LOW VELOCITY IMPACT OF ELECTRIFIED CARBON FIBER POLYMER MATRIX COMPOSITES

Sierakowski R. L.*, Telichev I. Y., Zhupanska** O. I.**
***Air Force Research Laboratory, **University of Florida, REEF**

Keywords: *polymer matrix composites, DC electric current, impact*

Abstract

The current work aims at experimental and theoretical investigations of the effects of an electric current on the dynamic mechanical response of 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 resistance to the impact load and damage. To develop an understanding and to quantify the observed phenomena we have conducted a series of low velocity impact tests on electrified unidirectional and cross-ply carbon fiber reinforced polymer matrix composites. The results of measurements show considerable dependence of the impact-induced damage upon the intensity of the electric field applied to the composite. On the theoretical side, we are developing multi-physics models to investigate the effects of coupling of mechanical and electromagnetic fields in composites in order to elucidate the mechanisms behind the observed phenomena and provide guidelines for further studies.

1 Introduction

Complex mechanical response of fiber-reinforced composite materials presents rich possibilities for enhancing their structural properties by subjecting them to additional electromagnetic, thermal, chemical, etc. treatment. In particular, existing experimental evidence [1] suggests that exposure of a 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. Carbon fiber polymer matrix unidirectional composite plates have been subjected to a mechanical impact in the presence of a DC electric current of 20 and 40 A, and without electric current. The results of the impact test have revealed that the damage resistance of the composite plates can be increased by the application of an electric current across the composite.

The factors promoting the observed phenomena are related to a complex multiphysic interaction of mechanical, electromagnetic, and thermal fields in carbon fiber polymer matrix composite materials. To quantify the phenomena observed in the experiments [1] we developed an experimental setup for low velocity impact testing of electric current-carrying composites [2] and have conducted preliminary studies [3] on electrified carbon fiber polymer matrix composites.

The present work is a continuation of our effort focused on the investigation of possibilities for improving impact resistance of carbon fiber reinforced polymer matrix composites by application of an electromagnetic field [2-6]. In this work we present further experimental results on the low velocity impact of electrified composites along with the analysis on the role of time of electric current application in the mechanical response of electrified composites.

2 Experimental Setup

The experimental setup used in this study was described in [3]. Here we briefly outline the procedures of application of an electric current and subsequent impact testing of electrified carbon fiber polymer matrix composites.

The GRC 8120 Drop Weight Impact Test Machine was used for testing (Fig. 1).

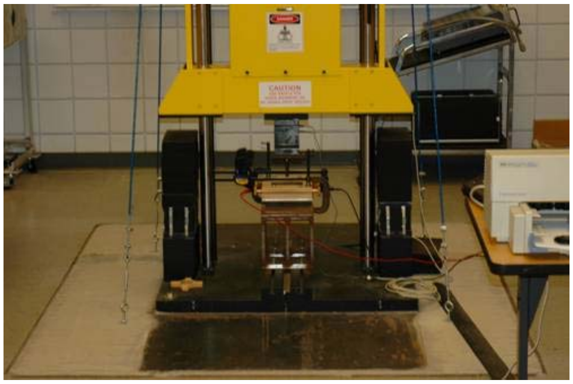


Fig. 1. GRC 8120 Drop weight impact test machine

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 fixture in order to provide an electrical contact of the composite coupon with copper bus bars. To improve electrical contact between copper bars and a composite plate, the edges of the plate at the contact zones were coated with highly electroconductive silver filled epoxy Duralco 120. A clamping fixture used in the experiments is shown in Fig. 2.

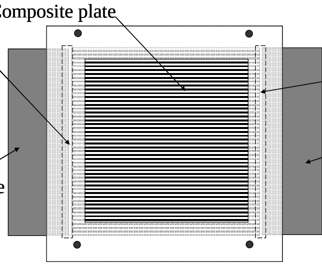


Fig. 2. Clamping fixture

We remark that various electroconductive materials (copper tapes, indium foil, silver filled epoxy) were tested in order to determine the one that provides the best 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. 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 0^0 or 90^0 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. We used a flat-ended cylindrical impact striker, which was partially fabricated of dielectric DELRIN® plastic in order to avoid electrical contact between the striker and an impacted plate. The diameter and length of the striker were 12.7 mm and 76.2 mm, respectively. The specimens used in the experiments were 4.5mm thick, 152.4 x 152.4 mm 32-ply carbon fiber polymer matrix composite plates. The copper bars were in 9.525 mm thick, 152.4 x 50.8 mm.

