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A STUDY OF COMPOSITE STRENGTHENING THROUGH APPLICATION OF AN ELECTRIC FIELD

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15. SUBJECT TERMS
Polymer Matrix Composites, DC Electric Current, Joule Heating, Low Velocity Impact

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This paper studies effects of an electric field on the mechanical response of unidirectional carbon fiber polymer matrix composites. The existing experimental evidence suggests that exposure of a composite material to the electromagnetic field leads to changes in the material's strength and resistance to delamination. We have analyzed the effects promoting this phenomenon: coupling of mechanical and electromagnetic fields and Joule heat effects and develop an experimental setup for impact tests of the composites carrying an electric current. Experimental results of low velocity impact tests on unidirectional carbon fiber polymer composite plates carrying a DC electric current show that electrified composites fail at higher impact load. Moreover, a larger electric field leads to a larger impact load that may be sustained by the composite. Finally, analysis of the Joule heat effects reveals that it is not a primary mechanism for the strengthening phenomenon observed in the experiments.

Key words: polymer matrix composites, DC electric current, Joule heating, low velocity impact.

INTRODUCTION

Future technological advancements depend to a great extent on the ability to optimize the existing materials and to utilize special properties of new materials in their multifunctional capacities. In this connection, there is an immediate need in materials that are capable to provide at least one additional function or adapt their performance in accordance to changes in the operating environment. For example, the critical importance of light-weight armor to the military and civilian applications calls for in-depth studies of

both fundamental and technological aspects of hybrid multifunctional material systems that offer structural capability and ballistic protection simultaneously. Therefore there is a strong interest in investigation of possibilities for improvement of multi-hit survivability in the composites by application of the electric current and magnetic fields. The complex mechanical response of composite materials presents rich possibilities for enhancing their structural properties by subjecting them to additional electromagnetic, thermal, chemical, etc. treatment. 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. Snyder et al. [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 the application of an electromagnetic field across the composite.

The factors promoting this phenomenon may be related to deformation of composites due to coupling of mechanical and electromagnetic fields and/or changes in the material properties associated with microscopic processes (Joule heat effects, changes at the fiber-matrix interface) resulted from the application of an electromagnetic field to the composite material. Moreover, some studies on crack propagation in metals in the presence of an electric current advocate that an electric field may lead to the crack arrest due active dissipation of energy at the crack tip where extensive plastic zone is

formed []. Which mechanism is the main contributor to the increased strength and resistance of the composite material remains an open research question.

The current work presents the experimental and theoretical investigations of the effects of an electric current on the dynamic mechanical response of carbon fiber polymer matrix composites. In the beginning we provide foundations of the theory of electrically and mechanically anisotropic current-conducting solids. We focus our attention on the interacting effects of the mechanical and electromagnetic loads and also Joule heat effects. After that an experimental setup for impact tests of the current-conducting composite panels is described and experimental results on unidirectional carbon fiber reinforced polymer matrix current-carrying composite plates are discussed.

NOMENCLATURE

a	=	plate width
$\vec{B}$	=	magnetic induction vector
$c^{(f)}$	=	specific heat of the fiber
$c^{(m)}$	=	specific heat of the matrix
$\vec{D}$	=	electric displacement vector
d	=	spacing between fiber bundles
$\vec{E}$	=	electric field vector
F_i	=	body force components
$\vec{F}^L$	=	Lorentz ponderomotive force
h	=	plate thickness
$\vec{H}$	=	magnetic field vector
h_{ep}	=	thermal fiber/matrix contact conductance
h_s	=	convection coefficient
I	=	electric current
$\vec{J}^*$	=	density of the external electric field
J_x^*	=	x component of the applied electric current density
$\vec{j}$	=	electric current density vector
$k_r^{(f)}$	=	thermal conductivity of the fiber in the radial direction
$k^{(m)}$	=	thermal conductivity of the matrix
Q	=	Joule heat density
R	=	electrical resistance
r	=	radial coordinate in the cylindrical coordinate system
r_b	=	fiber bundle radius
S	=	entire surface of the plate
$T^{(f)}$	=	temperature field in the fiber bundle
$T^{(m)}$	=	temperature field in the matrix
$T_{\max}$	=	maximum temperature in the plate
$T_{\min}$	=	minimum temperature in the plate

T_{outside}	=	temperature in the medium surrounding the plate
t	=	time
$\vec{u}$	=	displacement vector
u_i	=	displacement components
V	=	voltage
x, y, z	=	spatial coordinates
ϵ	=	electrical permittivity tensor
ϵ_0	=	electrical permittivity in vacuum
μ	=	permeability
ρ	=	density of the solid body
ρ_e	=	charge density
$\rho^{(f)}$	=	fiber density
$\rho^{(m)}$	=	matrix density
σ	=	electrical conductivity tensor
$\sigma_x^{(f)}$	=	electrical conductivity of the fiber
τ_{ij}	=	stress tensor components

COUPLING OF MECHANICAL AND ELECTROMAGNETIC FIELDS IN COMPOSITES AND ITS IMPLICATIONS

Although carbon fiber polymer matrix composites consist of the electrically conductive carbon fibers and dielectric polymer matrix, but on the macroscale such composites are electrically conductive. Therefore, simultaneous application of mechanical and electromagnetic loads inevitably leads to the coupling of mechanical and electromagnetic fields. Mathematically speaking the problem reduces to solving of equations of motion and Maxwell's electrodynamic equations, which are coupled through the Lorentz ponderomotive force that represents the effects of an electromagnetic field in the solid body.

