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ORIGINAL PAPER

Fracture toughness of epoxy-based stepped functionally graded materials reinforced with carbon nanotubes

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Abstract The aim of this work is to investigate the fracture characteristics of the epoxy-based stepped functionally graded materials (FGM) reinforced with carbon nanotubes (CNTs). The effects regarding fracture toughness in mode I were also studied. The specimens were fabricated with three different mass percentages of 0.1, 0.2 and 0.3%. An ultrasonic device was used to disperse the carbon nanotubes to have a uniform mixture without agglomeration of the CNT particles. Using the ASTM standard D-5045, the fracture toughness was obtained in the experiments. Some compact tension specimens were tested in a tensile machine in mode I. Two different notches were investigated to calculate the fracture toughness. For each notch, there were different fracture toughness and fracture forces values. The experiments showed that there is an improvement in the fracture resistance of FGMs and non-graded composite materials by increase in the CNTs content. The materials with the same content of carbon nanotubes do not have the same properties. It is seen that high fracture toughness can be obtained from different CNT content materials in each notch. In fact, the size of the notch affects the results. Comparing the fracture toughness values and fracture forces results showed that there is no specified rule to predict the increase in the fracture characteristics by increasing carbon nanotubes content. Fracture characteristics depend on the important parameters such as the size of the notch, CNTs content and dispersion of the carbon nanotubes.

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Keywords Functionally graded materials · Polymer matrix composites · Carbon nanotubes · Fracture toughness · Fracture force

Introduction

Improving polymer matrix composites by adding carbon nanotubes (CNTs) is an ongoing research task. There are many studies in this field, such as studies of thin polymeric films containing nanotubes under tensile stresses [1], effectiveness of reinforcement with CNTs [2], weaving CNTs to the electronic textiles and making electronic nanodevices [3, 4] to consider the effects of CNTs on the polymer properties. Nano-structured polymer composites have new perspectives for multifunctional materials since the material properties can be improved by adding further constituents. Polymer composites might have higher strength, stiffness, toughness, hardness, and electrical or thermal properties in comparison to unfilled polymers [5, 6]. Recently, polymer composites have been studied for radar absorbing materials [7] and a wide range of applications including biotechnology as well as automotive and aerospace industries [8–10]. CNTs have been utilized as nanofillers to increase the mechanical properties of the polymers [11, 12]. Within a brittle matrix such as epoxy, CNTs are able to behave as toughening agents by bridging the lamina interfaces. Apart from increasing the tensile strength [11, 13, 14], or flexural strength and modulus of epoxy using CNTs [15], the fracture toughness can be improved, as well [16, 17].

Carbon nanotubes are cylindrical structures of covalently bonded carbon atoms that have hexagonal forms. The concentric cylinders of these carbon atoms structures make multi-walled carbon nanotubes. Carbon nanotubes are ideal