C. Ageorges and L. Ye

ENGINEERING MATERIALS AND PROCESSES

Fusion Bonding of Polymer Composites

From Basic Mechanisms to Process Optimisation

Springer

C. Ageorges and L. Ye

Fusion Bonding of Polymer Composites

With 163 Figures

Springer

C. Ageorges, Ing, MSc, PhD
DaimlerChrysler AG, Research and Technology/Manufacturing Technology, FT4/T3, Wilhelm-Runge-Strasse 11, PO Box 2360, D-89013 Ulm, Germany

L. Ye, BSc, MSc, PhD
Centre for Advanced Materials Technology, School of Aerospace, Mechanical and Mechatronic Engineering, Bld. J07, The University of Sydney, NSW 2006, Australia

British Library Cataloguing in Publication Data
Ageorges, C.
Fusion bonding of polymer composites : from basic mechanisms to process optimisation. - (Engineering materials and processes)
1.Polymer melting 2.Polymeric composites
I.Title II.Ye, L.
668.9
ISBN 1852334290

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

Engineering Materials and Processes ISSN 1619-0181
ISBN 1-85233-429-0 Springer-Verlag London Berlin Heidelberg
a member of BertelsmannSpringer Science+Business Media GmbH
http://www.springer.co.uk

Printed in Great Britain

Typesetting: Electronic text files prepared by authors
Printed and bound by The Cromwell Press, Trowbridge, Wilts.
69/3830-543210 Printed on acid-free paper SPIN 10791792

Engineering Materials and Processes

Springer
London
Berlin
Heidelberg
New York
Barcelona
Hong Kong
Milan
Paris
Singapore
Tokyo

Series Editor
Professor Brian Derby, Professor of Materials Science
Manchester Science Centre, Grosvenor Street, Manchester, M1 7HS, UK

Other titles published in this series:
Probabilistic Mechanics of Composite Materials
M.M. Kaminski
Publication due 2002

Intelligent Macromolecules for Smart Devices
L. Dai
Publication due 2002

Preface

Fusion bonding is one of the three basic technologies available for joining polymer matrix composites (PMCs) and dissimilar materials. The other two are the traditional technologies of mechanical fastening and thermosetting adhesive bonding; these have been extensively used in industry, although they are not the best joining methods for composite structures. PMCs are particularly sensitive to the holes and cut-outs required for mechanical fastening, as they introduce significant stress concentrations. Adhesive bonding is excessively labour intensive, with stringent surface preparation requirements and long curing cycles. Fusion bonding, or welding, and the use of thermoplastic films as hot melt adhesives offer an alternative to the traditional techniques. The main advantages of fusion bonding over the other two technologies include short processing times, reduced surface preparation requirements (particularly for thermoplastic matrix materials), the absence of foreign material at the interface, the possibility of reprocessing if subsequent non-destructive evaluation reveals defects, and the potential for on-line quality control.

Fusion bonding, originally used in the thermoplastic polymer industry, has gained renewed interest with the introduction of thermoplastic matrix composites, which are currently regarded as candidates for primary structures in aeronautical and automotive applications. The improvement of thermoplastic polymer matrices, such as PEEK, PPS, PEI, PEKEKK, etc., has resulted in increased mechanical performance, service temperature and solvent resistance (for semi-crystalline systems), supporting the growth of interest for fusion bonding. In addition, the current ever-increasing recycling requirements require more and more manufacturers to choose adhesives that are recyclable (or at least allow for de-montage); these include most hot melt thermoplastic adhesives but exclude most thermosetting adhesives. This indicates that the future of thermosetting adhesive bonding is limited, whereas that of thermoplastic fusion bonding may be anticipated to prosper.