The general experimental procedure in all impact tests was as follows. First, non-electrified specimens had been tested and the corresponding V_{50} velocity had been determined. After that, impact tests on the specimens carrying 25 A and 50 A DC currents were conducted at the V_{50} velocity determined in the tests on non-electrified specimens. The results obtained on electrified composites were compared with those produced in tests on non-electrified composites.

Next section discusses the experimental results.

3 Experimental Findings

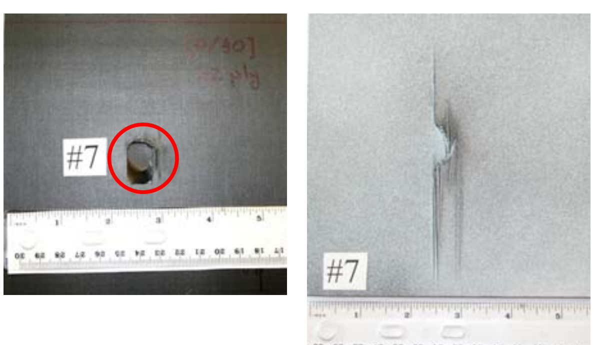
Experiments on unidirectional composites were reported by the authors previously [3]. Here we shortly reiterate on the findings for the purpose of further comparisons with the results on the cross-ply composites.

The results of measurements on unidirectional composites show considerable dependence of the impact-induced damage upon the intensity of the electric field applied to the composite. In particular, when an electric current of 25 A and 50 A was applied to a unidirectional carbon fiber polymer matrix composite plate, the maximum load sustained by the plate has increased up to 24.7% and 43.6% respectively. Moreover, both incipient and maximum load increase when an electric current is applied to the composites. Furthermore, there is a direct relation between the field applied to the composite and the propagation of the impact damage: the stronger was the applied field, the larger increase in the maximum impact load was observed in the experiments. The aforementioned results are valid for the case when an electric current is applied immediately before the impact. Remarkably, it was determined that prolonged application of an electric current to the carbon fiber polymer matrix composites leads to a significant Joule heating that eliminates the positive effect of the short-term current application.

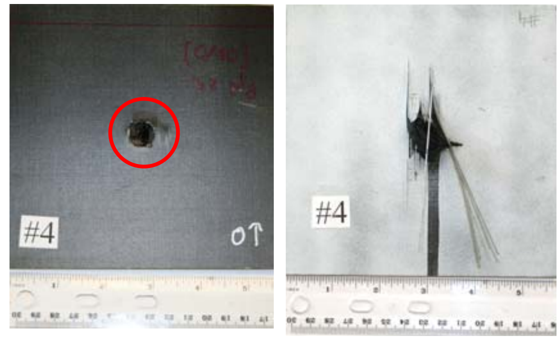
The effect of an electric field on cross-ply composites is quite different: application of current to cross-ply composite plates reduces significantly the amount of the impact damage and increases the amount of the absorbed energy, but does not alter the maximum load sustained by the composite. Next we report the results of impact tests on electrified cross-ply plates in more detail.

For every magnitude of the electric current (0 A, 25 A, and 50 A), four impact tests were conducted. In two of them the current was applied in 0^0 direction and in the other two the current was applied in 90^0 direction. All tests were conducted at velocity of about 1.585 m/s, determined in the preliminary tests on non-electrified plates. It turned out that with no electric current being applied, non-perforated specimens exhibited indentation of 3.556 mm deep on the front side of the specimens and extensive delamination along with matrix and fiber failures visible on the back side.

Figures 3 and 4 show a non-perforated non-electrified specimen and a perforated non-electrified specimen, respectively.

