3rd Edition

Reinforced Plastics Handbook

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Third edition

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Preface and Acknowledgement

The text is organized and written with useful information in the World of Reinforced Plastics to provide a source and reference guide for fabricator, mold maker, material supplier, engineer, maintenance person, accountant, plant manager, testing and quality control individual, cost estimator, sales and marketing personnel, new venture type, buyer, user, educator/trainer, workshop leader, librarian/information provider, lawyer, consultant, and others.

It will be useful for those using reinforced plastic (RP) composites as well as those contemplating their use. People with different interests will gain knowledge by focusing on a subject and interrelate across subjects that they have or do not have familiarity. Information and data presented includes some important history, detailed up dates, and what is ahead. As explained throughout this book, this type of understanding is required in order to be successful in the design, prototype, and manufacture of the many different, marketable, fabricated products worldwide. This approach provides potential innovations concerning materials of construction, fabricating techniques, improved products performance to cost, and designing new products.

The book provides an understanding that is concise, practical, and comprehensive and that goes from "A–to–Z" on the subject of RP. Its concise information for either the technical or the non-technical reader goes from interrelating and understanding basic factors starting with the materials of construction and plastics melt flow behavior during processing.

This third edition has been written to update the subject of reinforced plastics in the World of Reinforced Plastics. By updating the book, there have been changes with extensive additions to over 75% of the 2nd Edition's content. Many examples are provided of processing

different plastics and relating them to critical factors that range from product designs-to-meeting performance requirements-to-reducing costs-to-zero defect targets.

More information that is basic has been added concerning present and future developments, resulting in the book being more useful for a long time to come. Detailed explanations and interpretation of individual subject matters (3000 plus) are provided using many figures and tables. Information ranges from basic design principles to designs of different size fabricated products by different processes. Throughout the book, there is extensive information on problems and solutions as well as extensive cross-referencing on its many different subjects.

This book continues to represent the encyclopedia on RP. Even though the worldwide industry literally encompasses many hundreds of beneficial computer software programs, this book introduces these programs (ranging from operational training to product design to fabricating to marketing). However, no one or series of software programs can provide the details obtained and the extent of information contained in this single source book with its extensive cross references.

It is important to recognize that a major cost in the production of RP products, ranging from the design concept to the finished molded product, is that of the materials of construction. They range from 40 to 90% of the total product cost. Thus, it is important to understand how best to use the materials based on the appropriate design approach and processing technique. Design is interdisciplinary. It calls for the ability to recognize situations in which certain techniques may be used and to develop problem-solving methods to fit specific design requirements. Many different examples are presented concerning problems with solutions that may develop in different design approaches, fabricating techniques, etc., up to the final product in use.

In the manufacture of products, there is always a challenge to utilize advanced techniques, such as understanding the different plastic melt flow behaviors, operational monitoring and control systems, testing and quality control, and so on. However, these techniques are only helpful if the basic operations of fabricating are understood and characterized, to ensure the elimination or significant reduction of potential problems.

What makes this book unique is that the reader will have a useful reference of pertinent information readily available as summarized in the Table of Contents and Index. As past book reviewers have commented, the information contained in this book is of value to even the most experienced designers and engineers, and provides a firm basis for the beginner. The intent is to provide a complete review of all aspects of

the RP process that goes from the practical to the theoretical and from the elementary to the advanced.

This book can provide people, not familiar with RP, an understanding of how to fabricate products in order to obtain its benefits and advantages. It also provides information on the usual costly pitfalls or problems that can develop, resulting in poor product performances or failures. Accompanying the problems are solutions. It will enhance the intuitive skills of those people who are already working in plastics.

From a pragmatic standpoint, any theoretical aspect that is presented has been prepared so that it is understood and useful to all. The theorist, for example, will gain an insight into the limitations that exist relative to other materials such as steel, wood, and so on. Based on over a half century of worldwide production of all kinds of low to high performance RP products, they can be processed successfully, meeting high quality, consistency, and profitability. As reviewed in this book, one can apply the correct performance factors based on an intelligent understanding of the subject.

This book has been prepared with the awareness that its usefulness will depend on its simplicity and its ability to provide essential information. With the authors experience gained in working in the RP industry worldwide and in John Murphy's work in preparing the 1st and 2nd editions, we are able to provide a useful book. The book meets the criteria of providing a uniquely useful, practical reference work.

The material properties information and data presented are provided as comparative guides; readers can obtain the latest information from material suppliers, industry software, and/or as reviewed in this book's **Bibliography** section. Our focus in the book is to present, interpret, analyze, and interrelate the basic elements of RP to processing plastic products. As explained in this book, even though there are many reinforcements and plastic materials worldwide, selecting the right reinforcement/plastic requires applying certain factors such as defining all product performance requirements, properly setting up or controlling the RP process to be used, and intelligently preparing a material specification purchase document and work order to produce the product. Extensive selection information is provided.

