ABSTRACT

Epoxy has been extensively studied for structural composites in industries such as aerospace, automotive, marine, construction, shipbuilding, and electronics. Its cross-linked structure imparts desirable properties like high glass transition temperature, stiffness, creep resistance, dimensional stability, and chemical resistance. However, uncured epoxy exhibits poor mechanical, chemical, and thermal properties. Curing with suitable agents forms a strong 3-D cross-linked structure but diminishes strength, fracture toughness, and fatigue resistance. Researchers have explored various nanoparticles and microparticles for reinforcement, with graphene nanoplatelets (GNP) emerging as superior nanofillers. Yet, challenges in exfoliation, dispersion, orientation, and interfacial bonding hinder graphene's full potential, thus limiting the structural applications of graphene-reinforced epoxy.

This study aimed to overcome challenges associated with the dispersion and spatial orientation of GNP to enhance the benefits of GNP epoxy nanocomposites. A mathematical model is developed to optimize the alignment parameters of GNP and magnetite ferric oxide (Fe_3O_4)-GNP applying a weak DC magnetic field (0.05T), considering rotation, translation, migration, and slackening mechanisms of the nanoparticle in the epoxy. Optimisation of magnetic field, epoxy viscosity, and time required to complete all mechanisms before gelation of epoxy has been carried out to fabricate a highly aligned GNP nanocomposite.

The characteristic magnetic, viscosity, and hydrodynamic parameters required by the mathematic model are determined experimentally. The Fe_3O_4 synthesized by solve-thermal and attaching them to the GNP surface to increase its magnetic susceptibility in order to utilize the model's suggested optimized magnetic parameters. The Morphology, microstructure, and magnetic properties of GNP, Fe_3O_4, and Fe_3O_4-GNP nanoparticles have been characterized by

XRD, FTIR, Raman spectroscopy, TGA, AFM, XPS, BET, TEM, SEM, EDXMA, and VSM. A highly aligned Fe_3O_4-GNP nanocomposite is fabricated at 0.05T magnetic field and 40Pa-s dynamic viscosity of epoxy, as evident from the aforementioned characterization methods, DSC, optical microscopy, and studying the fracture surface morphology confirmed the highly aligned alignment Fe_3O_4-GNP epoxy nanocomposite.

Furthermore, our investigation focuses the influence and comparative impact of alignment, as well as wt% loading, of both nanoparticles GNP and Fe_3O_4-GNP on various mechanical properties, such as tensile and compressive strength, K_{IC}, G_{IC}, $CTOD_c$, crack propagation, and fracture mechanisms. This study utilizes AFM analysis to examine the roughness parameters of fractured surfaces. The conclusion asserts that nanoparticle alignment increases the likelihood of primary crack fronts interaction and results in a change in a stress state, deflection, branching, and bifurcation, ultimately leading to increased crack growth resistance.

Moreover, being a leading cause of catastrophic failure in structural materials, fatigue is the primary focus of this present study, which aims to investigate the fatigue thresholds (ΔK_{th} and ΔG_{th}) fatigue crack growth rate (FCGR) resistance, and the contribution of toughening mechanisms under cyclic fatigue loading in the nanocomposites. The investigation concludes that increasing the weight percentage (wt%) leads to higherΔK_{th}, ΔG_{th} and FCGR resistance, with alignment having a more significant impact. Moreover, the Paris law constants (C, C', and m) exhibit a decrease. Through fractography and roughness analysis, it has been determined that alignment enhances the probability of interaction among primary crack fronts, leading to tip shielding, crack bifurcation, deflection, local mixed mode, striation marks, shear yielding, crack twisting and tilting, micro-crazing, void nucleation, nanoparticle debonding, pullout, and cavitation. Consequently, the alignment significantly enhances resistance to FCGR.

As part of this Ph.D. study, we also investigated the fracture energy of CNT/epoxy nanocomposites using a mathematical model. The characteristics of the debonding process zone involving macro-scale, micro-scale and nano-scale mechanisms along CNT interface influence the fracture behaviour of nanocomposites and their structural integrity. In current study, a multi-scale and multi-mechanism modelling approach with a cylindrical RVE comprising CNT, interphase and matrix is developed to assess such damage progression and energy dissipation occurring at the nano-scale. The model considers the dominant damaging phenomena emerging in CNT/epoxy nanocomposites, i.e., CNT debonding with an interphase zone around nanoparticles, cavitation, and plastic deformation of nanovoids. Enhancement of fracture toughness with the weight fraction of CNT is investigated with a qualitative variation of geometric and mechanical properties of the interphase, cavitation and plastic yielding adopting strain energy release rate procedures. The fracture energy is shown to be critically influenced by the stiffness ratio of interphase to the matrix, interphase thickness, and hardening exponent. The Model is validated using experimental and analytical data.