# ADVANCED COMPOSITE MOLD MAKING

John J. Morena

Sponsored by the Society of Plastics Engineers, Inc.

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# ADVANCED COMPOSITE MOLD MAKING

TO GEORGE LUBIN
WITH SPECIAL GRATITUDE

# Foreword

*Advanced Composite Mold Making* is the first volume to treat, in-depth, the fabrication of molds using nonmetallic materials. As the only contemporary book covering this burgeoning field, it outlines a technology for making prototype and production tooling which currently has widespread applications in the aircraft, aerospace, and automotive industries. Future applications cannot help but touch a broad spectrum of other industries.

This volume has been written to serve a broad readership, as both a definitive text and a reference source. Among its potential readers and users are advanced tool designers, engineers involved with nonmetallic structuring, industry management concerned with the subject and its industrial ramifications, and students.

This work is unusually well-ordered, with a detailed introduction to all aspects of advanced composite mold making setting the stage. The chapters sequentially follow the entire materials and fabrication process of mold and tool building. The effects of statics and strengths of materials are examined in-depth, along with the basic elements involved in the design of a mold and the engineering aspects of the molds and mold materials. There is a particular emphasis on the large number of thermal elements influencing the mold or tool and its performance.

The most extensive treatment in the volume is that of fabricating master models and patterns, metallic and nonmetallic molds, mold accessories, mold assembly, and the actual tools involved. The vital, but often overlooked, aspects of mold handling, storage, safety, and quality control are also discussed. It is because of this exhaustive coverage of the subject that the Society of Plastics Engineers (SPE) is particularly pleased to recommend this book and add it to its list of sponsored volumes.

ROBERT D. FORGER
*Executive Director*
*Society of Plastics Engineers*

# Preface

*Advanced Composite Mold Making* is a definitive volume, compiled to collect, collate, and present the engineering, design, materials, and processes required to fabricate a composite mold or tool.

The use of composites today in all sectors of industry is vast. Given this fact, the scope of the book includes information for producing the molds and tools to form both the nonmetallic parts and bonded structures which are used in a multitude of industries, including military, aerospace, marine, transportation, leisure time, and commercial industrial applications.

*Advanced Composite Mold Making* also establishes the ground rules for the design of educational programs at all levels, as well as providing guidance for the engineer, designer, technician, or craftsman, through state-of-the-art methods of mold making.

The understanding of composites is widespread, and so the concepts covered in the book are intended for use in both domestic and international industries.

In addition, the detailed information is useful and practical. Thus, it is presented in a "hands-on" manner – a form that will appeal to both experts and beginners in the composites field.

It must be stressed at the outset that composite mold and tool making, because of the continuing advances in structural composite technology, has also become an "art of quality." For this reason, certain innovative, advanced materials and processes will be introduced in a thorough, easy to understand, form.

Locating concise and reliable data regarding the formation of composites is difficult. Locating similar information for the fabrication of molds and tools is sometimes an impossible task. This book endeavors to provide that information, answering questions as they arise, (and sometimes before they arise), in order to prevent errors in design or fabrication. It also utilizes extensive data to inform the reader so that mold and tool problems, in the area of both design and materials, can be solved expeditiously.

The early chapters acquaint the reader with the design and engineering tools required to produce a mold that will provide quality parts and remain trouble-free over a lengthy economic and production life.

The materials chapter examines the quality and state of the art of the materials of composites, mold, and tool making. The fabrication chapters illustrate the innovative processes involved, and the means by which state-of-the-art materials can be put to creative use for advanced composite mold making are immediately recognizable.

Finally, an extensive tabular data bank, along with a listing of additional tool innovations in related metallic part, assembly, and forming areas, is provided.