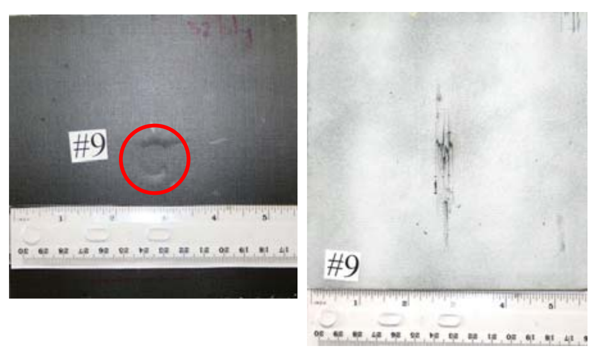


a) b)
Fig. 3. Non-electrified non-perforated cross-ply composite plate: a) front side; b) back side



a) b)
Fig. 4. Non-electrified perforated cross-ply composite plate: a) front side; b) back side

Although a 25 A current applied in either 0^0 or 90^0 direction had a similar effect on the impact response of the cross-ply plates (i.e. half of the specimens were perforated and the other half were not), the indentations in non-perforated electrified plates were considerably shallower comparing with those in the non-perforated non-electrified specimens. When a 50 A DC electric current was applied to the composites in either 0^0 or 90^0 directions, none of the tested specimens were perforated. The front side of impacted plates exhibited slight circular imprints of the striker and did not show any indentation (see Fig. 5).

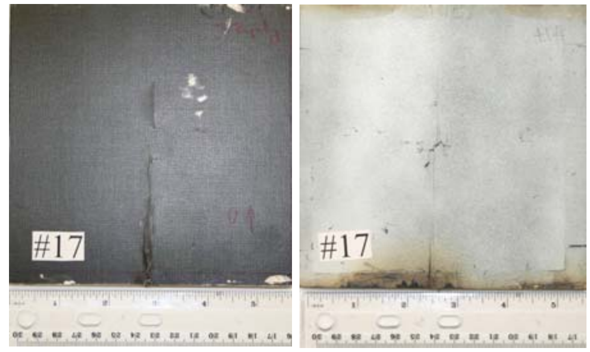


a) b)
Fig. 5. Cross-ply composite plate carrying a 50 A DC current: a) front side; b) back side; c) side view.

Obviously, an application of the electric current to the cross-ply composite plates leads to a substantial reduction of impact induced damage, which is also manifested by the considerable increase in the energy absorption. Once again, there is a direct relation between the field applied to the composite and the propagation of the impact damage: the stronger was the applied field, the less damage was observed in the experiments. As far as the impact load is concerned, we have not observed any essential difference in the electrified versus non-electrified cross-ply plates.

We emphasize again that in the experiments presented above it was essential that composite plates carried an electric current during the moment of the impact and that the current was applied immediately before the impact, so no temperature changes were observed at the plates' surfaces.

Carbon fibers are electrically conductive whereas a polymer matrix is dielectric. Therefore Joule heating, produced in conducting carbon fibers and transferred into a polymer matrix may play a certain role in the response of electrified carbon fiber polymer matrix composites. In order to evaluate heat effects due to a DC current we have performed somewhat different tests. In these tests, a 50 A DC current had been applied to the cross-ply composite plate until temperature in the plate reached a steady state (for considered 32-ply composite plates it took 36 min to reach steady state temperature of the 70 ^{0}C in the center of the plate's surface). After this, impact tests were conducted with the current still passing through the plates. The tests were carried out at the V_{50} velocity determined in the tests on the non-electrified plates. Remarkably, none of the tested specimens were perforated and no indentations were formed. At the same time, extensive heating in the electric contact at the composite-copper interface led to some degradation of the matrix in the region adjacent to the contact and resulted in a long crack formed during the impact (see Fig. 6) and reduction in the maximum impact loads compared to the plates that were subjected to the current for a short period of time before the impact.



a) b)

Fig. 6. Cross-ply composite plate carrying a 50 A DC current for 36 min before the impact: a) front side; b) back side

Hence, prolonged application of an electric current to the carbon fiber polymer matrix composites leads to a significant Joule heating that eliminates the positive effect of the short-term current application.

