

Compressive Properties and Failure Mechanisms of C/C-Cu Composites: Postprint

Authors: Deng Chaoyong, Zhang Hongbo, Yin Jian, Xiong Xiang, Wang Pei, Sun Miao, Li Wanqian

Date: 2017-04-10T00:00:00+00:00

Abstract

Three types of C/C-Cu composites with carbon fiber volume fractions of approximately 35%, 40%, and 45% were fabricated using pre-impregnated carbon cloth and copper mesh as raw materials via a compression molding method. The compressive properties were evaluated using an Instron 3369 mechanical testing machine. The results demonstrate that carbon fiber volume fraction constitutes a critical factor influencing the compressive behavior of the material. In the perpendicular direction, the compressive properties exhibit enhancement with increasing carbon fiber volume fraction. Specifically, the compressive properties of the specimen with 40% carbon fiber volume fraction increased by 20% compared to the 35% specimen, while the 45% specimen showed a 13% improvement over the 40% specimen, indicating a diminishing enhancement trend. In the parallel direction, however, the effect of carbon fiber volume fraction on compressive properties was less pronounced than in the perpendicular direction, showing a certain correlation with specimen density. Among the three specimens, the one with 45% carbon fiber volume fraction achieved the highest compressive strength in both perpendicular and parallel directions, reaching 190.13 MPa and 83.39 MPa, respectively. The disparity in compressive strength between parallel and perpendicular directions reveals significant anisotropy in the compressive properties of C/C-Cu composites. Regarding failure mechanisms under compression, under perpendicular loading with the stress direction approximately along the 45° diagonal, failure occurred through delamination between fiber layers, copper mesh, and carbon matrix, accompanied by crushing failure of the carbon matrix. Under parallel compression, carbon fibers underwent buckling, generating tensile and compressive stresses in the buckled region that caused fiber kinking or fracture, ultimately leading to interfacial delamination and splitting between carbon fibers and carbon matrix, as well as between carbon matrix and copper mesh.

Full Text

Compression Performance and Failure Mechanism of C/C-Cu Composites

DENG Chaoyong¹, ZHANG Hongbo¹, YIN Jian¹, XIONG Xiang¹, WANG Pei¹, SUN Miao¹, LI Wanqian²

¹College of Materials Science and Engineering, Central South University of Forestry and Technology, Changsha 410004, China

²Correspondent: YIN Jian, Tel: (0731)88836877, E-mail: melodycyd@163.com

Abstract: Three types of C/C-Cu composites with carbon fiber volume fractions of approximately 35%, 40%, and 45% were prepared using a compression molding method with pre-impregnated carbon cloth and copper mesh as raw materials. Their compressive properties were tested using an Instron 3369 mechanical testing machine. The results demonstrate that carbon fiber volume fraction is a critical factor influencing the compressive performance of the material. In the perpendicular direction, the compressive performance improves with increasing carbon fiber volume fraction. The compressive strength of the sample with 40% carbon fiber volume fraction is 20% higher than that with 35%, while the sample with 45% carbon fiber volume fraction shows a 13% improvement over the 40% sample, indicating a diminishing rate of improvement. In the parallel direction, the effect of carbon fiber volume fraction on compressive performance is less pronounced than in the perpendicular direction and correlates with sample densification. Among the three samples, the composite with 45% carbon fiber volume fraction exhibits the highest compressive strength in both directions, reaching 190.13 MPa in the perpendicular direction and 83.39 MPa in the parallel direction. The difference in compressive strength between parallel and perpendicular directions reveals significant anisotropy in the compressive properties of C/C-Cu composites. Regarding failure modes, under perpendicular compression, failure occurs along approximately 45° diagonal directions through delamination between fiber layers, copper mesh, and carbon matrix, accompanied by crushing of the carbon matrix. Under parallel compression, carbon fibers undergo buckling, generating tensile and compressive stresses in the buckled regions that cause fiber kinking or fracture, ultimately leading to interfacial delamination and splitting between carbon fibers and carbon matrix, as well as between carbon matrix and copper mesh.

Keywords: C/C-Cu composites, compressive properties, anisotropy, failure mechanism

Introduction

The construction of high-speed electrified railways represents an important indicator of a nation's industrial manufacturing level [1,2]. However, China currently

relies entirely on imported pantograph strip materials for its high-speed rail system [3]. Therefore, the development of high-performance pantograph strip materials with independent intellectual property rights is urgently needed. C/C-Cu composites exhibit high strength, high electrical conductivity, high fracture toughness, thermal shock resistance, low coefficient of thermal expansion, and excellent friction and wear properties, making them a novel electrical contact material suitable for harsh natural environments [4-8]. For pantograph strip applications, C/C-Cu composites must possess adequate electrical performance, friction and wear characteristics, and certain mechanical properties. This study investigates the compressive performance and failure mechanisms of C/C-Cu composites.

