, implied that the strength value increased by 35.8% [15].

As a representative metal mesh implant, the SS mesh can bring a uniform temperature distribution, but it causes joint weight gain and stress concentration. The CF bundle was considered the most promising implant to relieve above problems due to its homogeneity with the base material, while the bonding interface is also a key focus. In this work, a cross-scale implant of CNTs and macroscopic CFs was proposed to apply in resistance welding of CF/PEI composite. The CNTsgrafted CFs implant was obtained by flame-grown mothod. The morphology of grown CNTs and mechanical property of joints were discussed in turn.

2 MATERIALS AND METHODS

The CF/PEI composite laminate was prepared as the welding specimens by a traditional hot-pressing process. Figure 1A showed the evolution process of the surface morphology on CFs. The pure CFs bundle implant as the substrate for the growth of CNTs, and Ni(NO$_3$)$_2$·6H$_2$O was used as a catalyst. A rich carbon source and a high temperature condition was simultaneously provided by the ethanol fuel for the growth of CNTs on the surface of CFs. Whole preparation process of CNTs on CFs was followed: (1) The CF implant were cleaned in ethanol within a ultrasonic for 5min and then it was dried in air; (2) A Ni(NO$_3$)$_2$ ethanol solution formulated as 1mol/L was uniformly sprayed on the CFs surface, and then was dried at a 60°C environment for 30min; (3) The CFs implant covered with Ni(NO$_3$)$_2$ catalyst were placed in the flame, which had a temperature was between 700-900°C and kept for 1, 2, 3, 4 and 5min, as Figure 1B. The final implant was prepared by above mothod had a composite structure composed by the CNTs wrapped CFs (CFs@CNT).

The dimensions CF/PEI laminate was cut as 100mm×25mm×2mm as the welded specimens. The CFs@CNT composite implant was sandwiched by the two PEI resin films to construct a PEI/CNT-CFs/PEI component. The PEI/CFs@CNT/PEI component with a three-layer composite structure was added into a single lap CF/PEI laminate joint. A uniform initial pressure of 0.2MPa was applied at welding position (Figure 1C). The input power was 150W (including current and voltage were 10A and 15V, respectively), which was exerted on composite implant. A suitable heating period was set as 60s, and then cooled down to room temperature.

The microstructure and morphology of the interface and failure surface of the welding joints were observed by the scanning electron microscopy (SEM, FEI-Quanta 200). The element distribution was characterized by an equipment of energy dispersive X-ray spectroscopy (EDS). Transmission electron microscopy (TEM, FEI, Strata 400S) with EDS was used to characterize the interface structures. The apparent shear strength of the single lap welded joints were evaluated using mechanical property tests. Six samples were tested for each condition using an electromechanical testing machine (Instron-5569) and a test speed of 0.5mm/min. Interfacial shear strength (IFSS) of CF/PEI resin was tested with the
aid of a TA company Q800 film tensile model with a force loading rate of 0.5N·min⁻¹.

3 RESULTS AND DISCUSSION

The surface morphologies of different implants were shown in Figure 2. Seeing from Figure 2A, the surface of pure CFs was every smooth. The CNTs grew on the surface of the CFs with different growth times ($t_g$) in a nonuniform mode by the flame method are shown at Figures 2B-2F. The disordered tangled CNTs covered on the original
smooth CFs. When t_g are 1min and 2min, CNTs dispersed on the surface of CFs (Figure 2B and 2C). When t_g is 3min, the CNTs completely covered the surface of CFs (Figure 2D). In Figure 2E and 2F, the CNTs are covered completely by the amorphous carbon when t_g is longer than 4min. From the large image of Figure 2D, the CNT cluster composed by multiple CNT wires can be observed clearly (Figure 2G). The morphological observations from the TEM image demonstrates that CNTs with different diameters are multi-walled CNTs (MWCNTs) (Figure 2H).

Figures 3A-3D shown that the typical microstructures of the welding interface of CF/PEI composite under different t_g (2, 3, 4, 5min). The welding joint mainly was composed by two distinct parts, including CF/PEI laminates and bonding layer at the middle of the weldment. For the joints with t_g=2min and 3min, the PEI resin sufficiently melted and wetting the surface of CFs to obtained a perfect joining joint with stronger mechanical properties, final obtaining an excellent bonding interface (Figure 3A and 3B). When t_g was 4min, some cracks were found at the edge of the bonding interface (Figure 3C). When t_g reached 5min, a collapse first appeared in joint (Figure 3D). The cracks and collapses within the implant were typically defect of the composite welding interfaces. The defects were caused by the accumulation of amorphous carbon at the top of the CNTs. The cracks and collapses lead to a deteriorate of mechanical properties of the joint.