With all types of plastics that include primarily RPs, an opportunity will always exist to optimize its use, since new and useful developments in materials, processing, and design continually are on the horizon requiring updates. Examples of these RP developments are in this book, providing past to future trends in the World of Reinforced Plastics.

Recognize that with the many varying properties of the different RPs, there are those that meet high performance requirements such as long time creep resistance, fatigue endurance, toughness, and so on. Conversely, there are RPs that is volume and low cost driven in their use. As explained in this book, each of the different materials requires their specific RP processing procedures.

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In preparing this book and ensuring its completeness and the correctness of the subjects reviewed, use was made of the authors worldwide personal, industrial, and teaching experiences that total over 100 years, as well as worldwide information from industry (personal contacts, conferences, books, articles, etc.) and trade associations.

The Rosatos
2004

Acknowledgement

As the reinforced plastic industry worldwide continues to grow and expand its capabilities material wise, process wise, design wise, and product wise, so does the literature. This Third Edition of the *Reinforced Plastics* book and the *Reinforced Plastics* magazine published by Elsevier Advanced Technology provides important information.

This Third Edition is a tribute to John Murphy for the excellent work presented in the First and Second issues. Following Murphy's work the Rosatos' continue to provide updates and information on what is ahead.

About the Authors

Donald V. Rosato has extensive technical and marketing plastic industry business experience from laboratory, testing, through production to marketing, having worked for Northrop Grumman, Owens-Illinois, DuPont/Conoco, Hoechst Celanese, and Borg Warner/G.E. Plastics. He has written extensively, developed numerous patents within the polymer related industries, is a participating member of many trade and industry groups (Plastics Institute of America, Plastics Pioneers Association, Society of Plastics Engineers, Society of Plastics Institute, etc.), and currently is involved in these areas with PlastiSource, Inc., and Plastics FALLO. He received a BS in Chemistry from Boston College; MBA at Northeastern University; M.S. Plastics Engineering from University of Massachusetts Lowell (Lowell Technological Institute); Plastics Engineer of Society of the Plastics Engineers and Ph.D. Business Administration at University of California, Berkeley.

Dominick V. Rosato since 1939 has been involved worldwide principally with plastics from designing through fabricating through marketing products. They have been used on and in land, ocean/water, and air/space. Products in many different markets worldwide ranged from toys to electronic devices to transportation vehicles to aircraft to space vehicles products. Experience includes Air Force Materials Laboratory (Head Plastics R&D), Raymark (Chief Engineer), Ingersoll-Rand (International Marketing Manager), and worldwide lecturing. He is a past director of seminars and in-plant programs and adjunct professor at University Massachusetts Lowell, Rhode Island School of Design, and the Open University (UK). He has received various prestigious awards from USA and international associations, societies (SPE Fellows, etc.), publications, companies, and National Academy of Science (materials advisory board). He is a member of the Plastics Hall of Fame. He received American Society of Mechanical

Engineers recognition for advanced engineering design with plastics. He is a senior member of the Institute of Electrical and Electronics Engineers and licensed professional engineer of Massachusetts. He was involved in the first all plastics airplane (1944/RP sandwich structure). He worked with thousands of plastics plants worldwide, prepared over 2,000 technical and marketing papers, articles, and presentations and has published 28 books with major contributions in over 45 other books. He received a BS in Mechanical Engineering from Drexel University with continuing education at Yale, Ohio State, and University of Pennsylvania.

Abbreviations

AAM	American Architectural Manufacturers
ABL	Allegheny Ballistic Laboratory
ABC	acrylonitrile-butadiene-styrene
	acetal (*see* POM)
abs.	absolute
ABS	acrylonitrile-butadiene-styrene
AC	advanced composite
AC	alternating current
ACA	Automotive Composites Alliance
ACC	Automotive composites Consortium
ACCS	advanced composite construction system
ACG	Advanced Composites Group
ACMA	American Composites Manufacturers Association
ACN	acrylonitrile
ACTC	Advanced Composite Technology Consortium
ADC	allyl diglycol carbonate (also see CR-39)
adh.	adhesive
AEC	acrylonitrile-ethylene-styrene
AF	Air Force
AF	aramid fiber
AFML	Air Force Materials Laboratory
AFRP	aramid fiber reinforced plastic
Al	aluminum
AMBA	American Mold Builders Association
ANFI	Assoc. of the Nonwoven Fabrics Industry
ANSI	American National Standards Institute
ANTEC	Annual Technical Conference (SPE)
APC	American Plastics Council, unit of American Chemistry Council
APPR	Assoc. of Postconsumer Plastic Recyclers

