Stochastic Analysis of Isothermal Cure of Resin Systems

S. K. PADMANABHAN *and* R. PITCHUMANI*

Composites Processing Laboratory
Department of Mechanical Engineering
University of Connecticut, U-139
Storrs, Connecticut 06269-3139

Curing of catalyzed resin systems is an important and critical processing step in the fabrication of reinforced thermosetting composite materials. Strong uncertainties inherent in the associated process and material parameters, however, pose a stiff challenge to robust commercial manufacturing of quality composites in practice. Although deterministic models have been developed over the years to simulate the cure process, analysis of the effects of the parameter uncertainties on the process performance and the product quality variabilities has been the subject of little attention, and forms the focus of this study. This paper presents a methodology for a systematic analysis of the effects of the process and material parameter uncertainties on the isothermal curing of thermosetting resin systems. A stochastic model is developed, and parametric studies are presented to systematically examine the effects of the uncertainties in the processing temperature and the kinetic parameters on the process output variabilities. Optimum parameter spaces that minimize the variance of the output parameters are identified, as a first step towards robust manufacturing of composites.

INTRODUCTION

Fabrication of polymer matrix composites in general, and of reinforced thermosetting-matrix composites in particular, is a complex process that involves simultaneous anisotropic heat, mass, and momentum transport phenomena (1). Some of the widely used processes for manufacturing thermosetting matrix composites include autoclave molding, pultrusion, and liquid molding techniques. An important fabrication step shared by all these processes is the application of external temperature cycles to a resin-fiber mixture in order to initiate and sustain irreversible cross-linking chemical reactions in the resin, called *cure*, which results in the formation of a structural product. Since the cure step strongly governs the product properties, a fundamental understanding of the cure phenomena is critical to the fabrication of quality composites.

Towards this end, detailed theoretical and experimental investigations of the cure of various resin systems have been reported in the literature (2–6). The theoretical models have played an important role in improving process understanding and guiding process design and optimization (7) over the years. However, a fundamental gap exists between the simulations and practice, in that whereas practical manufacturing is carried out amidst a cloud of impreciseness in the material and process parameter values, the process simulations are deterministic in the way they treat the parameters. The uncertainties in the parameters arise from sources such as (a) microstructural variations, which lead to uncertainties in the composite thermal properties, and therefore, the material temperatures and cure rates, (b) variations in the composition of the resin-catalyst mixture, which result in uncertainties in the resin properties and the cure reaction parameters, (c) inaccuracies associated with the process monitoring and control, (d) material variabilities from one vendor to another, and from one batch to another, and (e) environmental uncertainties. These inherent parameter uncertainties in turn lead to variabilities in the product quality and process performance.

A systematic analysis of the interactive effects of the parameter uncertainties on the product quality variabilities is imperative for a realistic description of the fabrication processes, and forms the focus of this study. Furthermore, such an analysis is vital to a robust manufacturing endeavor, which seeks to identify operating regimes that minimize the process output variabilities. Experimental methods such as the

*To whom correspondence should be addressed.