*Advanced Composite Mold Making* represents the culmination of many years of trial and error experimentation, resulting in an extensive and detailed collection of proven information. This information is a collection and expression of the varied experiences of many associates and friends to whom the writer is indebted. Among them are: Lee Davis, prominent writer of varied interests and talents, whose guidance, assistance, and professional expertise helped to make this book a quality presentation of technical data; Bill Forster, mold and tool designer, researcher and technical assistant, for his continued support throughout the entire writing process; Paul Petervari, Art Nelson, Robert J. Sanderson, Bill Pagels, Bob Semprini, and Richard Chance, of Grumman Aircraft Systems, for providing assistance and data for certain sections of the manuscript; Lou Reidell, program manager and manager of composite mold and tool design, Grumman Aircraft Systems, for technical information, Dimitrios Maltezos, dean and professor, State University of New York, for reviewing sections of the manuscript, and especially Susan Munger, Gail Nalven, Alberta Gordon, Ray Kanarr, and the staff of Van Nostrand Reinhold, for their guidance in the preparation of the manuscript. Finally, to John and Terry Morena, who supported every aspect of the text.

# Contents

# 1
# Introduction

When fabricating a mold or tool to form a simple hand lay-up, or an advanced composite part, assembly, or thermoplastic composite material, the best materials and processes to use are the ones that result in the production of the best quality finished shape or contour at the lowest cost.

Molds, tools, and generally the models or masters, are required prerequisites for any molded part or assembly. With the continued increase in the use of composite part materials comes the necessity for more advanced materials and processes to form molds and tools. Composite forming molds and tools of the best quality can be produced from a mixed array of both metallic and nonmetallic materials. Innovative, as well as standard, fabrication methods are currently being employed to process the mold materials. The most advantageous mold or tool should also provide dimensional stability during use, be easy to fabricate, maintain, and repair, and be convenient to handle and store.

In the same sense that the attempt to obtain the lowest cost to produce a mold, tool, or part is coupled with the effort to ensure the lowest cost of operation, the factors of thermal mass and thermal uniformity in the heat-up rate play an important role in mold material choice and design.

Aluminum has always been a basic material for use in molding laminated fiberglass reinforcements and assemblies. When graphite-reinforced materials appeared in the aircraft and aerospace industries, new requirements developed. The old standby, steel, with its mass and high cost to process, fit hardly any application other than simple contours and loose tolerance applications.

Fiberglass-reinforced, low-temperature laminating materials serve well for fabricating checking and inspection tools, trim fixtures, prototype and intermediate molds, and low-temperature-curing molds with limited production rates.

The use of reinforced, high-temperature composite materials, which was just gaining acceptance in mold and tool fabrication, took a downward turn when the U.S. government declared certain constituents harmful to the health and safety of users. It was at this point that industry started to look not only at nonmetallic mold and tool materials, but to reexamine the materials used to form metallic molds and tools as well.

New machining methods were developed to form contoured electroformed or plated nickel tools because this material demonstrated a low coefficient of thermal expansion (CTE). The need for low CTE materials directed mold and tool researchers to examine other materials such as monolithic bulk graphite, castable reinforced cements and ceramics, specially formulated mass-cast resin compounds, graphite-reinforced low-temperature-precure epoxy prepreg materials, and high-temperature structural foams.

The introduction of the use of reinforced thermoplastic composites broadened the requirements necessary for low CTE mold and tool materials by increasing the molding temperatures of the part materials from the average of 350°F to 650°–750°F. This narrowed the mold material choices, leaving steel and some of the nonmetallic materials as acceptable options in this temperature range.

It is for the engineers of the future to decide which high-temperature mold and tool materials will be available for use in producing parts and assemblies made from state of the art and newly-developed reinforced thermoset composites or reinforced and self-reinforcing thermoplastic composites.

The management of industry, no matter what sector is involved, must realize that the cost of producing a mold, tool, or fixture for the formation of a composite material part must be disregarded if the part material and configuration dictate what that mold or tool material must be. Management should, at that point – especially if nonmetallic material is required – use every available resource to assure that the highest quality nonmetallic mold or tool is produced. Manual versus automated design, inexpensive or expensive masters, fair or good thermal and physical properties of mold materials, short cuts or careful procedures in mold fabrication, and close or detached management during mold use and storage are just some of the considerations that must be examined. The nature of mold making is such that there is little room for sacrifices to be made with respect to quality.