In this section we briefly dwell on the field equations for the mechanically and electrically anisotropic solids subjected to the mechanical and electromagnetic loads. All the details of the current discussion and derivations may be found in Zhupanska and Sierakowski [2,3]. It is well known that there is an interaction of the mechanical and electromagnetic fields in the electrically conductive solids when both mechanical and electromagnetic loads are applied. Equations of motion in the presence of an electromagnetic field are

$$\frac{\partial \tau_{ij}}{\partial x_j} + \rho(F_i + F_i^L) = \rho \frac{\partial^2 u_i}{\partial t^2} \quad (1)$$

Here τ_{ij} are the stress tensor components, u_i are the displacement components, ρ is the density of solid body, F_i are the body force components, F_i^L are the components of the Lorentz ponderomotive force that in the case of an electrically

anisotropic but magnetically isotropic solid body takes the form

$$\begin{aligned} \vec{F}^L = & \rho_e \left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B} \right) + \left(\sigma \cdot \left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B} \right) \right) \times \vec{B} \\ & + \left(((\epsilon - \epsilon_0 \cdot \mathbf{1}) \cdot \vec{E}) \times \vec{B} \right)_\alpha \nabla \left(\frac{\partial \vec{u}}{\partial t} \right)_\alpha + (\vec{J}^* \times \vec{B}), \end{aligned} \quad (2)$$

where $\mathbf{1}$ is the unit tensor of the second order, ϵ is electrical permittivity tensor, σ is electrical conductivity tensor, ϵ_0 is the permittivity in the vacuum, $\vec{u}$ is the displacement vector, $\vec{D}$ is the electric displacement vector, $\vec{B}$ is the magnetic induction vector, $\vec{E}$ is the electric field vector, ρ_e is the charge density (for electric conductors $\rho_e = 0$), $\vec{J}^*$ is the density of the external electric field, ∇ is the gradient operator, and Einstein's summation convention is adopted with respect to the index α . The third nonlinear term in Eq. (2) is due to anisotropy in electrical properties (it vanishes when electric field is isotropic), and the last term attributes to the electric current that the solid body carries. As one can see, the Lorentz force in composites depends on the external electric and magnetic fields, magnitude and orientation of the electric current with respect to the magnetic field, and velocity and the rate of deformation of the solid.

Maxwell's equations read as

$$\begin{aligned} \text{div} \vec{D} &= \rho_e, & \text{curl} \vec{E} &= -\frac{\partial \vec{B}}{\partial t}, \\ \text{div} \vec{B} &= 0, & \text{curl} \vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t} \end{aligned} \quad (3)$$

and equations of the electromagnetic field in electrically anisotropic but magnetically isotropic solids have the form

$$\begin{aligned} \vec{D} &= \epsilon \vec{E} + \mu (\epsilon - \epsilon_0 \cdot \mathbf{1}) \left(\frac{\partial \vec{u}}{\partial t} \times \vec{H} \right), \\ \vec{B} &= \mu \vec{H} - \mu \frac{\partial \vec{u}}{\partial t} \times ((\epsilon - \epsilon_0 \cdot \mathbf{1}) \cdot \vec{E}), \\ \vec{J} &= \sigma \left(\vec{E} + \frac{\partial \vec{u}}{\partial t} \times \vec{B} \right) + \rho_e \frac{\partial \vec{u}}{\partial t}, \end{aligned} \quad (4)$$

where μ is magnetic permeability, $\vec{J}$ is the current density vector, and $\vec{H}$ is the magnetic field vector.

The system of governing equations (1) and (3) is essentially nonlinear and coupled in the dynamic problems. But even in static problems, when equations of equilibrium (1) and Maxwell's equations (3) are not coupled, the Lorentz force (2) may be still present in (1) due to, for example, an externally applied DC current (the last term in (2)). For anisotropic thin plates the system of governing equations (1) and (3) may be

reduced to the 2D one by means of the classic Kirchhoff hypothesis of nondeformable normals and the corresponding electromagnetic hypothesis (see, for example [2], [3]). The systems of equations (1) and (3) or its 2D approximation constitute a mathematical framework within which a variety of problems involving electro-magneto-mechanical coupling for 3D and 2D bodies may be solved. For example, in [2] and [3] the problems of the static and dynamic mechanical response of DC and AC electric current-carrying composite plates in the presence of mechanical load and immersed in the magnetic field are considered. It is shown that electromagnetic field may significantly enhance or reduce the deformed state of the composite plate depending on the direction of its application and its intensity. Although the problems of interaction of mechanical and electromagnetic fields in solids have been studied in the past [4-7], the scope of these problems has been limited mostly to metals and superconductors.

Recently, changes in the local compression and deformation around the low velocity impact zone in a unidirectional current-carrying composite were studied in [8]. In this work the three-dimensional impact and electromagnetic loads induced stresses and displacements have been calculated. Analysis of the failure surface around the impact zone suggests that the electromagnetic load may move the failure envelope, which in turn may lead to the composite failure at higher mechanical load. Therefore, it is possible to amplify or counterbalance the effect of the mechanical load in composites by the specially applied electric current and magnetic field.

