FATIGUE AND FRACTURE ANALYSIS OF GRAPHENE AND CNT EPOXY NANOCOMPOSITES

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by

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Chapter 8. Conclusion and Future Scope

8.1. Introduction

This chapter has been the most important part of the research because it has brought together all the things we have learned and achieved. In the previous chapters, we have gone into great detail about what we have found and studied. Now, in this section, we will talk about the final conclusions we have come to base on our research. We will also give some important suggestions for future studies so that other researchers can build on what we have done and learn even more. This has marked the end of our research, but it has paved the way for new discoveries and progress in the future.

8.2. Conclusion

A novel mathematical model has been developed by the authors to address the alignment of nanoparticles within epoxy. This model takes into account rotational, translational, migration, and slackening mechanisms of the nanoparticles under the influence of a weak DC magnetic field. Aligned Fe_3O_4-GNP nanocomposites have been achieved using optimized conditions and a weak DC magnetic field. Viscosity and magnetic properties have been crucial, confirmed through optical analysis. The study has characterized nanocomposites with GNP and aligned Fe_3O_4-GNP, demonstrating improved fracture toughness and crack resistance. Additionally, the fatigue crack growth resistance and thermal stability of these nanocomposites have been significantly enhanced compared to GNP reinforcement alone, suggesting their potential for superior engineering materials.

The subsequent part of this study involves employing a multi-scale, multi-mechanism approach to examine the fracture characteristics of CNT/epoxy nanocomposites. The analysis focuses on stress distribution at different scales and investigates the impact of CNT interphase debonding, cavitation, and nanovoid plastic deformation on fracture toughness.

The specific conclusions are outlined as follows with respective studies:

8.2.1. Development of nanocomposite by Magnetic Field Induced Alignment of Graphene Nanoplatelets

- The alignment process of Fe_3O_4-GNP in epoxy during curing under the applied DC electromagnetic field is described by a mathematical model that is created based on the concepts of magnetophoretic (MAP) and classical hydrodynamics.
- The mathematical model explains such mechanisms as nanoparticle rotation, translation, migration, and slackening that occurs during alignment in epoxy matrices.
- To create a highly aligned Fe_3O_4-GNP nanocomposite, the model optimises the alignment parameters, including the magnetic field, epoxy viscosity, and time needed to complete all mechanisms.
- To prevent migration or slackening effects during nanoparticle alignment and ensure completion before epoxy gelation, magnetic field ($\overline{H}_0$) of 0.05 T and viscosity (η) of 40 Pa-s are found to be optimal.

8.2.2. Experimental Characterization Optimising Alignment Parameters of GNP epoxy base nanocomposite

- Characterization of Fe_3O_4, GNP, and Fe_3O_4-GNP using various techniques: HR-XRD, FTIR, Raman spectroscopy, TGA, BET, SEM, TEM, AFM, XPS, and VSM.
- Fe_3O_4-GNP exhibits superparamagnetic behavior due to Fe_3O_4 attachments to GNP surfaces, as shown by VSM study.
- Experimental setup based on proposed model used to align Fe_3O_4-GNP nanoparticles in liquid epoxy before gelation.

- Alignment of nanoparticles validated using XRD, SEM, Raman spectroscopy, and optical microscopy.
- Experimental characterization data agree with model results, demonstrating highly oriented Fe_3O_4-GNP solution in epoxy resin in a few minutes.
- Applied DC magnetic field only needed near gel point, not throughout entire curing process.
- Successful fabrication of Fe_3O_4-GNP nanoparticles achieved by attaching magnetite nanoparticles to GNP surfaces via non-covalent bonding.
- Production of suitably dispersed and aligned Fe_3O_4-GNP nanocomposites.
- Nanocomposites have numerous applications, including structural, functional, biomedical, membrane, and sensing.

8.2.3. Fracture and Failure Analysis of GNP and aligned Fe_3O_4-GNP epoxy Nanocomposite

- Properly dispersed GNP and Fe_3O_4-GNP nanoparticles reinforced nanocomposite was fabricated accompanied by aligned Fe_3O_4-GNP in the epoxy.
- The mechanical properties of nanocomposites are strongly influenced by the nanoparticles' wt% concentration for both GNP and aligned Fe_3O_4-GNP.
- GNP and aligned Fe_3O_4-GNP could effectively and efficiently enhance the mechanical properties of nanocomposites. At the same time, the alignment of the Fe_3O_4-GNP has incredible improvement on the structural properties of the nanocomposite.
- K_{IC} and G_{IC} were increased with both nanoparticles loading, while aligned Fe_3O_4-GNP nanoparticles greatly influenced both fracture properties.
- The value of fracture surface roughness indicated the crack propagation and toughness mechanism for both nanoparticles, while aligned nanoparticles greatly influenced the parameters.