1. Experimental Methods

1.1 Material Preparation Three types of C/C-Cu preforms with carbon fiber volume fractions of approximately 35%, 40%, and 45% were prepared using a compression molding method with pre-impregnated carbon cloth and copper mesh as raw materials. After multiple resin impregnation and high-temperature carbonization cycles, three C/C-Cu composites with densities around 1.9 g/cm³ were fabricated, designated as CFRCS-1, CFRCS-2, and CFRCS-3.

1.2 Property Testing The density and open porosity of C/C-Cu composites were measured using the drainage method. An electronic analytical balance with 0.001 g precision was used to weigh the dry sample mass (G_1), the sample mass in alcohol (G_2), and the sample mass after removal from alcohol (G_3). The density (ρ) and open porosity (π) were calculated as follows:

$$\rho = \frac{G_1}{G_1 - G_2} \times \rho_0$$

$$\pi = \frac{G_3 - G_1}{G_1 - G_2} \times 100\%$$

where ρ_0 is the density of alcohol (approximately 0.8 g/cm³).

Compressive properties were measured according to national standard GB8489-87 using an Instron 3369 mechanical testing machine. Sample dimensions were 10 mm × 10 mm × 10 mm, with 4-6 samples tested per group at a loading rate of 2 mm/min. Compressive stress was calculated as:

$$\sigma_c = \frac{P}{A}$$

where σ_c is compressive stress (MPa), P is the maximum load at failure (N), and A is the cross-sectional area of the compression surface (mm²). Due to structural differences between planes parallel and perpendicular to the carbon

fiber layers, compressive properties were tested in both directions, as illustrated in [Figure 1: see original paper].

2. Results and Discussion

2.1 Compressive Properties of C/C-Cu Composites The basic properties of C/C-Cu composites are listed in . The composites exhibit densities around 1.9 g/cm^3 , copper mass fractions of approximately 21%, and open porosities of 3.4%-4.4%. The carbon fiber volume fractions for samples CFRCS-1, CFRCS-2, and CFRCS-3 are 35.09%, 40.38%, and 45.55%, respectively.

[Figure 2: see original paper] presents the compressive strength values of C/C-Cu composites with carbon fiber volume fractions of 35.09%, 40.38%, and 45.55% in both parallel and perpendicular directions. In the perpendicular direction, compressive strength increases with carbon fiber volume fraction. The sample with 40% carbon fiber volume fraction shows a 20% improvement over the 35% sample, while the 45% sample exhibits a 13% increase over the 40% sample, demonstrating a diminishing enhancement trend. In the parallel direction, compressive strength initially decreases then increases with carbon fiber volume fraction. Among the three samples, the composite with 45% carbon fiber volume fraction achieves the highest compressive strength in both directions (190.13 MPa perpendicular and 83.39 MPa parallel). Furthermore, the compressive strength in the perpendicular direction significantly exceeds that in the parallel direction, confirming pronounced anisotropy in the compressive properties of C/C-Cu composites.

2.2 Compressive Stress-Strain Curves [Figure 3: see original paper] shows the compressive stress-strain curves. In the perpendicular direction ([Figure 3a: see original paper]), the maximum compressive stress increases progressively with carbon fiber volume fraction, with CFRCS-3 reaching the highest value of 190.13 MPa and CFRCS-1 the lowest at 140.74 MPa. The curves for all three samples increase almost linearly to the elastic limit before undergoing brittle fracture, characteristic of typical brittle failure.

In the parallel direction ([Figure 3b: see original paper]), the maximum compressive stress initially decreases then increases substantially with carbon fiber volume fraction, contrasting sharply with the perpendicular direction. While mechanical properties should theoretically improve with increasing carbon fiber content, the maximum stress for CFRCS-2 (40% fiber volume fraction) does not exceed that of CFRCS-1 (35%). This discrepancy arises from different fracture mechanisms. CFRCS-1 and CFRCS-3 exhibit typical brittle fracture with sharp stress drops after reaching maximum stress, whereas CFRCS-2 shows ductile fracture with a plateau-like gradual stress decline. The ductile behavior of CFRCS-2 primarily results from its lower densification, which introduces numerous microcracks and pores within the carbon matrix. These defects relieve stress concentration at crack tips, arrest crack propagation or cause crack deflection, requiring continued load increase for further crack growth or new crack

initiation, thereby producing a “serrated” pseudo-plastic characteristic.

2.3 Fracture Morphology of C/C-Cu Composites [Figure 4: see original paper] presents SEM images of compressive fracture surfaces. For parallel compression samples, interlaminar cracks propagate along fiber/matrix or copper mesh/matrix interfaces. Samples exhibiting serrated stress-strain curves also show partial buckling failure. Fiber bundle buckling accompanies delamination, creating step-like fractures through the sample that lead to ultimate failure. At fiber bundle buckling and fracture sites, holes remain where brittle-fractured fibers and crushed carbon matrix have been displaced. For perpendicular compression samples, delamination cracks also propagate along carbon fiber/matrix or copper mesh/matrix interfaces, but with relatively flatter morphologies compared to parallel compression. The crushed surfaces retain substantial carbon matrix debris and numerous shear-fractured carbon fiber bundles. Compressive failure manifests as shear failure, delamination, and crushing.