The art of mold making in the area of advanced composite molds can be divided into a number of sequential units. The expert mold or tool designer can look at a conceptual part design or model and visualize how the pattern or master for the mold, tool, and finished item should be fabricated.

It is the intent of this book to assist in formulating these concepts by presenting them in a logical and understandable form:

*Mold Materials:* An extensive overview of all of the important materials used in the formation and production of the masters, molds, tools, and fixtures utilized to produce state-of-the-art and advanced composite parts and assemblies is given. These materials include solid and resinous primary and secondary forms, both of which are examined here.

*Strengths of Materials and Mold Design:* A review of physical and thermal considerations that affect the design of molds and tools used in the composite molding process, and an examination from the point of view from the structural designer of the strengths of materials with the static aspects of these materials related to mold and tool design.

*Mold Engineering:* The entire engineering process is examined, presenting an overall approach to mold and tool cost, the projected life of the mold or tool during production use, and the various approaches in automated mold and tool design. Comparisons between low- and high-production molds and tools are made followed by statements regarding mold and tool refurbishment and replacement.

*Preparation of Masters:* Up-to-date procedures for preparing required master patterns, models, and masters to be used in the formation of advanced composite molds are detailed. Master and mold treatments, releases, and parting agents are thoroughly described.

*Fabricating Molds:* An encyclopedic amount of information regarding the production of master and expendable molds, and suggesting materials and tolerances needed for quality results, is given. Mass cast rigid, flexible, and laminated nonmetallic molds to be used to contour mold and bond structural composites, unique and innovative production methods to produce laminate molds and substructures, and metal-faced laminated molds and tools are all examined. The evolution of metallic molds and tools is investigated, beginning with conventional aluminum and steel, and finally resulting in the inexpensive approaches of electroformed or plated nickel mold or tool forms. The developing areas of nonsilicone and reversion-resistant silicone caul, pressure and intensifier elastomers, and the methods by which they are replacing conventional bagging materials as reusable production aids are described. An introduction to semiautomatic vacuum bagging systems, elastomeric expansion rubber molding for out-of-autoclave and out-of-press forming of composites, and a complete listing of mold fittings and accessories, support tools, and efficient production aids are all given. Finally, the necessary procedures to maintain and repair production molds and tools are detailed.

*Facility Requirements:* An introduction to the important area of the safe handling of the materials, equipment, molds, and tools of the composite craftsman is given. The overall industrial engineering aspects of storage and transportation, as well as the facilities requirements of waste disposal and safety are fully examined.

*Inspection, Quality Control, and the Future of Composite Mold Making:* Methods are suggested for materials acceptance, and for establishing and controlling manufacturing inspection procedures relating to the production and acceptance of a high quality mold or tool. The projected direction that advanced composite mold making may take in the future is investigated in the closing section of the book.

As the reader proceeds, it will become immediately apparent that the presentation format is directed toward educating the beginning as well as the advanced mold and tool maker. This book is designed to be used as an individual or group educational aid for engineers, designers, and craftsmen. It is hoped that, utilizing the information gained from this book, the reader will be better able to choose the most appropriate materials and processes to be used when producing an advanced composite mold or tool.

# 2
# Strength of Materials and Mold Design

Design sections of technical manuals or books usually present complicated and cumbersome design parameters that are difficult for the reader to understand and/or apply.

In an effort to ameliorate this situation, this book is designed with a "hands-on" approach to the materials and processes of advanced composite mold making. For this reason, the present chapter is structured in such a way that interpretation of the data can be made by readers possessing different levels of design background.

Since statics deals with forces and reactions on rigid bodies, and the strengths of materials expands the science of statics to include internal reactions, these two subjects are fundamental tools needed for proper mold design.

