Available online at www.sciencedirect.com
ScienceDirect
Composites Science and Technology 68 (2008) 639–649
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

On the impact response of electrified carbon fiber polymer matrix composites: Effects of electric current intensity and duration

Robert L. Sierakowski [a], Igor Ye. Telitchev [b], Olesya I. Zhupanska [c,*]

[a] Air Force Research Laboratory, Eglin AFB, FL 32542, USA
[b] University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4
[c] University of Iowa, 2416A Seamans Center for the Engineering Arts and Sciences, Iowa City, IA 52242-1527, USA

Received 17 April 2007; received in revised form 10 September 2007; accepted 26 September 2007
Available online 6 October 2007

Abstract

In this work, an investigation of the effects of an electric current on the low velocity impact response of carbon fiber polymer matrix unidirectional and cross-ply composites carrying an electric current is presented. Preliminary experimental results show that a short-term application of the DC electric current leads to an increase in the impact resistance of composites, whereas a prolonged application of the current induces a significant heating in the electrified composites and has rather a detrimental effect. The analysis focuses on elucidating the roles of current intensity, duration, and associated current-induced heating in alteration of the composites response. The contributions of Joule heat and contact resistance heat are particularly highlighted.

Keywords: A. Polymer–matrix composites (PMCs); A. Carbon fibers; B. Impact behavior; C. Damage tolerance; Electro-thermo-mechanical coupling

1. Introduction

Today's technology relies heavily on the use of the so-called hybrid materials that allow for achieving advanced structural and functional capabilities. Future technological advancements will demand materials with multifunctional capabilities that will be expected to provide at least one additional function to their primary function or adapt their performance in accordance to changes in the operating environment. In this respect, composite materials present rich possibilities for development of multifunctional and functionally adaptive structures where multifunctionality may be achieved through interaction of mechanical, electromagnetic, thermal, and other fields. In particular, the existing experimental evidence [1] suggests that exposure of a carbon fiber polymer matrix composite material to the electromagnetic field leads to changes in the material's strength and resistance to delamination. The authors of [1] performed a series of experiments to assess the effectiveness of laser photography in documenting the formation and propagation of cracks in composite materials with and without electromagnetic loading. Their preliminary results revealed that the strength of a composite material and its resistance to debris-induced fracture and delamination can be increased by application of an electric current to the composite. With respect to carbon fiber polymer matrix composites that we are interested in, we have identified a number of basic factors contributing to the phenomenon observed in [1]: (i) coupling of the mechanical and electromagnetic fields if both mechanical and electromagnetic loads are applied; (ii) Joule heating, produced in conducting carbon fibers and transferred into a polymer matrix; (iii) contact resistance heating developed at the composite–electrode contact; (iv) change in the failure mechanisms in the presence of the electromagnetic field. Our ultimate goal is to study experimentally and theoretically the combined effect of the aforementioned factors on the dynamic response of carbon fiber polymer matrix composites.

* Corresponding author. Tel.: +1 319 335 5678; fax: +1 319 335 5669.
E-mail address: ozhupans@engineering.uiowa.edu (O.I. Zhupanska).

0266-3538/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2007.09.019

Although the problem of coupling of mechanical and electromagnetic fields in solids have been studied in the past, the scope of these studies has been limited mostly to isotropic conductors, metals and superconductors [2,3]. Recently, the mechanical and electromagnetic fields in the fiber-reinforced polymer matrix composites have been investigated theoretically and experimentally by the authors in [4–7]. Carbon fiber polymer matrix composites consist of electrically conductive carbon fibers and dielectric polymer matrix, and are electrically conductive and electrically anisotropic at the macroscale. Therefore, simultaneous application of mechanical and electromagnetic loads to such materials results in a complex interaction of mechanical, electromagnetic, and associated thermal fields. This interaction is essentially multiphysic and occurs at various spatial and temporal scales. The corresponding mathematical models are essentially non-linear and involve simultaneous solving of equations of motion, Maxwell's equations, and heat transfer equations. It is worth mentioning that in the case of an electrically anisotropic but magnetically isotropic solid bodies (i.e. carbon fiber polymer matrix composites) coupling of mechanical and electromagnetic fields is especially complex since the Lorentz force depends not only on the external electric and magnetic fields, intensity and direction of an applied electric current, velocity of the body, but also on the rate of deformation [4]. Our study [4] was restricted to the macroscopic problem of dynamic interaction of the mechanical and electromagnetic fields in composites in the situations where Joule heating effects can be disregarded. Along with the general mathematical framework, we have developed a 2D approximation for thin composite plates and considered the problems of the static and dynamic mechanical response of DC and AC electric current-carrying composite plates subjected to mechanical load and immersed in the magnetic field. It was shown that an electromagnetic field, depending on the direction of its application and intensity, may significantly enhance or reduce the stress state of the mechanically loaded composite plate. Changes in the local compression and deformation around the low velocity impact zone in a unidirectional current-carrying composite have been studied in [5], where three-dimensional impact and electromagnetic load induced stresses and displacements have been calculated. Analysis of the failure surface around the impact zone revealed that the electromagnetic load may move the failure envelope, which in turn may lead to the composite failure at higher mechanical load. In short, the results of [4,5] suggest possibility to amplify or counterbalance the effect of the mechanical load in composites by a specially applied electric current and magnetic field.

The current work continues our ongoing research efforts [6,7] on the experimental investigation of the effects of a DC electric current on the impact response and damage of electric current-carrying carbon fiber polymer matrix composites. In particular, this study is focused on elucidating the role of the current intensity, duration, and the associated electric heating in alteration of the unidirectional and cross-ply carbon/epoxy composites response. Given the observed significance of current-induced heating on the impact behavior of composites, we complement our experimental results by a quantitative analysis of the heating effects in electrified composites that are caused by electric conduction (Joule heating) and composite–electrode electric contact (contact resistance heating).

Although to the best authors' knowledge investigation presented here is the first of its kind, several experimental studies on the effects of temperature on the impact response of polymer matrix composites were conducted in the literature [8–10]. In these studies low velocity impact tests were conducted using an environmental chamber to ensure specific temperature conditions.

With respect to the investigation of current induced heating in composites, a few works could be mentioned. In [11,12] heating of conductive fiber composites was investigated both experimentally and theoretically in the context of induction processing of composites. The focus of these studies was exclusively on the eddy current-induced thermal effects in composites immersed in an alternating magnetic field.

2. Experimental study of the impact response of electrified composites

2.1. Experimental setup

The purpose of the presented experimental studies was to elucidate the mechanisms contributing to the change in the impact resistance of electrified unidirectional and cross-ply carbon fiber polymer matrix composites first observed in [1] and later confirmed in [7]. The experimental setup used in this study was similar to that described by the authors in [6,7].

Here we outline the procedures of application of an electric current and impact testing of electrified carbon fiber polymer matrix composites (more detailed description can be found in [6]). An electric current was applied to the composite plates through the copper bar electrodes by means of a DC load regulated HP 6012B DC Power Supply (40 V) before each impact test and was running in the specimens during the test. A clamping fixture used in the experiments is shown in Fig. 1.

Electrical contact resistance between the copper bars and composite plates was minimized by coating the contacting edges of the composite plates with highly electroconductive silver filled epoxy Duralco 120. In the case of unidirectional plates an electric current was applied in the fiber direction, and in the case of cross-ply plates the current was applied in either 0° or 90° directions.

Various impact tests were conducted with no electric current and with a DC current of 25 A and 50 A applied to the composite plates. The GRC 8120 Drop Weight Impact Test Machine was used for testing. In order to avoid electrical contact between the striker and an