JOULE HEAT EFFECTS

Here we discuss Joule heating in composites due to an externally applied electric field. Joule heating is especially crucial in the mechanical response of electrified unidirectional carbon fiber polymer matrix composites that possess relatively low (in comparison to metals) electrical conductivity of fibers and thermal conductivity of the matrix. Our objective is to determine the variation in the temperature across the thickness of the carbon fiber polymer matrix composite plate due to an electric current passing in the carbon fibers.

A long cylindrical carbon fiber embedded in the polymer matrix and heated by DC current I produces Joule heat of the density Q :

$$Q = \frac{(J_x)^2}{\sigma_x^{(f)}}, \quad (5)$$

where J_x is electric current density, $\sigma_x^{(f)}$ is electrical conductivity of the fiber in the fiber direction. The electrical conductivity of the AS4 carbon fibers is $\sigma_x^{(f)} = \frac{1}{1.53} \times 10^3 \text{ 1/Omm}$, the electrical conductivity of copper, for instance, is $\frac{1}{1.72} \times 10^8 \text{ 1/Omm}$, and, according to (5), it means that Joule heat density produced in the carbon

fiber by a DC electric current is five orders of magnitude larger than that produced in the copper by the same current. Hence, in polymer matrix composites even moderate DC electric currents may lead to significant heating and subsequent alteration in the mechanical response.

In this section we evaluate the effects of Joule heating in electrified carbon fiber polymer matrix composites. The corresponding heat transfer problem between a conducting fiber and an insulator matrix is described by

$$\begin{aligned} k_r^{(f)} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T^{(f)}}{\partial r} \right) &= -Q + c^{(f)} \rho^{(f)} \frac{\partial T^{(f)}}{\partial t}, \\ k_r^{(m)} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T^{(m)}}{\partial r} \right) &= c^{(m)} \rho^{(m)} \frac{\partial T^{(m)}}{\partial t} \end{aligned} \quad (6)$$

with boundary conditions that correspond to the thermal contact resistance between the fiber and matrix

$$k_r^{(f)} \frac{\partial T^{(f)}}{\partial r} = k_r^{(m)} \frac{\partial T^{(m)}}{\partial r} = h_{cp} (T^{(m)} - T^{(f)}). \quad (7)$$

Here $T^{(f)}$ and $T^{(m)}$ are temperatures in the fiber and matrix correspondingly, $k_r^{(f)}$ is the thermal conductivity of the fiber in the radial direction that is assumed to be transversally isotropic, $k_r^{(m)}$ is the thermal conductivity of the matrix, which is isotropic, and h_{cp} is the thermal fiber/matrix contact conductance. Note that $h_{cp} = 0$ if there is no thermal resistance between the fiber and matrix, $c^{(f)}$ and $c^{(m)}$ are specific heat of the fiber and matrix correspondingly, and $\rho^{(f)}$ and $\rho^{(m)}$ are fiber and matrix densities. The first equation of (6) must be solved for fibers and the second equation of (6) must be solved for the matrix.

Let us consider unidirectional carbon fiber polymer matrix composite plate that carries a DC current I in the fiber direction (Fig. 1).

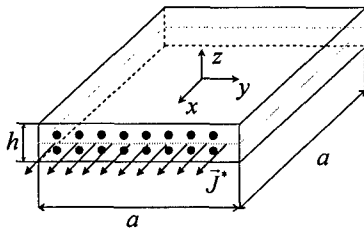


FIGURE 1. ELECTRIC CURRENT CARRYING COMPOSITE PLATE UNDER CONSIDERATION.

Assume that the ratio of the thickness, h , to the width, a , of the plate is small and Newton's convection takes place at the plate's surfaces $z = \pm h/2$, namely

$$\left(\frac{\partial T^{(m)}}{\partial y} \right) \Big|_{z=\pm h/2} = h_s (T_{\text{outside}} - T^{(m)}) \Big|_{z=\pm h/2}, \quad (8)$$

where h_s is the convection coefficient between the plate and the surrounding air and T_{outside} is the temperature of the surrounding air. The problem (7), (8), (9) for the composite plate is solved using finite element analysis.

Due to symmetry considerations instead of the entire plate we consider the strip: $0 \leq y \leq (r_b + d/2)$, $-h/2 \leq z \leq h/2$ (see Fig. 2), where r_b is the radius of the fiber bundle and d is the distance between fiber bundles.

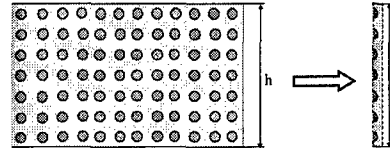


FIGURE 2. GEOMETRY FOR HEAT TRANSFER PROBLEM.

