Optimal Temperature and Current Cycles for Curing of Composites Using Embedded Resistive Heating Elements

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Curing is an important and time consuming step in the fabrication of thermosetting-matrix composite products. The use of embedded resistive heating elements providing supplemental heating from within the material being cured has been shown in previous studies (Ramakrishnan, Zhu, and Pitchumani, 2000, J. Manuf. Sci. Eng., ***122****, pp. 124–131; and Zhu and Pitchumani, 2000, Compos. Sci. Technol.,* ***60****, 2699–2712.) to offer significant improvements in cure cycle time and cure uniformity, due to the inside-out curing. This paper addresses the problem of determining the temperature and electrical current cycles, as well as the placement configuration of the conductive mats, for time-optimal curing of composites using embedded resistive heating elements. A continuous search simulated annealing optimization technique is utilized coupled with a numerical process simulation model to determine the optimal solutions for selected process constraints. Optimization results are presented over a range of material systems and different numbers of conductive mats to assess the effects of materials reactivity on the optimal number of conductive mats.* [DOI: 10.1115/1.1527903]

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1 Introduction

Fabrication of thermosetting-matrix composites is accomplished by subjecting the resin-fiber mixture to a prescribed temperature cycle in order to initiate and sustain an irreversible cross-linking exothermic chemical reaction in the resin, called cure. The cure process causes the initial mixture to be transformed into a rigid component whose structural integrity is retained upon the withdrawal of the external temperature variation. The magnitude and time duration of the imposed temperature variation, referred to as the cure cycle, is an important process parameter affecting the temperature distribution and the progress of the crosslinking reaction (measured in terms of a degree of cure) within the composite.

Initially during the cure process, the temperature of the outer layers of the composite which are exposed to the cure temperature cycle increases more rapidly than that of the inner layers, and as the process progresses, the exothermic cure reaction may bring the temperatures of the inner layers to exceed those of the outer layers. Moreover, the heat released during the cure reaction may lead to excessively rapid rate of temperature increase, or the temperature within the material exceeding an allowable maximum value. Maintaining spatial homogeneity in the temperature and degree of cure distribution within the matrix, and maintaining the exotherm-induced maximum temperature and temperature gradient within allowable limits constitute the principal constraints governing the total time of the cure process.

Determination of cure cycles that lead to minimum cure time in practice has relied on trial-and-error or empirical procedure where either simulations based on numerical models or experimental trials are carried out for several candidate cure cycles (Pillai et al. [3]; Loos and Springer [4]; Han et al. [5]; Bogetti and Gillespie [6]; Ciriscioli et al. [7]). This approach does not warrant the best possible process parameters, and, in turn, leads to suboptimal manufacturing times and cost. A rigorous approach to determining the optimal cure cycle was reported by Rai and Pitchumani [8], in which an optimization problem was formulated over a numerical process model and solved using a nonlinear programming scheme. The results were reported for a wide range of resin materials and process constraints. It was shown that the constraints on temperature and cure homogeneity fundamentally limit the magnitude of the temperature ramps in the optimal cycles. This constitutes a fundamental limitation of the curing of composites using peripheral heating.

The foregoing limitation may be alleviated via an inside-out curing strategy, where the inner layers are also subjected to a heat source that allows them to cure in synchronization with the outer layers. Such a strategy provides for temperature and cure homogeneity through the composite cross section during the cure process, and in turn offers the potential to significantly reduce the cure time. One approach toward realizing volumetric internal heating is the use of microwave energy (Lee and Springer [9]; Thostensen and Chou [10]). This approach provides improvement to conventional curing; however, the problem of differential curing persists since the microwave energy attenuates with thickness.

The objective of inside-out curing may also be realized through the use of conductive carbon fibers as resistive heating elements embedded within the cross-section of the composite being cured. Ramakrishnan et al. [1] and Zhu and Pitchumani [2] investigated the approach numerically and experimentally for several resistive heating configurations and demonstrated improved temperature and cure homogeneity, and significant savings in the cure time. The investigation focused on a prescribed cure temperature cycle while varying the steady current supplied to the resistive heating elements. It may be envisioned that significant enhancement to the process could be realized through the use of a time varying current cycle, whereby the current supplied may be better tailored to accelerating the process. In this case, process design calls for determination of the optimal temperature and current variations during the process, which is the focus of the present study.

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