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One-Step Fabrication of Piezoelectric Ceramics/Carbon Fiber Reinforced Polymer Composites with Enhanced Performance

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Summary:

Recently, a composite combining $K_xNa_{1-x}NbO_3$ nanoparticle-filled epoxy with carbon fiber-reinforced polymer (CFRP) electrodes has been developed, showing enhanced mechanical and piezoelectric properties. However, the fabrication process is time-consuming, and the incorporation of resin may weaken the material's piezoelectric properties. In this work, we proposed a new strategy for combining piezoelectric material and CFRP, which reduces the time and effort required and improves the piezoelectric performance of the material.

Keywords: Piezoelectric composite, Carbon fiber-reinforced polymer, One-step fabrication, Corona-poling, Mechanical property

Background

Carbon fiber reinforced polymer (CFRP) is widely used in aerospace and construction due to its lightweight, high strength, and stability. However, its complex structure and the use of thermoset resins make it difficult to detect and repair once it is broken. Structural health monitoring (SHM) is essential for real-time crack detection. Traditional SHM methods like ultrasound and thermal imaging are costly and complex. Sensor-based approaches have gained attention, but external power remains a challenge. Piezoelectric materials offer a self-powered solution by converting mechanical stress into electrical signals and work as self-powdered sensors [1]. While lead zirconate titanate (PZT) is widely used for its excellent properties, its lead content raises environmental concerns. In contrast, lead-free sodium potassium niobate ($K_xNa_{1-x}NbO_3$ (KNN)) has emerged as a promising lead-free alternative, featuring good piezoelectric performance and high Curie temperature [2]. However, as ceramics, KNN suffers from inherent brittleness and poor fatigue resistance, which limits its durability. Recently, a composite combing KNN nanoparticle-filled epoxy (Ep) with twill weave (TW) CFRP electrodes has been developed, showing enhanced mechanical and piezoelectric properties [3]. This composite has high sensing sensitivity for damage detection, indicating potential applications in SHM. However, the fabrication process is time-consuming, and the incorporation of resin may weaken the material's piezoelectric properties. Besides, TW-KNN-Ep must be polarized by direct poling in silicon oil. If there are any weak points within the composites, they will break during the fabrication process, resulting in a low yield rate. Additionally, as the KNN content in the composites increases, weak points increase, limiting the KNN content to under 40 vol. %. This constraint has become a significant barrier to the CFRP-KNN-Ep composite. To reduce the time and effort required and improve the piezoelectric performance, in this study, a one-step molding method for ceramics/CFRP piezoelectric composites and a new piezoelectric CFRP structure was proposed, where micro-sized KNN layers were sandwiched between CFRP layers. The fabrication conditions were examined, and the performance of the KNN-CFRP composites was investigated. The cross-section of the fabricated composites was observed using scanning electron microscopy (SEM). The piezoelectric, electric, and mechanical properties were measured by a d_{33}-meter, an impedance analyzer, and a 3-point bending test on a universal machine, respectively.

Experimental Procedure

Unlike previous studies, we eliminated adding resin or hardener in this work. Instead, the composites were manufactured by directly combining piezoelectric material powder with CFRP. KNN powder was uniformly distributed onto the surface of the CFRP and then sandwiched by (0/90/KNN/0) CFRP prepregs. The unidirectional

(UD) CFRP and TW CFRP were used. A hot press was used to apply high pressure to the CFRP and KNN powder, ensuring a strong bond between the two materials while the heating process solidified the CFRP. After curing, the UD-KNN and TW-KNN were polished to prepare the specimens with a length of L=55 mm, a width of W=10 mm, and a thickness of H=1.3 mm (KNN h=0.5 mm). Next, corona-poling poled the specimens under 16 kV/mm at 105 °C for 60 min along the thickness direction. Then, a d_{33}-meter was used to measure the piezoelectric coefficient d_{33} of the composite, and a 3-point bending test measured the mechanical properties of the composite.

Results and Discussion

The SEM micrograph of the cross-section of the composites indicated that the KNN powder in the composites prepared by one-step molding is tightly bound compared to the TW-KNN-Ep in previous work (see Fig. 1). However, there are still some micro-sized voids between the particles in the TW-KNN composite.

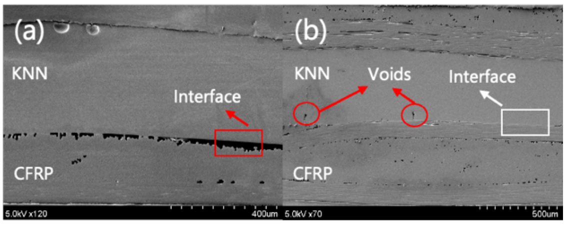

Fig. 1. SEM micrograph of the cross-section of the KNN composites.

The piezoelectric coefficient d_{33} of the composites was measured by d_{33}-meter after corona-poling along the thickness direction. As expected, the incorporation of resin affected the piezoelectric performance of the composite. The piezoelectric coefficient d_{33} of the TW-KNN composites prepared by one-step molding reached values twice (~9 pC/N) as high as those of TW-KNN-Ep in previous work (~4 pC/N), and the UD-KNN composites reached six times (~25 pC/N). The piezoelectric layer of the composites in this work is almost composed of KNN powder, resulting in a significant enhancement in piezoelectric properties. Impedance analysis was also conducted to investigate further resin's influence on the composites' piezoelectric properties. The results indicate that the TW-KNN-Ep composite exhibited the lowest relative permittivity (ε_r= 21) and electrical conductivity (G= 5×10^{-6} S, at 1MHz), due to the incorporation of resin. Besides, the UD-KNN and TW-KNN showed a higher dielectric loss, which can be attributed to the micro-sized voids in the KNN layer, which is consistent with the SEM results. The results of the 3-point bending test of the composites are shown in Fig. 2. Compared to the TW-KNN-Ep composite (E= 3.8 GPa, σ_b= 170 MPa), the TW-KNN and UD-KNN composites exhibited a significant improvement in both Young's modulus and bending strength (E= 46.4 GPa, σ_b= 700 MPa, E= 6.4 GPa, σ_b= 323 MPa, respectively). However, the toughness of the TW-KNN composite was substantially reduced. It is primarily because the KNN in the TW-KNN sample existed in a ceramic state, leading to greater brittleness and reduced composite toughness.

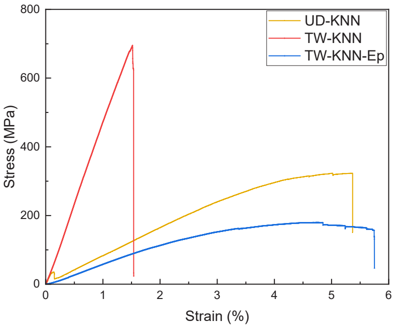

Fig. 2. Bending strain-stress curve of the KNN composites.

Conclusion

In this work, we proposed a new strategy for combining piezoelectric material and carbon fiber reinforcement, which reduces the time and effort required and improves the material's piezoelectric and mechanical properties compared to previous research. The piezoelectric coefficient d_{33} of the TW-KNN composites prepared by one-step molding reached values twice as high as those of TW-KNN-Ep in previous work, and the UD-KNN composites reached six times. Besides, the composites in this work showed a significantly higher Young's modulus and greater bending strength than the TW-KNN-Ep in previous work, although the toughness of TW-KNN was reduced.

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