The following parameters were used in computations: fiber bundle radius $r_b = 69.444 \mu\text{m}$, fiber bundle spacing $d = 17.361 \mu\text{m}$ (based on 62% fiber volume in the composite), fiber thermal conductivity $k_r^{(f)} = 1.8 \text{ W/mK}$, matrix thermal conductivity $k_r^{(m)} = 0.2 \text{ W/mK}$ (epoxy matrix), fiber electrical conductivity $\sigma_x^{(f)} = \frac{1}{1.53} \times 10^3 \text{ 1/Omm}$ (as for AS4 carbon fibers), convection coefficient $h_s = 1000 \text{ W/m}^2\text{K}$, $h_{cp} = 0$, specific heat of the carbon fibers $c^{(f)} = 0.22 \text{ cal/(g K)} = 920.92 \text{ cal/(kg K)}$ at $167^\circ \text{F} = 75^\circ \text{C}$, specific heat of the epoxy matrix $c^{(m)} = 0.5 \text{ cal/g K} = 2093 \text{ cal/kg K}$, carbon fibers density $\rho^{(f)} = 1790 \text{ kg/m}$, and the epoxy matrix density $\rho^{(m)} = 1300 \text{ kg/m}$. Computations have been performed for different electric current densities J_x and plate thicknesses h .

Fig. 3 shows typical temperature variation across the thickness of the composite plate. As it could be expected, the maximum temperature, T_{max} , reaches in the middle of the plate ($z = 0$), the minimum temperature, T_{min} , is at the surface, $z = \pm h/2$. Moreover, in carbon fiber polymer matrix composite plates a strong temperature gradient appears as a result of application of a DC electric current.

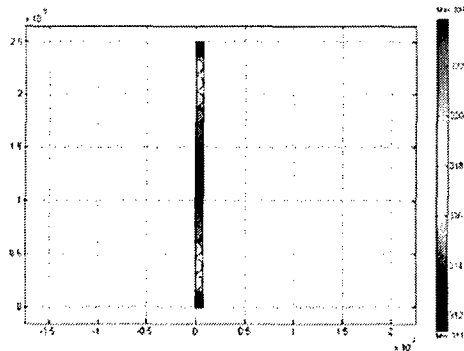


FIGURE 3. TEMPERATURE PROFILE ACROSS THE COMPOSITE PLATE THICKNESS.

It is worth noting that for the given volume of fibers in the composite and for electric current densities $J_x > 5 \times 10^4 \text{ A/m}^2$ the temperature in the matrix in the middle of the plate is practically the same as the temperature in the neighboring fiber bundle. Figure 4 shows the temperature jump $T_{\min} - T_{\text{outside}}$ at the composite plate surface as a function of the plate thickness h under different current densities J_x . As one may see there is strong nonlinear dependence between the electric current density and an increase in the temperature at the composite plate surface.

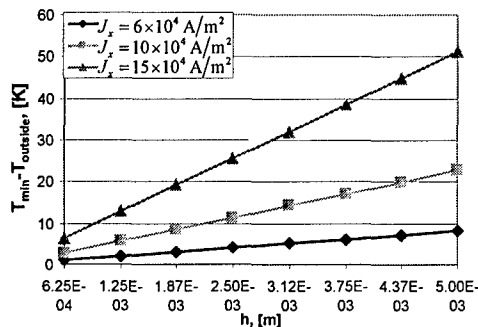


FIGURE 4. TEMPERATURE JUMP AT THE PLATE SURFACE VS. PLATE THICKNESS.

Figure 5 shows the difference in the temperature in the middle of the plate ($T_{\max}$) and the plate surface ($T_{\min}$) as a function of the plate thickness under different current densities J_x .

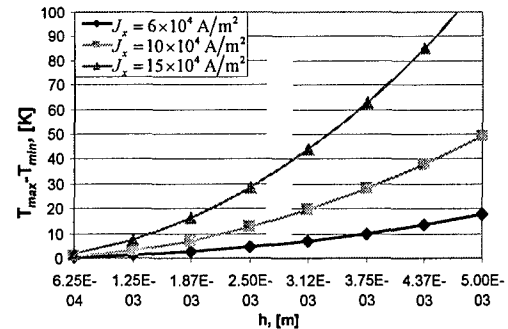


FIGURE 5. THE DIFFERENCE IN TEMPERATURE IN THE MIDDLE OF THE PLATE AND AT THE PLATE SURFACE VS. PLATE THICKNESS.

Results show that Joule heating leads to the significant temperature gradients across the composite plate. For example, in the composite plate of thickness $h = 0.005 \text{ m}$, the temperature at the plate surface $T_{\max} = 316.91 \text{ K} = 43.76^\circ \text{ C}$ but at the same time temperature in the middle of the plate can reach as high as $T_{\max} = 366.0676 \text{ K} = 92.92^\circ \text{ C}$, when the electric current density is $J_x = 10 \times 10^4 \text{ A/m}^2$. This may change, for example, the polymer matrix response from elastic to viscoelastic. Moreover, the thermal stresses cannot be ignored in such situation. Note that such temperature gradients correspond to the moment of time when the temperature in the composite plate reaches steady state. Short time applications of the DC current would not produce such large temperature changes, but still some temperature gradient across the plate thickness would arise. We have analyzed Joule heat effects in the polymer matrix composite plates in order to understand the phenomenon and design better the experiments.

The next sections contain the description of the experimental setup and discussion of the experimental results of the impact tests on the electrified carbon fiber polymer matrix composites.