The mechanical performance was crucial for verifying the above manufacturing process of resistance welding joints. Figure 3E shows the LSS of the tensile joints, which shown a trend of first increasing and then decreasing. For the joint manufactured by pure CFs element, the LSS of the joints only reached 24.2MPa. The joint obtained by pure CNT graft-CFs element with t_g of 1min shown a similar value with the joint manufactured by pure CFs element. When t_g of CNT on CFs element rose to 2min, the LSS increased to 34.7MPa. The LSS of joint addition of CNTs reached maximum 35.8MPa when t_g was 3min. Above result proved that the LSS of the joints with CNTs for different t_g values were obviously higher than those of the joints without CNTs when t_g was less than 4min. The surface modification of CFs by coating flame-grown CNT layer was a very effective method to improve the welding joint strength of the CF/PEI laminate. However, the LSS of joint decreased to 26.3MPa when t_g was 4min, and further the LSS of joint continued to decline to 11.2MPa when t_g increased to 5min. It had been proved that amorphous carbon increased on the surface of CNTs due to prolonged deposition, which prevented the wetting and spread of the resin. Interface bonding deteriorated due to above reason.

The CNTs is beneficial for improving wettability of PEI resin on the CFs (Figure 4A), which had been proved in other studies \[16-18\]. The capillary action played an important role when the PEI resin solution contacted the high porosity CNTs coating for wetting process. The nanogap of CNTs enhanced the filling capacity of the resin, and spreading wetting was achieved rapidly. So, following CNT grafting, CFs became easier to wet with PEI resin. The molten PEI resin can fully wet and wrap the CFs surface during welding process, which lead to a good welding interface and finally manufacturing a welding joint with the excellent mechanical properties. In addition, the CNTs on the surface of the CFs can act as interface enhancement connector of the CF/PEI composite and CFs of implant and played a nano reinforce effect for enhancing their interface strength (Figure 4B).

IFSS was used to measure the interfacial bonding strength between the single CF and PEI resin by pull-out test. The IFSS experimental apparatus and process are shown in schematic, a PEI resin droplet adhered circumferentially on the outer surface of CF are peeled off by the blade under loading from the metal clamp. The IFSS
of the pure CF/PEI without CNTs was only 4.12MPa, while that of CNTs-incorporated CF/PEI reached 6.68MPa. It indicated an improvement of the intralayer strength of the CF/PEI implant and the welded joint strength (Figure 4C).

SEM images of fracture surfaces indicated that PEI resin adhering to the surface of CF was drawn as some filaments during the mechanical properties test process. The PEI resin was not unstacked, which exhibited more ductility during the fracture process. These results proved that the interface strength was reliable, there existed improved interfacial adhesion between the CFs and PEI resin matrix due to enhancement effect of CNTs (Figure 4D). Other studies have proved that the synergetic effects of multiscale reinforcements consisted by the CFs and the CNTs showed a potential improving effect to the overall properties of bonding interface like Figure 4E[19-23].

4 CONCLUSION
In this work, a cross-scale implant of CNTs and macroscopic CFs was applied to resistance welding of CF/PEI composite. The surface of CF was gradually covered by CNTs and finally completely wrapped with increase of \( t_g \), and CNTs appeared as MWCNTs. The PEI resin was sufficiently melted and obtained a perfect bonding joint when \( t_g \) was 2min and 3min. The cracks appeared at the edge of the welding interface and a collapse first appeared in joint when \( t_g \) was 4min and 5min, respectively. The defects were caused by the accumulation of amorphous carbon at the top of the CNTs. The CFs@CNT implant prepared by flame method were used to synergistically enhance the welding joint, and the joint strength increased by 47.9% compared with the joint obtained by CFs implant alone when \( t_g \) was 3min. The CNTs achieved the purpose of strengthening the joint by improving the wettability of PEI resin on CFs lead to the molten resin in the welding process can fully wrap the CFs.

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Not applicable.

Conflicts of Interest
The authors declared that they have no known competing financial interests or personal relationships.

Author Contribution
In this study, Jiao M was responsible for data curation, formal analysis, investigation, methodology, and writing the original draft. Wang D supervised the work and contributed to writing review and editing. Zhao P contributed to methodology, supervision, and writing review and editing. All authors approved the final version of the manuscript.

Abbreviation List
CF, Carbon fiber
CF/epoxy, Carbon-fiber-reinforced epoxy
CF/PEEK, Carbon fiber reinforced polyetheretherketone
CF/PEI, Carbon-fiber-reinforced polyetherimide
CF/PPS, Carbon-fiber-reinforced polyphenylene sulfide
CFs@CNT, CNTs wrapped CFs
CNTs, Carbon nanotubes
EDS, Energy dispersive X-ray spectroscopy
GF/PEI, Glass-fiber-reinforced polyetherimide,
IFSS, Interfacial shear strength
LSS, Lap shear strength
MWCNTs, Multi-walled carbon nanotubes
SEM, Scanning electron microscopy
SS, Stainless steel
TEM, Transmission electron microscopy
\( t_g \), Growth time

References


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