2.4 Failure Mechanisms of C/C-Cu Composites [Figure 5: see original paper] shows macrographs of compressive failure. As illustrated in [Figure 5a: see original paper], individual fiber and copper mesh layers bend outward sequentially, even fracturing, creating a series of delamination cracks between broken and unbroken fibers. Based on microstructural analysis, the dominant failure mechanism is delamination splitting.

For C/C-Cu composites, the distinct layering of fibers and copper mesh, combined with poor wettability between carbon and copper phases, results in low interlaminar shear strength. Under parallel compression, the loading direction is parallel to the interfaces between carbon fibers and carbon matrix, as well as between carbon matrix and copper mesh. Before pure shear fracture occurs, shear stresses first induce interlaminar splitting, making delamination the primary failure mode under parallel compression. During parallel compression, fiber bundle deformation and failure produce tensile and compressive stresses in buckled regions ([Figure 6a: see original paper]), causing fiber kinking or fracture and ultimately leading to interfacial delamination and splitting.

In contrast, under perpendicular compression, shear failure on any cross-section causes fiber and copper mesh fracture. The fiber layers, copper mesh, and carbon matrix collectively bear the load ([Figure 6b: see original paper]), and due to relatively low sample density, failure occurs through separation between fiber layers, copper mesh, and carbon matrix, accompanied by carbon matrix crushing. As shown in [Figure 5b: see original paper], crack propagation occurs at approximately 45° to the loading direction. This results from the combined action of normal load perpendicular to the compression surface and shear force parallel to the vertical surface. According to force composition principles, the resultant force is:

$$F_{\text{resultant}} = \sigma_c \sin \theta$$

where c is the applied load and α is the angle between loading direction and the normal to the sample's transverse plane. When c is constant and $\alpha = 45^\circ$, the resultant force reaches its maximum, causing cracks to propagate along this direction.

Conclusions

1. Carbon fiber volume fraction significantly affects the compressive performance of C/C-Cu composites. Among the three samples tested, the composite with 45% carbon fiber volume fraction exhibits the highest compressive strength in both perpendicular (190.13 MPa) and parallel (83.39 MPa) directions.
2. In the perpendicular direction, compressive performance improves with increasing carbon fiber volume fraction, though the enhancement rate diminishes. In the parallel direction, the effect of carbon fiber volume fraction is less pronounced and correlates with sample densification. The strength difference between directions demonstrates clear anisotropy in compressive properties.
3. Under perpendicular compression, failure occurs along approximately 45° diagonal directions through delamination between fiber layers, copper mesh, and carbon matrix, combined with carbon matrix crushing. Under parallel compression, carbon fiber buckling generates tensile and compressive stresses that cause fiber kinking or fracture, ultimately leading to interfacial delamination and splitting between fibers and matrix, as well as between matrix and copper mesh.

References

- [1] Froidh O. Perspectives for a future high-speed train in the Swedish domestic travel market[J]. *Journal of Transport Geography*, 2008, 16: 268
- [2] Kubo S, Kato K. Effect of arc discharge on wear rate of Cu-impregnated carbon strip in unlubricated sliding against Cu trolley under electric current[J]. *Wear*, 1998, 216(2): 172
- [3] Yu Z P, Zhang H, Wu H B, et al. A Study on high-speed catenary-pantograph system[J]. *China Railway Science*, 1999, 20(1): 59
- [4] Tan C. Research on preparation, microstructure and properties of carbon/carbon-copper composites[D]. Changsha: Central South University, 2013
- [5] Wang W F, Xiu S F, Ying M F, et al. Study on the microstructure and properties of copper-coated graphite/Cu matrix composite material[J]. *Materials for Mechanical Engineering*, 1999, 23(2): 41
- [6] Kestursatya M, Kim J K, Rohatgi P k. Wear performance of copper graphite composite and a leaded copper alloy[J]. *Materials Science & Engineering A*, 2003, 339(1-2): 150
- [7] Kubota Y, Nagasaka S, Miyauchi T, et al. Sliding wear behavior of copper

alloy impregnated C/C composites under an electrical current [J]. *Wear*, 2013, 302(s1-2): 1492

[8] Yang L, Ran L P, Yi M Z. Carbon fiber knitted fabric reinforced copper composite for sliding contact material[J]. *Materials & Design*, 2011, 32(4): 2365

[9] Yin J, Zhang H B, Xiong X, et al. Effect of porous C/C substrate density on compressive property of C/C-Cu composites[J]. *Powder Metallurgy Materials Science and Engineering*, 2014, 19(6): 989

[10] Xiong X, Huang B Y, Xiao P. Compressive properties and fracture mechanism of quasi-3D C/C composites[J]. *J. Central South University (Science and Technology)*, 2004, 35(5): 702

[11] Huang B Y. *Manufacturing of Carbon/carbon Composites for Aircraft Brakes*[M]. Hunan: Science and Technology Press, 2007

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.