Fusion bonding has been addressed in about 400 scientific papers and in some book chapters. Our aim in writing this book is to consolidate the knowledge in a comprehensive publication. The principal objective of this book is to confer to the reader the capability of designing and optimising fusion bonding. The book aims at explaining the physical mechanisms occurring during the fusion bonding process. Modelling techniques and tools available to describe these mechanisms are unveiled in order to develop mechanism-based processing models. An in-depth understanding of the mechanisms leads to establishment of processing–microstructure–performance relationships. Eventually, both mechanistic and experimental procedures are used to construct an optimised processing window.

The research work from which this book arises was performed at the Centre for Advanced Material Technology in the School of Aerospace, Mechanical and Mechantronic Engineering, University of Sydney, Australia, from 1996 to 2000. The authors would like to thank their friends and colleagues for useful discussion, and help in the preparation of this book. The authors are particularly grateful to Y.-W. Mai, M. Hou, A. Beehag, Q. Yuan and M. Yang, who have commented on various chapters. Further thanks are due to K. Debschütz, H.-J. Dilling and U. Hald from DaimlerChrysler, whose encouragement made it possible to write this book.

Finally, L. Ye would like to thank his family, especially his wife, Pei, for their patience, understanding and assistance over so many years.

Christophe Ageorges (Sindelfingen, 31.10.01)
Lin Ye (Sydney, 31.10.01)

Notation and Abbreviations

a	Geometric parameter for surface roughness
a	Length of a surface crack
a^*	Geometric parameter for initial surface roughness
a_0	Geometric parameter for initial surface roughness
A	Cross-section of heating element
A	Pre-exponential factor in thermal degradation model
ABS	Acrylonitrile butadiene styren
A_d	Surface area of the welding interface being thermally degraded
AFM	Atomic force microscopy
AIAA	American Institute of Aeronautics and Astronautics
A_M	Parameter for calculating the crystal nucleation density
APC-2	CF-reinforced PEEK with v_f=61% manufactured by ICI
A_r	Parameter in Arrhenius law for reptation time
ARW	Automatic resistance welder
ASM	American Society for Materials
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
A_T	Total surface area of the welding interface
b	Width of the clamps
b	Geometric parameter for surface roughness
b_0	Geometric parameter for initial surface roughness
B_M	Parameter for calculating the crystal nucleation density
BMI	Bismaleimide (resin)
B_r	Pre-exponential parameter in Arrhenius law for reptation time
c	Crystallinity
C_1, C_2, C_3	Parameters in Icenogle's crystallisation model
$C1_1$, $C1_2$	Pre-exponential parameters in the Velisaris and Seferis crystallisation model
$C2_1$, $C2_2$	Empirical parameters in the Velisaris and Seferis crystallisation model
$C3_1$, $C3_2$	Empirical parameter in the Velisaris and Seferis crystallisation model
CAA	Chromic acid anodisation
C_{area}	Contact area in a gap

CCD	Charge-coupled device
CF	Carbon fibre
CIF	Composite integral fit
CMC	Ceramic matrix composite
c_r	Relative crystallinity
CTSF	Composite transfer squeeze forming
c_∞	Equilibrium crystallinity
d	Distance between the heating element mid-plane and the "de-consolidation front"
D_{au}	Degree of autohesion
D_b	Degree of bonding
DCB	Double cantilever beam
D_d	Degree of thermal degradation
DEA	Diffusion-enhanced adhesive
D_{ic}	Degree of intimate contact
D_p	Degree of penetration
E	Activation energy for thermal degradation model
E_a	Activation energy for crystal melting process in the Maffezzoli *et al.* model
E_d	Activation energy for Choe and Lee's crystallisation model
FEA	Finite element analysis
FEM	Finite element model
FIRE	Focused infrared energy welding
FPL	Forest Product Laboratory (etching technique)
FRP	Fibre-reinforced plastics
F_{vc1}	Relative volume fraction crystallinity for first crystallisation process in the Velisaris and Seferis crystallisation model
F_{vc2}	Relative volume fraction crystallinity for second crystallisation process in the Velisaris and Seferis crystallisation model
G	Spherulitic growth rate in Icenogle's crystallisation model
g	acceleration of gravity (9.81 m/s^2)
g^*	Single geometric parameter for initial surface roughness
G_0	Parameter in Icenogle's crystallisation model
GF	Glass fibre
G_{Ic}	Interlaminar fracture toughness
Gr	Grashof number (dimensionless)
h	Heat transfer coefficient for natural convection
HAZ	Heat-affected zone
HE	Heating element
HDPE	High density polyethylene
H_T	Total heat of crystallisation for a given cooling rate
H_u	Ultimate latent heat of crystallisation (for very slow cooling rate)
I	Current Intensity
IPN	Interpenetrating network
IR	Infrared
IRW	Impulse resistance welding
IVW	Institut für Verbundwerkstoffe