EXPEPRIMENTAL SETUP

The *experimental part* of the work consists in low velocity impact tests of current carrying composite plates. The GRC 8120 Drop Weight Impact Test Machine was used for testing. This is a gravity driven impact machine equipped with controls for release of the drop weight (crosshead) and motorized hoist mechanism for easy return of the cross head to a predetermined drop position. This machine offer impact energies up to 1554 ft-lb (2105 J) and impact velocities up to 22.3 ft/s (6.9 m/s). An instrumented tup provides the measurement of force applied to a specimen by the falling drop weight assembly.

One of the major challenges of the experimental part was to develop a setup that enabled for effective application of an electric current to carbon fiber polymer matrix composites. We used a wooden-aluminum plate clamping device in order to

provide an electrical contact of the composite coupon with copper bus bars (Fig. 6).

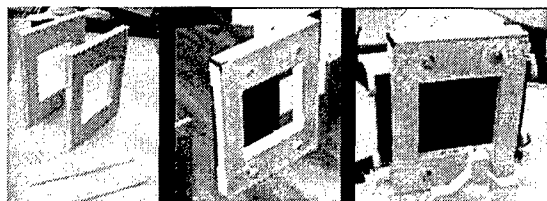


FIG. 6. PLATE CLAMPING DEVICE.

In order to improve electrical contact between copper bars and a composite plate, the edges of the plate at the contact zones (Fig. 7) were coated with an electroconductive material.

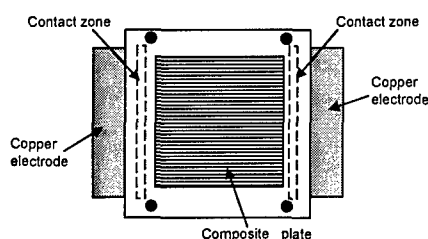


FIG. 7. DIAGRAM OF PLATE CLAMPING.

Various electroconductive materials were tested in order to determine the one that provides a good electrical contact between copper bus bars and a composite plate. We have determined that the silver filled epoxy and indium tape allow for the lowest impedance interface. The measurements have also shown that the electrical resistance of the copper-composite interface decreases when compression is applied to the jointed elements. After compression is released the best results are obtained for silver filled epoxy. The results of measurements for 16-ply unidirectional composite coupons with various electroconductive materials are shown in Table 1 and Fig. 8.

TABLE 1. RESULTS OF MEASUREMENTS OF ELECTRICAL CONTACT RESISTANCE FOR VARIOUS ELECTROCONDUCTIVE MATERIALS ON 16-PLY UNIDIRECTIONAL CARBON FIBER POLYMER MATRIX COUPONS.

		CONTACT RESISTANCE, OHM					
		direct contact	indium foil	copper tape, single sided adhesive	copper tape, double sided adhesive	3M XYZ electric. conductive adhesive tape	silver filled epoxy
initial joint	#1	failed	1.2	failed	5.8	10.2	25.5
	#2	failed	failed	failed	2.5	10.7	13.9
	#3	failed	3.2	2.4	5.7	19.5	2.2
	aver.	failed	failed	failed	4.67	13.47	13.87

compressed	#1	0.7	0.5	1.1	1.6	2.7	0.4
	#2	0.9	0.6	0.7	0.9	2.9	0.4
	#3	0.7	0.5	1.1	1.9	3.0	0.5
	aver.	0.77	0.53	0.97	1.47	2.87	0.43
Released	#1	1.9	0.7	1.7	2.5	6.7	0.5
	#2	2.0	0.7	1.0	1.5	5.8	0.5
	#3	2.0	0.6	1.4	3.9	8.1	0.5
	aver.	1.97	0.67	1.37	2.63	6.87	0.50

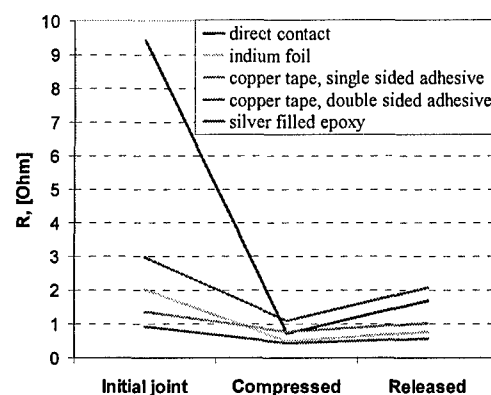


FIG. 8. ELECTRICAL CONTACT RESISTANCE (R) FOR DIFFERENT ELECTROCONDUCTIVE MATERIALS.

The complete experimental setup is shown in Fig. 9.

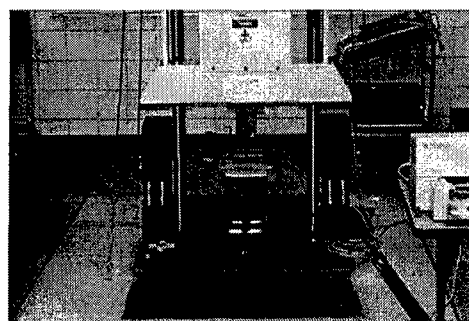


FIG. 9. IMPACT TESTING SETUP ENABLED FOR APPLICATION OF AN ELECTRIC CURRENT.