When current was switched on and off before the impact, no change in response comparing to non-electrified composite plates was observed. Therefore, it seems that an increase in the impact resistance due to an electric current is a reversible effect that disappears when the current is turned off. In other words, an increase in the damage resistance can be achieved in composite structures by a short-term current application at the moment of impact; a prolonged application of the current is not only unnecessary, but detrimental.

The results for energy absorptions and maximum loads for short-term, long-term current applications and for the case when current was turned on and off briefly before the impact are shown in Fig. 7. As one may see, an electric current greatly affects the amount of energy absorbed by cross-ply plates. Namely, all cross-ply plates carrying a DC electric current of 50 A were not perforated in the experiments. And the result of non-perforation was achieved under both short-term and long-term electric current applications. At the same time, when the current was turned on and off briefly before the impact and the composite plates were not carrying an electric current during the moment of impact, there was no change in the response compare to the plates that were non-electrified at all. As regards the impact load there is a clear dependence in the maximum impact load on the time of the current's application. Long-term application of an electric current results in the considerable drop in the maximum impact load as it shown in Fig. 7.

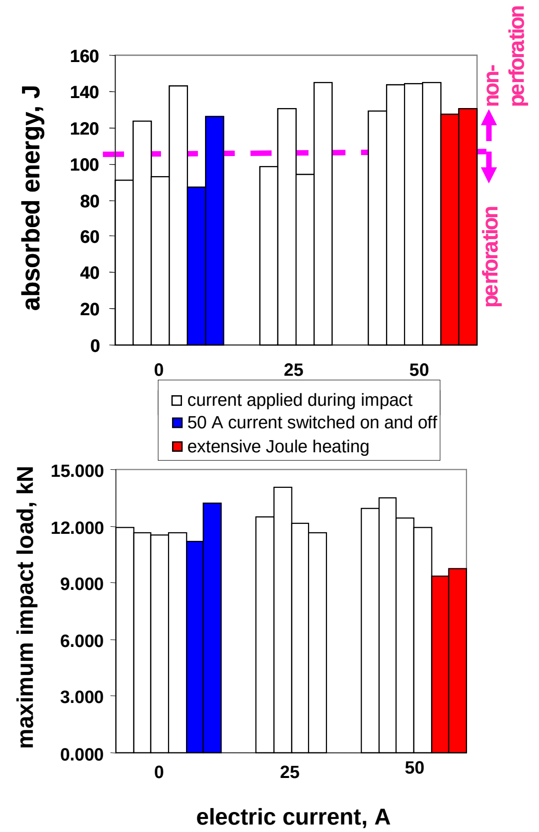


Fig. 7. Energy absorption and maximum impact loads as function of the electric current magnitude in low velocity impact tests on cross-ply composite plates

To further an understanding of coupling between mechanical, electric and thermal fields we have conducted an analysis of the temperature field that develops in the electrified composite. Next section discusses the issue and reports the results of computational studies.

4. Analysis of the Temperature Changes Due to an Electric Current

Heating in the composite observed in the experiments occurs due to Joule heat produced in the conductive fibers and due to contact resistance heat developed in the electric contact of the composite with electrodes (in our case – copper bars).

The density of the heat, q_c, developed in the electrical contact with contact resistance R_c due to a DC current I flowing through the contact surface, A_c, is determined as

$$q_c = \frac{I^2 R_c^2}{A_c}. \quad (1)$$

The Joule heat density due to the applied DC current is

$$Q^{DC} = \frac{I^2}{A^2 \sigma}, \quad (2)$$

where A is the cross-sectional area through which the current is passing, and σ is the electrical conductivity of the composite in the direction of the current.