To complement the understanding of strengths of materials, stress-strain relationships and diagrams will be presented. These stress-strain relationships provide the equations necessary to arrive at a safe stress strength. The stress-strain diagrams will characterize a material's strength properties. Thus, by combining statics, strengths of materials, the stress-strain diagrams, and stress-strain relationships, proper loading conditions and safe stress can be calculated.

Lap joint strength and the theory of elasticity determine the maximum stresses a material can withstand without failure. These maximum stresses are adjusted using the stress-strain relationships. Once this is accomplished, a final formula is used to determine the size of load-carrying members.

Since molds or tools are rarely used at the temperature at which they were created, and differences exist between ambient and cure temperatures, thermal effects and heat transfer rates are presented in this chapter. Proper understanding of heat transfer modes is imperative in calculating tool heat-up rates in the autoclave, press, and in oven heating. These will also be covered in detail in the following pages.

## 2.1. STATICS AND THE STRENGTHS OF MATERIALS

The degree of tolerance, reliability of performance, and strength characteristics are the global design parameters in tool design.

In terms of tolerance, a designer should know what loads will be placed on the mold or tool in order to design this mold or tool with the proper strength characteristics. These strength characteristics will have safety factors associated with them to insure reliability, in spite of any irregularities in materials or unanticipated mold or tool loading.

A designer should also possess an understanding of statics and strength of materials, for these are the primary analytical methods used in tool design. Statics deals with externally applied loads and their reactions on rigid bodies. Strengths of materials is a more in-depth analysis than statics, and examines the internal reactions within deformable bodies when external loads are applied.

### 2.1.1. Statics

Statics studies forces acting upon bodies at rest. When a body is pushed or pulled, a force is exerted upon that body to either deform it or move it. A force consists of two components: magnitude and direction. For example, if a cable lifts a tool and the force exerted by the cable is considered positive, then the downward force exerted by the tool on the cable is negative. This exemplifies Newton's third law, which states that for every action there must be an equal and opposite reaction.

Although the choice of direction or sense is arbitrary, a good rule of thumb is: If a force acts upon a mold, it is positive, and the reaction of the mold on that force is negative.

Since forces have both a magnitude and direction, a body at rest is not viewed as having zero forces acting upon it, but rather, the body has many forces acting upon it which cancel each other because of the sense of the forces.

A force which deforms a body by decreasing the body size is a compressive force, (for instance, the squeezing of a sponge). The complementary force, a tensile force, tends to increase the body size (for example, stretching a rubber band).

A diving board, fabricated from a reinforced plastic laminate, experiences both tensile and compressive forces (Fig. 2.1).

If the diving board is of uniform rectangular cross section, then the board is in tension above the center line, and the board is in compression below the center line.

This diving board example can be used to demonstrate important properties of materials:

If the board were fabricated from a cementitious material and subjected to an end load, the board would break. To transfer this to our frame of reference: Although cementitious compounds have excellent compressive properties, their tensile properties are poor, and thus failure can occur under heavy end loads.

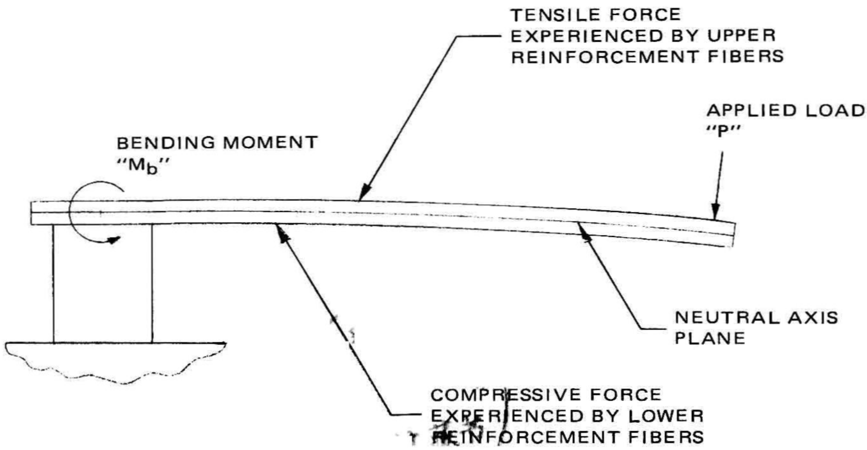


Fig. 2.1. Diving Board.