ARMI	Assoc. of Rotational Molders International
ARP	advanced reinforced plastics
ASA	acrylic-styrene-acrylonitrile
ASA	American Standard Association
ASM	advanced stitching machine
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
atm	atmosphere
B	boron
bbl	barrel
Be	beryllium
BeCu	beryllium copper
BF	boron fiber
BM	bag molding
BM	blow molding
BMC	bulk molding compound
BO	biaxial-oriented
bpd	barrels per day
BPF	British Plastics Federation
BPO	Benzoyl peroxide
BS	British Standard
BSI	British Standard Institute
Btu	British thermal unit
Buna	polybutadiene
Butyl	butyl rubber
C	carbon
C	Celsius
C	Centigrade (preference Celsius)
C	composite
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacture
CAT	computer-aided testing
cal	calorie (see also C)
CAR	carbon fiber
CAT	computer-aided testing
CBA	chemical blowing agent
CCA	cellular cellulose acetate
CCPIA	China Plastics Processing Industry Assoc.
CCV	Composite Concept Vehicle
CEO	chief executive officer
CF	carbon fiber
CFA	chemical foaming agent

CFC	chlorofluorocarbon
cfm	cubic foot per minute
CFRP	carbon fiber reinforced plastics
CFRTP	continuous fiber reinforced thermoplastics
cg	center of gravity
CLTE	coefficient of linear thermal expansion
cm	centimeter
CM	compression molding
CNC	computer numerical control
CO	carbon monoxide
CO_2	carbon dioxide
cP	centipoise
CP	Canadian Plastics
CPE	chlorinated polyethylene
CPET	chlorinated polyethylene terephthalate
CPVC	chlorinated polyvinyl chloride
Cr	chromium
CR	compression ratio
CR-39	diethylene glycol bis-allyl carbonate
CRP	carbon reinforced plastics
CSM	continuous strand mat
cu	cubic
Cu	copper
3-D	three dimension
D	diameter
3-D	three-dimensional
DIN	Deutsches Institut fur Normung (German Standard)
DMC	dough molding compound
DMC-12	DeLorean motor car (plastic body)
DN	Deutscher Normenausschus
DNA	deoxyribonucleic acid
DOD	Department of Defense
DSQ	German Society for Quality
DV	design verification
DVR	design value resource
DVR	Dominick Vincent Rosato
DVR	Donald Vincent Rosato
E	modulus of elasticity (Young's modulus)
EC	European Community
EEC	European Economic Community
E-glass	glass fiber
EI	modulus (times) moment of inertia (stiffness)
EMI	electromagnetic interference

EP	epoxy
EPA	Environmental Protection Agency
EPS	expandable polystyrene
ER	epoxy resin
EUROMAP	European Committee of Machine Manufacturers for the Rubber & Plastics Industries (Zurich, Swiz.)
EVAL	ethylene-vinyl alcohol copolymer (or EVOH)
F	force
F	Fahrenheit
FALLO	Follow ALL Opportunities
FDA	Food & Drug Administration
FEA	finite element analysis
FP	fluoroplastic
FPL	Forrest Products Laboratory
fpm	feet per minute
FRP	fiber glass reinforced plastic
FRTP	fiber reinforced thermoplastic
FRTS	fiber reinforced thermoset
ft	foot
FW	filament winding
g	gram
G	giga (10^6)
G	torsional modulus
gal	gallon
GDP	gross domestic product (see also GNP)
GF	glass fiber
GFRP	glass fiber reinforced plastic
GLARE	GLAss fiber-REinforced aluminum
GM	General Motors
GM	glass mat
GMRP	glass mat reinforced thermoplastic
GMT	glass mat thermoplastic
GNP	gross national product (GDP replaced GNP in US 1993)
GP	general purpose
gpd	grams per denier
gpm	gallons per minute
GR	glass reinforced
GS	glass sphere
GSP	Generalized System of Preferences
h	hour
H_2	hydrogen
HDBK	handbook
HDPE	high density polyethylene (also PE-HD)