The heat equation that has to be solved in the composite is

$$\nabla \cdot (\mathbf{k} \nabla T) = -Q^{DC} + c\rho \frac{\partial T}{\partial t}. \quad (3)$$

Here T denotes temperature, t is time, c is the specific heat and $\mathbf{k}$ is the thermal conductivity tensor. The boundary condition at the composite-electrode bar contact interface is as follows

$$k_x^{(composite)} \frac{\partial T^{(composite)}}{\partial x} - k^{(electrode)} \frac{\partial T^{(electrode)}}{\partial x} = q_c. \quad (4)$$

Here $k_x^{(composite)}$ and $k^{(electrode)}$ are thermal conductivities of the composite and electrode, correspondingly, and x is the axis orthogonal to the contact interface. Note that in the case of cross-ply plate the boundary condition (4) holds only at those regions of the composite-electrode interface, where an electric contact is present. Similarly, Joule heat (2) is produced only in the plies that carry an electric current. Moreover, surfaces S_j of the composite plates and copper bars, other than those that are in the electric contact, are exposed to air, and Newton's convection is taking place:

$$\left(\frac{\partial T}{\partial x_i} \right) \Big|_{S_j} = h_k \left(T^{amb} - T \right) \Big|_{S_j}, \quad (5)$$

where h_k is the convection coefficient between the composite plate (or copper bars) and air, and T^{amb}

is the temperature of the surrounding air. We solve the boundary-value problem (3), (4), (5) using finite element analysis.

The following material parameters were used: composite thermal conductivity in the fiber direction $k_x^{(composite)} = 11.236\ \mathrm{W/mK}$, composite thermal conductivity in the direction perpendicular to fibers $k_r^{(composite)} = 1.696\ \mathrm{W/mK}$, composite specific heat $c^{(composite)} = 1366.310\ \mathrm{J/kg\,K}$, composite density $\rho^{(composite)} = 1603.8\ \mathrm{kg/m^3}$, composite-air convection coefficient $h^{(composite/air)} = 23\ \mathrm{W/m^2K}$, composite electrical conductivity in the fiber direction is $\sigma_x^{(composite)} = 40650.407\ \ 1/\mathrm{Om\,m}$. These parameters were calculated using the rule of mixture assuming 62% AS4 fiber volume content. Copper material parameters are as follows: thermal conductivity $k^{(copper)} = 401\ \mathrm{W/mK}$, specific heat $c^{(copper)} = 380\ \mathrm{J/kg\,K}$, density $\rho^{(copper)} = 8700\ \mathrm{kg/m^3}$, copper-air convection coefficient $h^{(copper/air)} = 12\ \mathrm{W/m^2K}$, electrical conductivity $\sigma^{(copper)} = 58139534.9\ \ 1/\mathrm{Om\,m}$. The contact resistance for the 32-ply cross-ply plate was $R_c = 0.0848\ \mathrm{Om}$. The ambient temperature during the experiments on cross-ply plates was $T^{amb} = 23.44\ {}^{o}C$.

We have analyzed the temperature changes in the cross-ply plates described in the experiments of the previous section. Figures 8 show computational results for temperature variations at the center of the plate surface, T_{surf}, which was also measured in the experiments presented in the previous section, and the temperature in the center of the plate at the plate-electrode interface, which is denoted as $T_{\max}$. The plate carried a 50 A DC current.

As one may see, the computational model captures quite well the temperature variation with time in the middle of the plate at the plate surface as compared to the experimentally measured temperature. The maximum discrepancy between computational and experimental results does not exceed 7%.

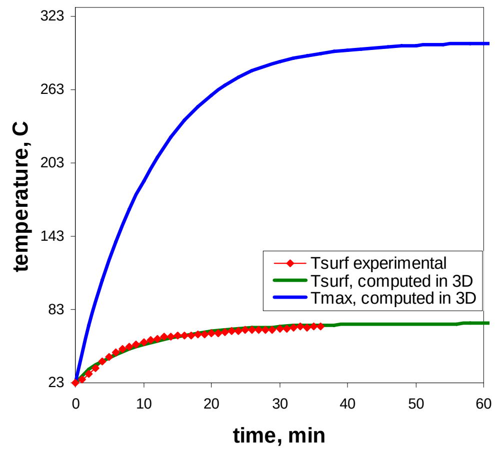


Fig. 8. Variation of temperature with time in the cross-ply composite plate carrying a 50 A DC current

The temperature gradient that is developed in the cross-ply plate is quite dramatic: after a 36 min current application the temperature at the surface is $T_{surf} = 67.1\ {}^{o}C$ and the maximum temperature at the composite-copper interface is $T_{\max} = 272.5\ {}^{o}C$. Such temperatures inevitably alter the mechanical response of the cross-ply composite plate to the impact. It is worth noting that glass transition temperature for the tested composites was around $190\ {}^{o}C$. There is also significant temperature gradient across the plate in the direction of the current flow (see Fig. 9).