All specimens in the presented here impact experiments were 6 x 6 in (152.4 x 152.4 mm) unidirectional graphite epoxy composite plates with thickness 0.18 in (4.5 mm), 32 plies. An electric current was applied prior to each impact test by means of a DC load regulated Power Supply (40 V). An impact striker was flat-ended cylindrical striker partially fabricated of

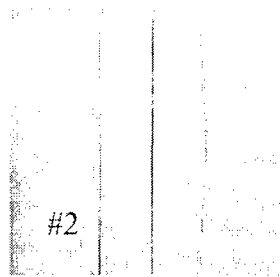
dielectric DELRIN® plastic. We used dielectric striker in order to avoid electrical contact between a striker and an impacted plate. The diameter and length of the striker were 0.5 in (12.7 mm) and 3.0 in (76.2 mm) respectively.

EXPERIMENTAL RESULTS

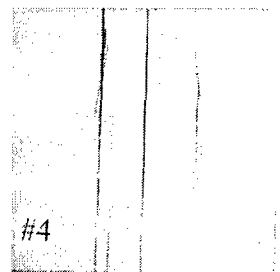
IMPACT TESTS ON ELECTRIFIED COMPOSITES

A series of tests was conducted with no electric current and with a DC current of 25 A and 50 A applied to the composite plate. The impact tests were performed at V_{50} velocity. This critical impact velocity has been determined in a series of preliminary experiments where two successive impact velocities were determined: the first one corresponded to the complete perforation of the plate and the other one led to failure of the plate without perforation. The latter velocity was taken as V_{50} . The measured difference in magnitude of these two successive velocities was 1 ft/s (0.3048 m/s). All conducted impact tests were fully instrumented. An electric current was applied immediately before the impact tests.

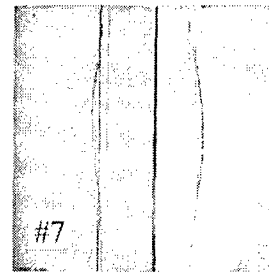
Figure 10 a), b), and c) show impacted plates for the case of 0 A, 25 A, and 50 A DC current applied to the plates.



a)



b)



c)

FIG. 10. IMPACTED PLATES: a) NO CURRENT WAS APPLIED TO THE PLATE; b) 25 A DC CURRENT WAS APPLIED TO THE PLATE; c) 50 A DC CURRENT WAS APPLIED TO THE PLATE.

In all three cases presented in Fig. 10 the plates were broken by major cracks propagating in the polymer matrix along the fiber direction. Therefore, the presence of an electric current has not changed the failure mode in the composite. But despite the similarity in the failure pattern, the impact load sustained by the composite with no current applied and in the presence of a DC electric current was different. Figure 11 illustrates the evolution of the impact response of the unidirectional composite plate with and without a DC electric current applied to the plate in the fiber direction.

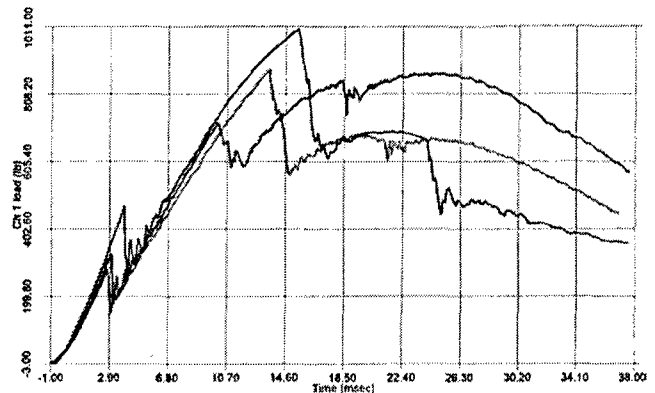


FIG. 11. EVOLUTION OF THE IMPACT RESPONSE OF UNIDIRECTIONAL GRAPHITE EPOXY COMPOSITE PLATE WITHOUT AND WITH A DC ELECTRIC CURRENT APPLIED TO THE PLATE IN THE FIBER DIRECTION.

The green line in Fig. 11 corresponds to the impact test with no electric current applied to the composite, the red line corresponds to the impact test on the plate carrying 25 A DC current, and the blue line corresponds to the impact test on the composite plate carrying 50 A DC current. All three tests were conducted for the impact velocity 2.7 ft/s (0.82 m/s) and height 1.4 in (3.5 cm). The maximum loads are the maxima of the spikes between 10 to 15 ms. The spikes at around 2.9 ms correspond to the force that causes incipient damage in the material (the so called incipient load). As one can see, application of the electric current increases plate's resistance to

impact induced damage. When an electric current of 25 A and 50 A was applied to the composite plate, the maximum load, sustained by the composite plate, has increased up to 24.7% and 43.6% respectively. Moreover, both incipient and maximum loads increase when an electric current applied.

Figure 12 shows the force-displacement relations for the same experiments. The green line in Fig. 12 corresponds to the impact test with no electric current applied to the composite, the red line corresponds to the impact test on the plate carrying 25 A DC current, and the blue line corresponds to the impact test on the composite plate carrying 50 A DC current.