k	Thermal conductivity
K	Kinetic constant for the Maffezzoli *et al.* model
K_0	Pre-exponential factor for the Maffezzoli *et al.* model
k_1	Kinetic parameter in the Choe and Lee crystallisation model
k_2	Kinetic parameter in the Choe and Lee crystallisation model
k_{air}	Thermal conductivity of air
$k_{\mathrm{f}x}$	Longitudinal thermal conductivity of a reinforcing fibre
$k_{\mathrm{f}y}$	Transverse thermal conductivity of a reinforcing fibre
k_{gap}	Thermal conductivity of an interface modelled using a gap concept
k_{m}	Thermal conductivity of the matrix
k_x	Longitudinal thermal conductivity of a unidirectional composite
k_y (or k_z)	Transverse thermal conductivity of a unidirectional composite
l	Length of a resistor
L	Relevant dimension of the surface for determination of convection heat transfer coefficient
l^*	Equivalent length of heating element for computing power density
L_i (i=1, 2)	Length of heating element
L_{con}	Contact length at an interface modelled using a gap concept
LF	Load factor (for IRW)
L_{tot}	Total length of one unit cell in an interface modelled using a gap concept
LS	Lap shear
LSS	Lap shear strength
M	Molecular weight
M	Nucleation density in Icenogle's crystallisation model
M	Mass of a sample
$M_{\mathrm{composite}}$	Mass of a composite
M_0	Original mass of a sample (before any thermal degradation)
M_{f}	Final mass of a sample (after thermal degradation for infinite time)
M_{matrix}	Mass of the matrix in a composite
MMC	Metal matrix composite
n	Kinetic parameter in Ozawa's crystallisation model
n	Kinetic order in the Maffezzoli *et al.* model
n	Reaction order in thermal degradation model
n_1	Avrami exponent in the Velisaris and Seferis crystallisation model
n_2	Avrami exponent in the Velisaris and Seferis crystallisation model
N	Number of finite elements
NDE	Non-destructive evaluation
N_{hex}	Number of finite elements in the non-embedded part of the heating element along x-axis
N_{impulse}	Number of impulses for IRW
Nu	Nusselt number (dimensionless)
$N_{\mathrm{s}x}$	Number of finite elements in welding stack along x-axis
N_y	Number of finite elements along y-axis
P	Power