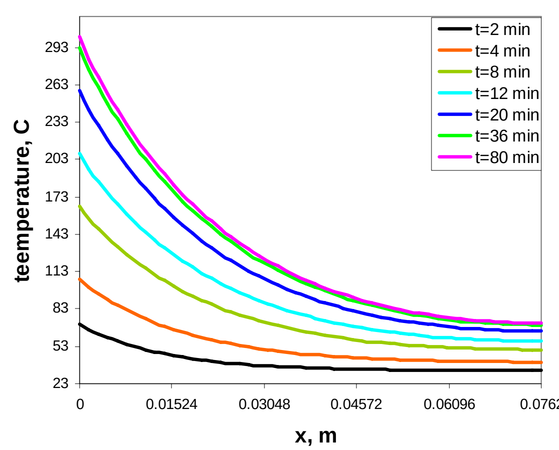


Fig. 9. Temperature variation in the direction of the current's flow in the middle plane of the cross-ply composite plate carrying a 50 A DC current

There is practically no variation in the composite in the plane perpendicular to the direction of the current flow when the temperature at the surface of the plate reaches steady state.

In order to understand the contribution of the heating in the overall mechanical response of the electrified composite, it is important to quantify the contribution of Joule heat (2), as compared with the contact resistance heat (1). Owing to the linearity of the considered problem, we can easily decompose the solution of the heat transfer problem in two parts. The first part of the solution disregards the heat generation at the contact interface and takes into account only the Joule heat (2) produced in the composite as well as in the copper bars. The second part of the solution corresponds to the situation when the contact resistance heat (1) is taken into account but the Joule heat term in the heat transfer equation (3) is omitted. Figure 10 shows the complete solution along with the solutions due to Joule heating and contact resistance heating for the cross-ply composite plate carrying a 50 A DC current.

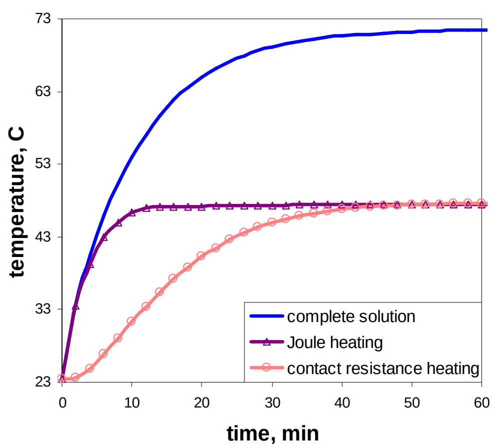


Fig. 10. Variation of temperature with time at the plate surface in the middle for the cross-ply composite plate carrying a 50 A DC current: effect of Joule heat and contact resistance heat

As one may see, during the first five minutes the temperature in the center of the plate (location of the impact) is largely controlled by the Joule heating produced in conductive carbon fibers. As time progresses, the contact resistance heating becomes comparable to Joule heating. Moreover, the time when the Joule heating prevails does not depend on the magnitude of the electric current applied and will be the same for any current. The temperature, however, does greatly depend on the current magnitude.

We have also investigated the effect of the current magnitude on the temperature field in the composite. Figure 11 illustrates the results.

