Abstract

Polymers inherently exhibit lower strength and stiffness compared to ceramics and metals, rendering them inadequate for many structural applications. To enhance their mechanical performance and broaden their range of structural uses, polymers are often reinforced with high-strength synthetic fibers. However, the inherently smooth surface morphology of synthetic fibers leads to weak interfacial bonding with the polymer matrix. To address this limitation, surface modification techniques such as chemical treatments or nanoparticle coatings are employed to increase fiber surface roughness, thereby improving fiber-matrix adhesion and overall composite performance. This study systematically explores the surface modification of fibers using carbon nanotubes (CNTs), graphene oxide (GO), and their hybrid (CNTs/GO) coatings to enhance the mechanical, thermal, and tribological performance of fiber-reinforced polymer composites. The focus is placed on developing strong fiber-matrix interfacial bonding, improving load transfer, and reducing wear through various experimental and data-driven approaches. The different composite samples were prepared using the hand layup method.

In the first segment of thesis work, aramid fibers and CNTs were subjected to chemical oxidation using a sulfuric and nitric acid mixture. This treatment functionalized the fiber and nanoparticle surfaces by introducing oxygen-containing groups such as C=O, COOH, and OH. These functional groups significantly enhanced the surface reactivity, promoting better chemical compatibility and mechanical interlocking at the fiber-matrix interface. The tribological performance of the composites was evaluated under varying normal loads (30 N, 40 N, 50 N, and 60 N), sliding frequencies (6 Hz, 8 Hz, 10 Hz, and 12 Hz), and temperatures (30°C, 40°C, 50°C, and 60°C), with a constant stroke length of 1.5 mm. Results demonstrated that CNT-coated aramid fiber composites exhibited

considerable improvements in mechanical properties. Specifically, the specific wear rate decreased by 32.41%, while tensile strength, tensile modulus, hardness, and thermal conductivity increased by 23.3%, 22.9%, 27.27%, and 36.56%, respectively. Thermogravimetric analysis (TGA) further revealed that the weight loss of CNT-coated aramid fibers was 27.27% lower compared to uncoated fibers within the temperature range of 24°C to 800°C, indicating superior thermal stability. Scanning electron microscopy (SEM) analyses of the worn surfaces illustrated improved fiber-matrix adhesion and reduced fiber and matrix breakage, confirm the formation of strong interfacial bonding. The coefficient of friction increased with rising normal loads but decreased with elevated temperatures and sliding frequencies.

The next segment of thesis work addresses, a spray-coating approach was employed to deposit CNTs, GO, and their hybrid (CNTs/GO) onto carbon fibers to fabricate enhanced carbon fiber reinforced epoxy (CFRE) composites. The synergistic effect between the one-dimensional CNTs and two-dimensional GO facilitated the development of a robust three-dimensional network within the matrix, greatly improving load transfer and interfacial adhesion. Comparative mechanical characterization revealed that hybrid CNTs/GO-coated carbon fiber reinforced epoxy (HCFRE) composites outperformed uncoated CFRE composites. Specifically, HCFRE exhibited improvements of 38.73% in interlaminar shear strength (ILSS), 30.40% in flexural strength, 33.53% in tensile strength, and 32.64% in hardness. Fracture toughness, tensile modulus, and flexural modulus enhancements of 36.36%, 31.66%, and 57.68%, respectively, were recorded for HCFRE composites relative to CFRE. TGA results further confirmed that nanoparticle-coated carbon fibers exhibited enhanced thermal stability compared to uncoated fibers across the 24°C to 800°C range. Tribological evaluation of HCFRE composites under the same sliding conditions revealed a 42.84% reduction in specific wear rate compared to CFRE composites. The coefficient of friction was observed to rise with increasing normal load but decrease with higher sliding frequencies. To study the wear mechanism SEM analysis of worn surface of different composites sample is investigated.

To extend the scope of tribological assessment, solid particle erosion tests were conducted using alumina particles. The influence of impact velocity, discharge rate, and impingement angle on erosion behavior was systematically studied. A Taguchi L_{16} orthogonal array design combined with analysis of variance (ANOVA) indicated that impact velocity was the most significant factor affecting the erosion rate. The hybrid-coated composites demonstrated superior erosion resistance, with the minimum erosion rate observed at an impact velocity of 20 m/s, a discharge rate of 2 g/min, and an impingement angle of 15°. SEM analysis of eroded surfaces revealed typical damage mechanisms, such as micro-cutting, plowing, matrix cracking, fiber breakage and fiber pull-out.

The other segment of thesis work focused on addition to experimental investigations, a computational machine learning (ML) approach was adopted to predict the coefficient of friction (COF) of CNT-coated aramid fabric reinforced epoxy composites. The input dataset comprised mechanical, thermal, and tribological properties. Three ML algorithms—artificial neural network (ANN), gradient boosting machine (GBM), and random forest (RF)—were employed for model development. The predictive performance, measured through R^2 values, was 0.9088 for ANN, 0.92807 for GBM, and 0.85294 for RF, demonstrating high predictive accuracy, with GBM yielding the most reliable predictions. The best model achieved a minimal error percentage of 0.003658%, while the highest observed error was 13.56625%. Feature importance analysis from the ML models highlighted that normal load, sliding frequency, and CNT content were the most influential parameters governing COF behavior. This data-driven insight validate experimental observations and provided a powerful predictive framework for the design and optimization of fiber-reinforced polymer composites for high-performance automotive and aerospace applications.