博　士　論　文　の　内　容　の　要　旨
Abstract of Doctoral Dissertation

氏名 Full Name	ﾔﾝ ﾘ YANG LI
学位名 Name of Degree	博士 Doctor of（工学／ENGINEERING）
学位授与年月日 Date of The Degree Conferral	2023 年　3 月 20 日/March 20th
論文題目 Dissertation Title	Mechanical properties of CFRPs enhanced by carbon film using magnetron sputtering technology （マグネトロンスパッタ炭素膜強化 CFRPs の力学特性に関する研究 ）

（博士論文の内容の要旨　Abstract of Doctoral Dissertation）

In this study, the magnetron-sputtering technology was introduced to deposit a carbon film on the surface of the carbon fibers to repair defects by exploiting the homogeneity of the sputtering target and carbon fibers. The interfacial and mechanical properties of the carbon fibers and its composites were improved obviously by using the nanoscale magnetron-sputtering deposition. To investigate the effects of the magnetron-sputtering process on the morphology and structure of deposited carbon films, carbon-film deposition was performed on two substrates: silicon wafer and carbon fibers. The effects of the magnetron-sputtering process on the surface morphology, microstructure, and phase composition of the carbon fibers were analyzed with the magnetron-sputtering time and power as variables. To evaluate the structural properties of the magnetron-sputtered carbon films, the carbon films deposited on silicon wafers were heat-treated at 800–1200 °C. The structural properties of the magnetron-sputtered carbon films were analyzed, with a focus on the effects of magnetron sputtering on the properties of the carbon-fiber body and the mechanism underlying the effects on the mechanical properties of the CFEP composites. The most significant results of this study are presented below.

(1) The carbon film deposited via magnetron sputtering was made of carbon nanoparticles. There were microcracks on the surface of the film and a columnar structure in the cross-section of the film. The thicknesses of the carbon films deposited on the silicon wafers and carbon fibers deposited via the same magnetron-sputtering process were comparable. The surface roughness of the carbon fibers was increased after modification by magnetron sputtering, and the degree of increase depended on the scanning conditions. The carbon-fiber surface roughness (Ra) increased by a maximum of 9.79% under the 3 μm × 3 μm scanning condition. The surface roughness of carbon fibers subjected to 250 W, 50 min modification increased by 58.87% under the 1 μm × 1 μm scanning condition. In the 0.2 μm × 0.2 μm scanning condition, the surface roughness of the carbon fibers increased by a factor of 3.46 after 250 W, 50 min modification. The magnetron-sputtering modification treatment had no effect on the microstructures or material compositions of the carbon fibers and did not affect the intrinsic properties of the carbon fibers and CFEP composites. The surface morphology and microstructure of the magnetron sputtering-deposited carbon film were changed after heat treatment. The heat treatment transformed the particle stacking structure of the original magnetron-sputtered carbon film into a continuous layer structure, and the surface changed from a surface morphology with microcracks to a carbon stacking structure with a lamellar crystal morphology. As the heat-treatment temperature increased, the lamellar crystal structure on the surface of the carbon fibers transformed into a rheological yarn-like stacking structure. The heat treatment enhanced the ordered structure of the carbon film

and increased the surface roughness. Additionally, it improved the mechanical properties of the carbon film: the hardness, Young's modulus, and friction resistance increased, and the wear rate of the carbon film after heat treatment at 1000 ℃ was reduced by 28% compared with that before heat treatment.

(2) The mechanical properties of the carbon fibers were improved by magnetron-sputtering modification. The tensile breaking strengths of single and multifilament carbon fibers were increased by 9.93% and 6.9%, respectively, after the magnetron sputtering. Additionally, the magnetron sputtering significantly improved the dispersion of the tensile breaking strength of the carbon fibers; the CV value of the tensile breaking strength of single carbon fibers decreased by 57.5% at maximum, and that of multifilament carbon fibers decreased by 31% at maximum. The tensile fracture toughness of the modified carbon fibers was significantly improved through the crack effect mechanism in the tensile process. The tensile fracture work of the single and multifilament carbon fibers was increased by 19.73% and 23%, respectively, after 250 W, 50 min magnetron-sputtering modification treatment. The surface energy of the carbon fibers was increased by 38.7% after 350 W, 20 min magnetron-sputtering treatment.

(3) The mechanical properties of the CFEP composites modified by magnetron sputtering were significantly improved, including the in-plane shear strength, tensile strength, bending strength, and toughness. Owing to the deposition of the carbon film on the surface of the carbon fibers, a composite interface layer was created between the interface layers of the CFEP composite, and the load-transfer effect of the composite interface layer was used to meet the delayed failure of carbon-fiber composite damage. The in-plane shear strength of CFEP composites subjected to 250 W, 30 min modification exhibited the largest increase among all the modification conditions, with a 39.02% increase in shear strength. The modified CFEP composites not only had stress yielding during the tensile process, avoiding the brittle damage of the CFEP composites, but also make the tensile strength, tensile modulus and tensile fracture work of CFEP composites significantly improved. The tensile strengths of the modified CFEP composites were 13.71%–31.54% higher than those of the unmodified ones. The tensile breaking work was approximately 1.44 times higher for the modified composites. The surface modification of the carbon fibers by magnetron sputtering significantly affected the flexural modulus of the CFEP composites, which was increased by a factor of 1.18 after 250 W, 30 min modification.

The successful implementation of magnetron sputtering technology on carbon fiber surface modification provides a new method for carbon fiber surface repair and damage free carbon fiber composite interface modification, and also provides a theoretical basis for the controlled construction of multi-layer interfaces of CFEP composites.