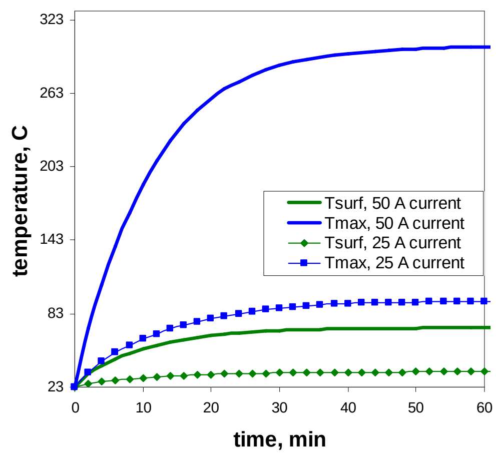


Fig. 11. Variation of temperature with time in the electrified cross-ply composite plate: the effect of the current's magnitude

It is clear that the current magnitude has a dramatic effect on the temperature distribution in the composite.

5 Concluding Remarks

Low velocity impact tests on electrified carbon fiber composites were conducted in order to asses the effect of a DC electric current on the impact resistance of composites. The results show considerable dependence of the impact-induced damage upon the intensity of the electric field applied to the composite: application of the electric current to cross-ply composite plates reduces significantly the amount of the impact damage and increases the amount of the absorbed energy. For example, none of the tested cross-ply plates carrying 50 A DC electric current were perforated in the impact tests at V_{50} velocity determined in tests with no current applied to the plates. Moreover, there is a direct relation between the field applied to the composite and the propagation of the impact damage: the stronger was the applied field, the less damage was observed in the experiments. The aforementioned results are valid for the case when an electric current is applied immediately before the impact. Remarkably, it was determined that prolonged application of an electric current to the carbon fiber polymer matrix composites leads to a significant heating that eliminates the positive effect of the short-term current application. Furthermore, it seems that an increase in the impact resistance due to an electric current is a reversible effect that disappears when the current is turned off. In other words, an increase in the damage resistance can be achieved in composite structures by a short-term current application at the moment of impact; a prolonged application of the current is not only unnecessary, but detrimental.

Analysis of the temperature field shows that an extensive application of the electric current results in large temperature gradients across the composite plate in the current's direction and ultimately contributes to the negative outcome of the subsequent impact tests. In the center of the plate the Joule heat produced by the conductive carbon fibers plays dominant role in the first ten minutes of the current's application. Later contribution of the contact resistance heat is very significant as well. The contact resistance heat needs to be controlled in the experiments in order to avoid the degradation of the polymer matrix at the composite's edges contacting with electrodes.

Acknowledgments

We would like to extend our gratitude to Dr. Charles Lee (AFOSR) for the encouragements and support and Dr. Greg Schoeppner (AFRL/ML) for many helpful discussions and assistance with materials. O. I. Zhupanska and I. Y. Telichev would like to acknowledge the support of AFRL/MN and AFOSR under the grant F08635-03-D-0130.

References

[1] Snyder, D. R., Sierakowski, R. L., Chenette, E. R., and Aus, J. W. "Preliminary Assesment of Electro-Thermo-Magnetically Loaded Composite Panel Impact Resistance/Crack Propagation with High Speed Digital Lazer Photography", *24th International Congress on High-Speed Photography and Photonics, Proceedings of SPIE*, 4183: pp. 488-513, 2001.

[2] Telichev I. Y., Sierakowski R.L. and Zhupanska O. I. "Low Velocity Impact Testing of Electrified Composites; Part I. Application of an Electric Current", *Experimental Techniques*, accepted.

[3] Telichev I. Y., Sierakowski R. L. and Zhupanska O. I. "Low Velocity Impact Testing of Electrified Composites; Part II. Experimental Setup and Preliminary Results", *Experimental Techniques*, under review.

[4] Zhupanska O. I., Sierakowski R. L. "Mechanical Response of Composites in the Presence of an Electromagnetic Field", *Proceedings of 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, paper No. 1949, 2005.

[5] Zhupanska O. I., Sierakowski R. L. "A Study of Impacted Electromechanically Loaded Composite Plates", *Proceedings of 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*. paper No. 1694, 2006.

[6] Zhupanska O. I., Sierakowski R. L. "Effects of an Electromagnetic Field on the Mechanical Response of Composites", *Journal of Composite Materials*, Vol. 41 No. 5, pp 633-652, 2007.