SMART AUTOCLAVE CURE OF COMPOSITES

PETER R. CIRISCIOLI
GEORGE S. SPRINGER

SMART AUTOCLAVE CURE OF COMPOSITES

PETER R. CIRISCIOLI
GEORGE S. SPRINGER
Stanford University

TECHNOMIC PUBLISHING CO., INC.
LANCASTER · BASEL

Smart Autoclave Care of Composites
a **TECHNOMIC**® publication

Published in the Western Hemisphere by
Technomic Publishing Company, Inc.
851 New Holland Avenue
Box 3535
Lancaster, Pennsylvania 17604 U.S.A.

Distributed in the Rest of the World by
Technomic Publishing AG

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Main entry under title:
Smart Autoclave Care of Composites

A Technomic Publishing Company book
Bibliography: p.

Library of Congress Card No. 90-71382
ISBN No. 87762-802-5

SMART AUTOCLAVE CURE OF COMPOSITES

Preface

Manufacturing composites in an autoclave has largely been an empirical art. Only recently have more rational approaches been applied to the selection of autoclave temperature and pressure histories. As a first step away from empiricism, the manufacturing process was described by equations founded on fundamental engineering principles. These equations were then used to select the autoclave temperature and pressure. This approach was followed by expert systems which, on the basis of preestablished rules, select and control in real time the autoclave conditions. The advantages of rule based expert systems are numerous. They require little information about the material, can be used for complex shaped parts, provide instantaneous feedback control of the autoclave temperature and pressure, and result in high quality parts cured in the shortest time.

In this book we present process models for both thermosetting and thermoplastic matrix composites and an expert system applicable to autoclave curing of thermosetting matrix composites. We recognize that the models and the expert system described in this book are only first steps towards a complete solution of the problem. Nevertheless, the unified presentations given here are deemed appropriate. First, in their present forms the models and the expert system are already practical and useful. Second, the subjects are presented in sufficient detail to acquaint the reader with the rationale behind the models and the rules and with the numerical procedures, the software, and the hardware. Thus, this book should be useful as a reference to practicing manufacturing engineers as well as to workers new to the field.

The authors thank the many individuals and corporations who contributed to this work. The thermosetting model is based on the Loos-Springer formulation. W.I. Lee helped with the thermoplastic model and the expert

system rules.
Q. Wang assisted with curing and computer runs and K. Perry with mechanical testing. A.C. Goetz made available mechanical test facilities at Lockheed Missiles and Space Corporation. R.J. Downs had useful suggestions for the design of the apparatus. Micromet Incorporated and TMI Incorporated provided some of the equipment.

Peter R. Ciriscioli
George S. Springer

Stanford, California
July, 1990

Contents

CHAPTER 1

Introduction

When fabricating structures made of fiber reinforced organic matrix composites careful attention must be paid to the manufacturing procedures. The quality of the part may suffer and the cost may become excessive if improper manufacturing processes are used. Therefore, the manufacturing process must be selected carefully to ensure that both the quality and the cost are acceptable. The major process variables which must be selected and controlled are the heat and pressure applied during autoclave curing of thermosetting matrix composites, and the cooling rate and pressure applied during the processing of thermoplastic matrix composites.

Although the aforementioned process variables can be chosen empirically, the empirical approach is undesirable and often impractical. Empirical, trial and error methods are expensive and time consuming, and do not ensure that the resulting processing conditions are optimum. It is far more advantageous and convenient to establish the required process conditions and process variables either by the use of analytical models, or by expert systems.

In this book two models are described, one applicable to the cure of thermosetting matrix composites, the other to the processing of thermoplastics. In addition, a rule based expert system is presented which can be used for real time control of the autoclave temperature and pressure during the cure of thermosetting matrix composites.