PA	Polyamide
PAA	Phosophoric acid anodisation
p_{app}	Applied pressure
PAS	Polyarylene sulfide
PC	Polycarbonate
PMC	Polymer matrix composite
PCM	Polymer-coated material
Pd_i (i=1 to 3)	Power density; definition 1, 2 or 3
PE	Polyethylene
PEI	Polyetherimide
PEEK	Polyetheretherketone
PES	Polyethersulfone
PI	Polyimide
p_{init}	Initial pressure
p_{max}	Maximum pressure
PMC	Polymer matrix composite
p_{min}	Minimum pressure
P_{nom}	Nominal power
PP	Polypropylene
PPS	Polyphenylene sulfide
PPQ	Polyphenylquinoxaline
Pr	Prandtl number (dimensionless)
PSU	Polysulfone
R	Resistance
R	Universal gas constant
Ra	Rayleigh number (dimensionless)
R_{clamps}	Resistance of clamps
R_{con}	Contact resistance between clamps and heating element
RF	Radio frequency
RH	Relative humidity
R_{he}	Resistance of the heating element
R_{mes}	Measured resistance
RT	Room temperature
R_{wires}	Resistance of electrical wires
SAM	Scanning acoustic microscope
SEC	Solar energy concentrator
SHA	Sodium hydroxide anodisation
Sol–gel	Solution–gelation
SRW	Sequential resistance welding
T	Period of signal for IRW
t	time
T_∞	Temperature at a remote location
t_b	Time required to achieve full bonding
T_d	Thermal degradation temperature
t_{elec}	Electrified time
T_{film}	Maximum local temperature in neat resin film
t_g	Gap duration for IRW

T_g	Glass transition temperature
T_{he}	Maximum local temperature in heating element
$t_{heating}$	Total heating time
th_{final}	Final thickness of the welding stack
th_{gap}	Thickness of a gap
th_i	Initial thickness of welding stack
t_i	Impulse duration for IRW
T_i (i=1 to 4)	Temperature at point *i*
t_{ic}	Time required to achieve full intimate contact
T_L	Liquidus temperature
T_{lami}	Maximum local temperature in mid-plane of a laminate
T_m	Melting temperature
T_m^0	Equilibrium thermodynamic melting temperature
t_m	Time required to achieve melting
t_p	Total processing time for resistance welding
TP	Thermoplastic polymer
TPMC	Thermoplastic matrix composite
t_r	Reptation time, or tube renewal time
T_S	Solidus temperature
TS	Thermosetting polymer
TSMC	Thermosetting matrix composite
UTL	Ultrasonic tape lamination
v_f	Fibre volume fraction
v_m	Matrix volume fraction
w	Width of the heating element
w	Geometric parameter for surface roughness at time *t*
w^*	Geometric parameter for initial surface roughness
w_0	Geometric parameter for initial surface roughness
w_1	Weight factor for the Velisaris and Seferis crystallisation model
w_2	Weight factor for the Velisaris and Seferis crystallisation model
w_f	Fibre mass fraction
X_f	Degree of crystal melting in Maffezzoli *et al.*'s model
X-PIA	Poly-amideimide
X_{vci}	Initial crystal volume fraction in Maffezzoli *et al.*'s model
X_{vc}	Crystal volume fraction at *t* in Maffezzoli *et al.*'s model
α	Coefficient of thermal expansion
α	Degree of conversion in thermal degradation model
Δa	Increment of crack growth
Δc	Increment in crystallinity
$\Delta D_{ic}(i)$	Increment in degree of intimate contact during step *i*
ΔH	Increment in latent heat
ΔT_1	Temperature amplitude along welding line determined experimentally including edge effects
ΔT_2	Temperature amplitude along welding line determined experimentally ignoring edge effects
ΔT_c	Temperature amplitude along welding line at the end of the cooling gap preceding t_m in IRW

ΔT_h	Temperature amplitude along welding line at the end of the heating impulse preceding t_m in IRW
ΔT_{h1}	ΔT_h at the end of the first heating impulse in IRW
ΔT_x	Temperature amplitude along welding line
$\Phi(T)$	Temperature-dependent parameter for Ozawa's crystallisation model
η	Viscosity
η_{mf}	Viscosity of the fibre–matrix system
ρ	Density
ρ	Resistivity
υ	Kinematic viscosity
σ	Mechanical strength of a surface experiencing autohesion
σ_∞	Mechanical strength of a surface at infinite time
ψ_1	Kinetic parameter in Choe and Lee's crystallisation model
ψ_2	Kinetic parameter in Choe and Lee's crystallisation model

Table of Contents