If the board were fabricated from rubber and subjected to an end load, the board would deform greatly. The analogy is that rubber contains excellent tensile properties, but poor compressive ones.

The force that the diving board exerts to counter the applied end load and still remain stationary is called a moment. A moment is defined as the force which causes rotation of a body at rest. The magnitude of the moment is equal to a force multiplied by a distance. Thus, a proper understanding of the loading conditions of a structure should be achieved before a design structure and the materials for that structure are selected.

Equilibrium occurs when a body subjected to forces and moments is at rest. Furthermore, if equilibrium is to occur, the sum of all forces must equal zero and the sum of all moments must equal zero. Hence, utilization of the equilibrium conditions and their associated equations will allow the reaction forces to be solved.

### 2.1.2. Strength of Materials

In order to successfully design a mold or tool which will make finished parts reliably throughout its intended service life, a designer must be familiar with both engineering mechanics and strength of materials. Therefore, this section is designed to present these fundamental principles in a clear and concise manner.

Mechanics is the study of forces which act on rigid bodies. But, since a rigid body neglects internal reactions, the strength of that body cannot be determined

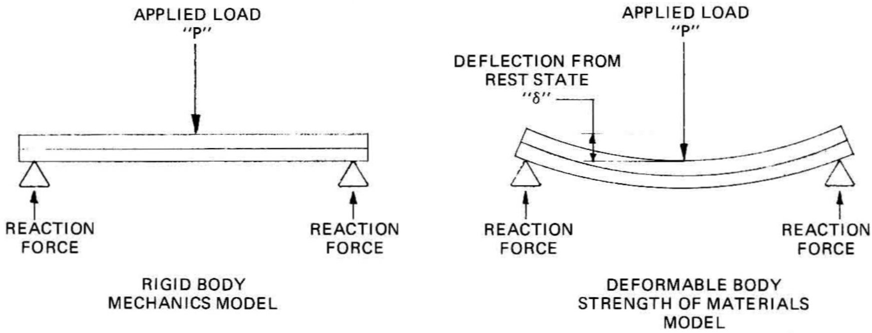


Fig. 2.2. Simply Supported Beam.

through mechanics. Thus, the strengths of materials, which is the study of externally applied forces on a body and the corresponding internal reactions of that body on the applied forces, must be utilized.

To exemplify the difference between statics and strengths of materials, a loaded, simply supported beam is considered in Fig. 2.2.

In statics, the beam is viewed as being a rigid body that does not bend or deflect. Hence, through the use of statics, the reaction forces can be found by summing moments about either supporting point and then summing forces.

Since the strengths of materials is a more in-depth study of forces and internal reactions, it provides useful extended solutions. Among these is the maximum allowable load prior to failure and the deflection distance compared to the rest state. For a further explanation of this, refer to Table 2.1.

**Stress and Strain.** To properly design a structural mold or tool member, the characteristics of that member must be known. Among these characteristics are strength, strain, and stiffness. In engineering applications, strength is defined in terms of stresses. Stresses are defined as force per unit cross-sectional area:

$$\sigma = P/A \tag{2.1}$$

where:

$\sigma$ = force per unit area (psi) or ($N/cm^2$)
$P$ = applied load (lb) or (N)
$A$ = cross-sectional area ($in^2$) or ($cm^2$).

The usual unknown in tool design is the cross-sectional area. In most cases, the applied load ($P$) is known. Once the material is chosen, the maximum stress $\sigma_{MAX}$ (otherwise known as the proportional limit) can be read from a chart of material properties.