PART 1

Curing of Thermosetting Matrix Composites

CHAPTER 2

General Considerations for Curing Thermosetting Matrix Composites

Parts and structures constructed from continuous fiber reinforced thermosetting resin composites are manufactured by arranging the uncured fiber-resin mixture into the desired shape and then curing the material. The curing process is accomplished by exposing the material to elevated temperatures and pressures for a predetermined length of time. The elevated temperatures applied during the cure provide the heat required for initiating and maintaining the chemical reactions in the resin which cause the desired changes in the molecular structure. The applied pressure provides the force needed to squeeze excess resin out of the material, to consolidate individual plies, and to compress voids.

The elevated temperatures and pressures to which the material is subjected are referred to as the cure temperature and the cure pressure. The magnitudes and durations of the temperatures and pressures applied during the curing process (denoted as the cure cycle) affects the following parameters of interest:

a) the temperature inside the composite,
b) the degree of cure of the resin,
c) the resin viscosity,
d) the resin flow, the amount of resin in the composite, and the amount of resin in the bleeder,
e) the changes in the void sizes,
f) the residual stresses and strains in the composite, and
g) the cure time.

By affecting these parameters, the cure cycle has a significant effect on the quality of the finished part. Therefore, the cure cycle must be selected specifically for each application and controlled during the cure process.

Some major considerations in selecting the proper cure cycle for a given composite material are listed in the following table.

Table 2.1

Requirements to be Met During Autoclave Curing of Thermosetting Matrix Composites

- The temperature inside the autoclave and at any point inside the cure assembly (composite as well as surrounding layers) must not exceed a preset value at any time during the cure.
- The temperature distribution must be reasonably uniform inside the composite, and there cannot be significant temperature increases due to exotherms induced by chemical reactions.
- The composite must be fully compacted.
- The formation and growth of voids must be minimized.
- The residual ("curing") stresses must be reduced or eliminated.
- Complete and uniform cure must be reached in the shortest time.

The temperature and pressure conditions inside the autoclave are set by adjusting the heater, cooler, and pressure controllers. There are several ways in which the processing conditions and the corresponding autoclave controls (heater, cooler, pressure) can be selected for a given application; 1) by adopting the "manufacturer recommended cure cycle", 2) by using empirical methods, 3) by employing analytic models and, 4) by using expert systems.

Manufacturer recommended cure cycle

The material supplier generally recommends a "cure (pressure-temperature) cycle". Such cycles are based on tests performed on small samples, and do not take into account the geometry of the part. Therefore, the cycle recommended by the manufacturer is inappropriate for most applications, and should not be used without extensive trial beforehand.

Empirical methods

In principle, the processing conditions can be chosen empirically. The schematic of the empirical approach is shown in Figure 2.1. In practice,

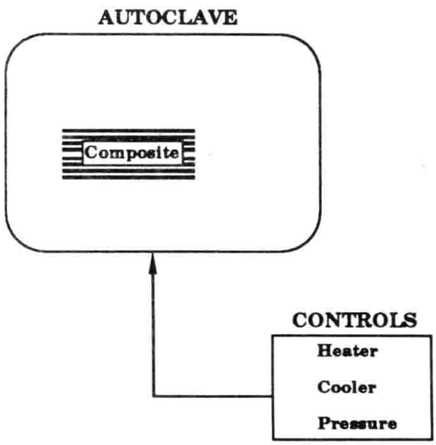

Figure 2.1 The empirical approach for selecting the autoclave temperature and pressure.

empirical approaches are fraught with difficulties. Empirical, trial and error methods are impractical even for thin, small parts, and are impossible for thick, large parts. The obvious difficulties with empirical methods are that a) they are expensive and time consuming, b) their results can not be generalized to parts made of different shapes and different materials, and c) they cannot be used to control the manufacturing process.

Analytic models

The "optimum" processing conditions can be established by analytic models as illustrated by the schematic in Figure 2.2. Such models have already been developed for autoclave curing [1-7] and filament winding [8-11] of thermoset matrix composites and for processing of thermoplastic composites [12-16]. Although analytic models may provide the processing conditions for certain problems, they are beset by difficulties. Most notably, analytic models a) require extensive material data which often are difficult to measure, b) can only be applied to simple geometries, c) do not take into account "batch to batch" variations in material properties, and, last but not least, d) cannot be used to control the manufacturing process.