- Aligned Fe_3O_4-GNP in nanocomposites exhibited slower crack propagation rates under dynamic loading than GNP and neat epoxy.
- Upon examination of the stereo zoom optical and AFM images, it was noted that the alignment of Fe_3O_4-GNP increased the probability of the primary crack encountering them, leading to an increase in toughness mechanisms.
- Fracture toughness mechanisms include degree of crack bifurcation and branching, crack deflection, formation of sub-critical crack, micro crazing, nucleation of voids, debonding of the nanoparticles and cavitation, tilting and twisting of cracks were verified by analysis of stereo zoom optical and AFM images.
- The increase in total fracture surface roughness parameters and morphology were directedly correlated with K_{IC}, G_{IC} and $CTOD_c$.
- The presence of plastic deformation processes in the nanocomposite, specifically in the aligned Fe_3O_4-GNP nanocomposite, was indicated by $CTOD_c$ measurements that showed crack tip blunting

8.2.4. Fatigue Analysis of GNP and aligned Fe_3O_4-GNP epoxy Nanocomposite

- Addition of GNP and aligned Fe_3O_4-GNP additives (0.600 wt. %) to an epoxy system resulted in a significant reduction in fatigue crack growth rate. The reduction was influenced by the weight fraction of nanotubes and, more significantly, by aligned Fe_3O_4-GNP nanoparticles.
- Epoxy filled with aligned Fe_3O_4-GNP nanoparticles exhibited significantly higher fatigue life compared to unfilled epoxy and GNP epoxy nanocomposites, indicating the effectiveness of aligned Fe_3O_4-GNP nanoparticles in improving fatigue behavior.
- GNP enhances thermal conductivity and fatigue life in GNP epoxy nanocomposites. Aligned Fe_3O_4-GNP further improves thermal conductivity and reduces damping,

offering superior properties compared to GNP epoxy. Inclusion of GNP and aligned Fe_3O_4-GNP prevents thermal softening, prolonging the failure process.

- Graphene hinders crack growth by redirecting it along easier paths, while aligned Fe_3O_4-GNP nanoparticles perpendicular to the crack growth direction slow down crack propagation under dynamic loading compared to GNP and neat epoxy, possibly due to increased encounter probability with the main crack.
- The increased resistance to fatigue crack growth in GNP and aligned Fe_3O_4-GNP nanoparticle-filled epoxy is attributed to reduced stress levels at the particle-matrix interface due to higher surface area. This observation was strongly supported by the Paris equation, which demonstrated significantly reduced values of constants "*C*", "*C*'" and '*m'* resulting in a slower rate of crack growth.
- Fracture toughness mechanisms observed in stereo zoom optical and AFM images included crack bifurcation, deflection, tip shielding, crack twisting and tilting, transitioning from 2D to 3D strains sub-critical crack formation, micro-crazing, void nucleation, nanoparticle debonding, and pullout, as well as cavitation. Aligned Fe_3O_4-GNP reinforcement exhibited superior mechanical properties, fracture toughness, crack propagation resistance, and toughening mechanisms compared to GNP alone, indicating their potential for advanced engineering applications.

8.2.5. Fracture Energy of CNT/Epoxy Nanocomposites with Progressive Interphase Debonding, Cavitation, and Plastic Deformation of Nanovoids

- The study investigates the fracture characteristics of CNT/epoxy nanocomposites.
- A strain energy release rate procedure is developed using multi-scale and multi-mechanism techniques.
- The radial distribution of stress is estimated at different scales.

- Fracture toughness improvement is predicted considering debonding, cavitation, and plastic deformation of nanovoids along the interface.
- Cavitation mechanisms are strongly influenced by the interphase stiffness rather than thickness.
- Plastic deformation of nanovoids is a dominant energy absorption mechanism.
- The influence of interphase thickness and stiffness on fracture energy enhancement is less compared to the hardening exponent.
- The model's performance is encouraging, showing qualitative agreement with experimental and analytical data from the literature

In the final conclusion, this study develops a mathematical model to describe the alignment mechanisms of nanoparticles under a magnetic field, optimizing alignment parameters to create a fully cured nanocomposite with aligned Fe_3O_4-GNP. The research validates the alignment of Fe_3O_4-GNP in epoxy and successfully synthesizes Fe_3O_4-GNP nanoparticles for diverse applications. The investigation further highlights the improved mechanical properties and fracture toughness of nanocomposites with aligned Fe_3O_4-GNP compared to GNP alone. Additionally, the study reveals that these nanocomposites exhibit enhanced fatigue properties, reducing fatigue crack growth rate and improving fatigue life. The analysis of fracture characteristics in CNT/epoxy nanocomposites shows promising results, with the model aligning well with experimental data. Overall, this research demonstrates the potential of aligned Fe_3O_4-GNP reinforced nanocomposites for various engineering applications.

8.3.Future Scope

Graphene nanocomposites offer diverse applications in various fields, including electronics, energy storage, aerospace, automotive, biomedical engineering, environmental remediation, coatings, sensing devices, construction, and sports. Their exceptional properties, such as high conductivity, strength, and biocompatibility, make them versatile for many industries and technologies. Consequently, there are numerous future research opportunities. As a machine design researcher, we recommend exploring the potential of graphene nanocomposites in structural applications. Some future scopes in this regard include:

- The fracture resistance of aligned nanoparticle nanocomposites under mode II and mixed I/II loading needs evaluation to assess potential variations from the significant improvement observed in this Ph.D. project's mode I loading.
- Engineers and physicists find dynamic fracture in solids fascinating because it is important for technology and science. Therefore, it is worth researching how aligned nanoparticle nanocomposites behave during dynamic fracture.
- The mechanical properties of the nanocomposites were evaluated at room temperature. However, since their performance can vary with temperature, it is recommended to conduct tests in both high-temperature and cryogenic environments to understand their behavior in different temperature conditions.
- To minimize uncertainty in strength failure and fracture of susceptible components made of bimodular materials, load-bearing structures must consider the bimodularity parameter. Therefore, it is essential to study the impact of bimodularity behavior of the nanocomposite on fracture parameters and energy release rate.

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