HDT	heat distortion temperature
H_2O	water
hp	horsepower
HRc	hardness Rockwell cone
Hz	Hertz (cycles)
I	moment of inertia
IDSA	Industrial Designers Society of America
IM	infusion molding
IM	injection molding
IMM	injection molding machine
in.	inch
I/O	input/output
J	joule
JF	jute fiber
JIS	Japanese Industrial Standard
JIT	just-in-time
JSW	Japan Steel Works
JV	joint venture
K	Kelvin
K	Kunststoffe (plastic in German)
Kg	kilogram
l	length
L	liter
lb	pound
LCTE	linear coefficient of thermal expansion
LDPE	low density polyethylene (also PE-LD)
LF	long fiber
LFP	long fiber prepreg
LLDPE	linear low density polyethylene (also PE-LLD)
LMDPE	linear medium density polyethylene
LPE	linear polyethylene
m	matrix
m	metallocene (catalyst)
m	meter
mg	milligram
M	mega
M	million
$\underline{M}_m$	micrometer (see also µm)
MA	Manufacturers Alliance
MAD	molding area diagram
MD	machine direction
MDAFRPCA	Material Development Alliance of the FRP Composites Industry

MDPE	medium density polyethylene (also PE-MD)
MEK	methyl ethyl ketone
MF	melamine formaldehyde
mg	milligram
Mg	magnesium
MI	melt index
mike	microinch (10^{-6} in.)
mil	milliinch/one-thousand of inch (10^{-6} in.)
ml	milliliter
mm	millimeter
MM	billion
mol.wt.	molecular weight
MPa	mega-Pascal
MPA	Massachusetts Plastics Alliance
MPF	melamine-phenol-formaldehyde
mph	miles per hour
Msi	million pounds per square inch (psi × 10^6)
MT	metric ton
MVD	molding volume diagram
MW	molecular weight
MWD	molecular weight distribution
N_2	nitrogen
NA	not available
NAM	National Association of Manufacturers
NBR	nitrile-butadiene rubber
NBS	National Bureau of Standards (since 1980s renamed National Institute of Standards & Technology or NIST)
NC	numerical control
NDT	nondestructive testing
NEAT	nothing else added to it
NEN	Dutch standard
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
nm	nanometer
NPCM	National Plastics Center & Museum
NPE	National Plastics Exhibition (SPI)
NR	natural rubber (polyisoprene)
NTMA	National Tooling and Machining Association
O_2	oxygen
O_3	ozone
OEM	original equipment manufacturer
OSHA	Occupational Safety & Health Administration

%vol	percentage by volume (prefer vol%)
%wt	percentage by weight (prefer wt%)
P	load
P	poise
P	pressure
Pa	Pascal
PA	polyamide (nylon)
PAE	polyarylether
PAEK	polyaryletherketone
PAI	polyamide-imide
PAK	polyester alkyd
PAM	modified acrylic fiber
PAM	polyacrylamide
PAN	polyacrylonitrile
Pb	lead
PBA	physical blowing agent
PBI	polybenzimidazole
PC	personal computer
PC	polycarbonate
PC	printed circuit
PC	process control
PE	polyethylene
PE	polythene
PEEK	polyetheretherketone
PEEKK	polyetheretherketoneketone
PEK	polyetherketone
PEKEKK	polyetherketoneetherketoneketone
PEKK	polyaryletherketoneetherketone
PEKK	polyetherketoneketone
PET	polyethylene terephthalate
PETG	polyethylene terephthalate glycol
PEX	cross-linked polyethylene (or XLPE)
PF	phenol formaldehyde (phenolic)
Phr	parts per hundred
pi	$\pi = 3.141593$
PI	isoprene rubber
PI	polyimide
PIA	Plastics Institute of America
PLTA	Plastic Lumber Trade Association
POM	polyacetal
PP	polypropylene
ppb	parts per billion
pph	parts per hour

ppm	parts per million
ppm	parts per minute
PPS	polyphenylene sulfide
PS	polystyrene
psi	pounds per square inch
psia	pounds per square inch, absolute
PTFE	polytetrafluoroethylene (TFE)
PU	polyurethane (PUR)
PUR	polyurethane (PU)
PVA	polyvinyl acetate
PVAB	polyvinyl acetal butyral
PVAL	polyvinyl alcohol (PVOH)
PVF	polyvinyl fluoride
pVT	pressure-volume-temperature (also P-V-T or pvT)
QC	quality control
QPL	qualified products list
R	Rankin
R	Reynold's number
R	Rockwell (hardness)
R&D	research & development
radome	radar dome
RF	radio frequency
RFI	radio frequency interference
RFI	resin film infusion
r.h.	relative humidity
RIM	reaction injection molding
RM	rotational molding
ROI	return on investment
RP	reinforced plastic
RP/C	reinforced plastics/composites
RP/CI	reinforced plastics/Composites Institute (SPI)
RPMP	reinforced plastic Marco process
rps	revolutions per second
RRIM	reinforced reaction injection molding
RTM	resin transfer molding
RTP	reinforced thermoplastic
RTS	reinforced thermoset
s	second
SAE	Society of Automotive Engineers
SAMPE	Society for the Advancement of Material and Process Engineering
SF	safety factor
SG	specific gravity