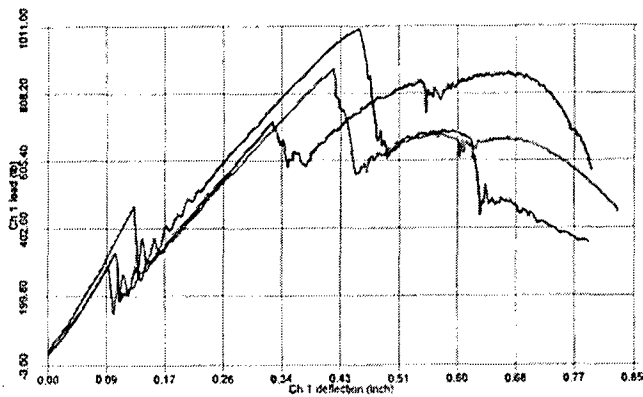


FIG. 12. FORCE-DISPLACEMENT RELATIONS DURING THE IMPACT OF UNIDIRECTIONAL GRAPHITE EPOXY COMPOSITE PLATE WITHOUT AND WITH A DC ELECTRIC CURRENT APPLIED TO THE PLATE IN THE FIBER DIRECTION.

An immediate conclusion follows from our experiments: an electric current increases the impact resistance of the unidirectional carbon fiber polymer matrix composite plates to the impact damage and enables the composite to fail at a higher impact load. But the character of failure does not change whether or not a unidirectional composite plate carries an electric current.

In the spirit of our previous discussion of the electromagnetic field and Joule heating effects in polymer matrix composites carrying an electric current, we have carried out the measurements of the magnetic field and investigated the Joule heat effects. The next sections contain the results of these studies.

MAGNETIC FIELD MEASUREMENTS

The measurement of the magnetic flux density was performed by Hall Effect Gaussmeter using transverse and axial magnetic field probes located near the surface of the composite plate. The plate thickness was 0.18 in (4.5 mm) with 32 plies of unidirectional carbon fiber mats, the plate dimensions were 6 x 6 in (152.4 x 152.4 mm). An electric current was applied prior to each magnetic flux measurement by means of a regulated DC Power Supply that provided an

electric current within the range from 0 to 50 A. All three components of the magnetic induction, B_x - in the fiber direction, B_y - in-plane component perpendicular to the fiber direction, B_z - transverse component perpendicular to the plate middle plane, were measured (see Fig. 1 for the reference of axes). The axial and transverse magnetic field probes were mounted in the center of the plate at $h=0.16$ in (4 mm) above the plate surface. The results of the measurements are presented in Table 2 and Fig. 13.

TABLE 2. RESULTS OF MEASUREMENTS OF MAGNETIC FLUX DENSITY.

I, [A]	U, [V]	B_x , [G] transverse probe	B_z , [G] transverse probe	B_y , [G]	
				transverse probe	axial probe
0	0	0	0	0	0
5	0.426	0	0.46	0.2	0.29
10	0.82	0.025	0.93	0.5	0.58
15	1.12	0.04	1.32	0.8	0.91
20	1.43	0.07	1.65	1.15	1.12
25	1.75	0.075	2.15	1.45	1.5
30	2.02	0.095	2.6	1.65	1.75
35	2.09	0.13	3	2.2	2.1
40	2.33	0.23	3.2	2.55	2.4

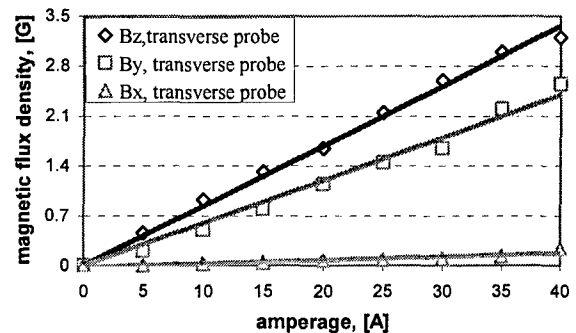


FIG. 13. MAGNETIC FLUX DENSITY AS FUNCTION OF THE APPLIED CURRENT FOR 32-PLY UNIDIRECTIONAL GRAPHITE EPOXY PLATE.

As it is expected, B_y is the largest component of the magnetic field and B_x is almost equal to zero. Besides this, there is a linear variation between the magnitude of an electric current and its magnetic field. Such behavior of the magnetic field is predicted from the solution to the magnetostatic problem. For the considered plate (Fig. 1), the magnetostatic problem is formulated as

$$\begin{aligned}\text{curl } \vec{H}^{(i)} &= \vec{J}^*, \text{div } \vec{B}^{(i)} = 0, \\ \text{curl } \vec{H}^{(e)} &= 0, \text{div } \vec{B}^{(e)} = 0,\end{aligned}\quad (9)$$

with boundary conditions

$$\vec{H}^{(i)}|_S = \vec{H}^{(e)}|_S, \quad (10)$$

where the superscripts "i" and "e" correspond to the interior and exterior of the plate respectively and S is the plate surface. Although in the case of rectangular plate a simple analytical solution to the problem (9)-(10) does not exist, the structure of the equations (9) and (10) immediately suggests that the magnetic field is a linear function of the electric current density, which is a linear function of the electric current.

JOULE HEAT EFFECTS: EXPERIMENTAL

The previously discussed impact tests were conducted immediately after application of an electric current. So we have not observed any temperature change at the plate surfaces due to a passing current. The measured temperature at the plate surfaces was around 70°F (21°C) before and after an impact test.

In order to evaluate Joule heat effects due to DC current we have performed somewhat different tests. In these tests, 25 A DC current had been applied to the composite plate until temperature in the plate reached a steady state (for considered 32-ply composite plates it took 24 min to reach steady state temperature of the 96.7°F (35.94°C) in the center of the plate surface). After this, an impact test was performed with the current still passing in the plate. Figure 13 shows impacted plates for the case when a 25 A DC current had been applied immediately before the impact test (#4) and for the case when a 25 A DC current was being applied for 24 min (until the temperature reached a steady state) before the impact test was performed.

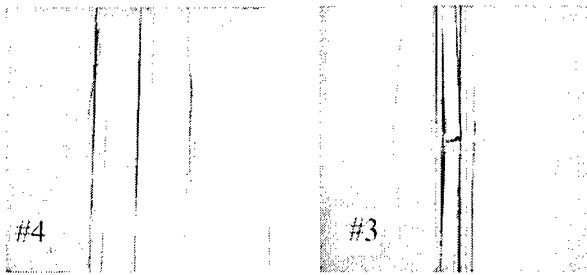


FIG. 13. IMPACTED PLATES: #4 – 25 A DC CURRENT WAS APPLIED IMMEDIATELY BEFORE THE IMPACT TEST, #3 – 25 A HAD BEEN APPLIED FOR ABOUT 24 MIN BEFORE THE IMPACT TEST WAS CARRIED OUT.

As one can see the Joule heat has a distinct effect on the failure mode. Short application of the electric current

(specimen # 4) led to the polymer matrix failure along the fiber direction, and an extensive application of the current caused significant Joule heating of the composite plate which resulted in the "localization" of the damage zone (perforation of the plate across the fibers) and both fiber and matrix failure (specimen #3). Further we notice that according to our analysis of the Joule heating in the carbon fiber polymer matrix composite plate discussed above, there is a large temperature gradient in the plate #3 due to extensive application of the DC current. Under the conditions of the experiment #3 we may expect a 30°C difference in the temperature in the middle of the plate and at the plate surface. Therefore, if the measured temperature at the surface of the plate was 35.94°C, the temperature in the middle of the plate is expected to be about 66°C.

Figure 14 illustrates the evolution of the impact response of the unidirectional composite plates carrying 25 A DC current for short period of time (red line) and for 24 min before the actual impact test was carried out (blue line).

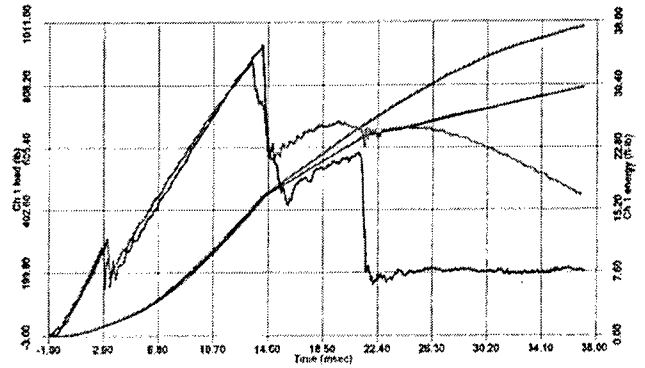


FIG. 14. EVOLUTION OF THE IMPACT RESPONSE OF COMPOSITE PLATE CARRYING A 25 DC ELECTRIC CURRENT: RED LINES – CURRENT WAS APPLIED IMMEDIATELY BEFORE THE IMPACT, BLUE LINES – CURRENT WAS APPLIED FOR 24 MIN. BEFORE THE IMPACT.

Although an extensive application of the DC electric current increased the maximum load sustained by the plate (see the spikes between 10.7 ms and 14.6 ms), the following failure induced a considerable drop in the amount of impact energy absorbed by the plate (see the red (no Joule heating) and blue (extensive Joule heating) lines on the right of the Fig. 14). The Joule-heated plate absorbed 24.4 % less energy compare to the plate that carried a DC current only briefly before the impact.

Based on these experiments, we can draw a preliminary conclusion that Joule heating is not a primary factor responsible for the increase in the impact resistance of current carrying composites.

CONCLUSIONS

In this work we have developed an experimental setup for study of the impact response of carbon fiber polymer matrix composites in the presence of an electric field. This setup includes procedure to apply an electric current, impact testing, along with the temperature and magnetic field measurements. A series of low velocity impact tests have been performed in order to assess the damage resistance of electrified carbon fiber polymer matrix composites. The tests have been carried out under 0 A, 25 A, and 50 A DC electric currents applied to the composites plates. The results of measurements have shown an increase in the impact resistance of the composites in the presence of the DC electric current. Moreover, we have observed considerable dependence of the impact-induced damage upon the intensity of the electric field applied to the composite: a larger electric field leads to a larger impact load that may be sustained by the composite. Analysis of the Joule heat effects reveals that it is not a primary mechanism for the strengthening phenomenon observed in the experiments.

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