

Friction Stir Welding and Processing

Editors
Rajiv S. Mishra
Murray W. Mahoney



ASM International®
Materials Park, Ohio 44073-0002

www.asminternational.org

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, March 2007

Great care is taken in the compilation and production of this Volume, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Book Committee (2006–2007), James C. Foley, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Steven R. Lampman, Technical Editor; Diane Grubbs, Editorial Assistant; Bonnie Sanders, Manager of Production; Madrid Tramble, Senior Production Coordinator; and Kathryn Muldoon, Production Assistant

Library of Congress Cataloging-in-Publication Data

Friction stir welding and processing / editors Rajiv S. Mishra, Murray W. Mahoney.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-87170-848-9

ISBN-10: 0-87170-848-5

1. Friction welding. I. Mishra, Rajiv S. II. Mahoney, Murray W., 1945–

TS228.9F739 2007

671.5'2—dc233

2007060365

SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Contents

Preface	v
Chapter 1 Introduction	1
Rajiv S. Mishra, Center for Friction Stir Processing, University of Missouri-Rolla Murray W. Mahoney, Rockwell Scientific Company	
Chapter 2 Friction Stir Tooling: Tool Materials and Designs	7
Christian B. Fuller, Rockwell Scientific Company	
Chapter 3 Temperature Distribution and Resulting Metal Flow	37
J.A. Schneider, Mechanical Engineering Department, Mississippi State University	
Chapter 4 Microstructure Development in Aluminum Alloy Friction Stir Welds	51
A.P. Reynolds, Department of Mechanical Engineering, University of South Carolina	
Chapter 5 Mechanical Properties of Friction Stir Welded Aluminum Alloys	71
Murray W. Mahoney, Rockwell Scientific Company	
Chapter 6 Friction Stir Welding of Ferrous and Nickel Alloys	111
Carl D. Sorensen and Tracy W. Nelson, Department of Mechanical Engineering, Brigham Young University	
Chapter 7 Microstructure and Mechanical Properties of Friction Stir Welded Titanium Alloys	123
T.J. Lienert, MST Division, Los Alamos National Laboratory	

Chapter 8	Microstructures and Properties of Copper Alloys after Friction Stir Welding/Processing	155
	Terry R. McNelley, Keiichiro Oh-Ishi, and Alexander P. Zhilyaev, Naval Postgraduate School, Department of Mechanical and Astronautical Engineering	
Chapter 9	The Corrosion Properties of Friction Stir Welded Aluminum Alloys	175
	Jesse Lumsden, Rockwell Scientific Company	
Chapter 10	Process Modeling	187
	Hugh R. Shercliff and Paul A. Colegrove, Department of Engineering, University of Cambridge	
Chapter 11	Robots and Machines for Friction Stir Welding/Processing	219
	Christopher B. Smith, Friction Stir Link, Inc.	
Chapter 12	Friction Stir Spot Welding	235
	Harsha Badarinarayan, Frank Hunt, and Kazutaka Okamoto, Hitachi, America Ltd. R & D	
Chapter 13	Application of Friction Stir Welding and Related Technologies	273
	William J. Arbogast, NSF Center for Friction Stir Processing (CFSP) & Advanced Materials Processing and Joining Center (AMP), South Dakota School of Mines and Technology	
Chapter 14	Friction Stir Processing	309
	Rajiv S. Mishra, Center for Friction Stir Processing, University of Missouri-Rolla Murray W. Mahoney, Rockwell Scientific Company	
Chapter 15	Future Outlook for Friction Stir Welding and Processing	351
	Rajiv S. Mishra, Center for Friction Stir Processing, University of Missouri-Rolla Murray W. Mahoney, Rockwell Scientific Company	
Index		353

Preface

This volume is the first comprehensive compilation of friction stir welding (FSW) and friction stir processing (FSP) data. It should be a valuable handbook to students studying joining and metal working practices, to welding engineers challenged to improving properties at reduced costs, to metallurgists needing new tools to locally improve properties, and to all engineers interested in sustainability; i.e., the ability to build structures while minimizing the negative impact to our environment. In the 15 years since the invention of FSW at TWI in 1991, research throughout the world has been extensive, and considerable information has been published in conference proceedings and technical journals. Although FSP arrived later, publications describing benefits attributable to FSP are increasing rapidly. Unfortunately, access to the data is not always convenient and thus potential users, students, educators, and others, cannot and are not fully aware of the benefits offered by FSW/P. This limits understanding and thus the ability of FSW/P to expand beyond the laboratory and into structural applications. Notable and successful exceptions to these are illustrated in the chapter on applications. However, the expansion into production applications can accelerate if an understanding of FSW/P and the associated benefits were more readily accessible. Within this volume, we have tried to compile the current understanding of the fundamentals of FSW/P as well as to provide a moderately extensive database. This volume includes an accessible state-of-the-art overview; essentially the starting point from which a more detailed search of the literature can be initiated when more information is required. It is not intended to provide all the data presented in the literature but does guide the reader to detailed references. Since both FSW and FSP are young technologies, this is just the beginning. Hopefully, this volume will be followed with an updated information base as more data become available and as we gain a more complete understanding of the process fundamentals.

FSW/P was first applied to aluminum alloys; therefore, the data presented herein for the most common aluminum alloys are quite extensive. These data illustrate mechanical, fatigue, and corrosion properties that can be realized for each alloy category when using sound FSW/P procedures. However, the reader is cautioned not to extrapolate even within the same alloy class because of subtle processing differences, which can result in considerable differences in resultant properties. A data base for the higher temperature alloys is growing. With the recent development and improvement in tooling capable of higher temperature operation, FSW/P is starting to be applied to the copper, iron, and nickel base alloys. The data for these alloys is not extensive, but what is available is presented herein. Due to the considerable benefits and ease of application, we anticipate friction stir welding and friction stir processing will be technologies of rapid

growth following the normal progression of fundamental research, data development and eventually structural applications.

This initial reference volume is the collective effort of leading researchers who are active in the FSW/P community and whose by-lines appear throughout this volume. We gratefully thank and commend each of them for their contributions and considerable efforts. Each contributor to this volume has drawn on the research of colleagues and associates whose work is dutifully referenced. We thank these many researchers and their support staffs. Only through our composite efforts can we continue to advance science and engineering and contribute to society as a whole.

Rajiv S. Mishra
University of Missouri-Rolla
Murray W. Mahoney
Rockwell Scientific Company



ASM International is the society for materials engineers and scientists, a worldwide network dedicated to advancing industry, technology, and applications of metals and materials.

ASM International, Materials Park, Ohio, USA
www.asminternational.org

This publication is copyright © ASM International®. All rights reserved.

Publication title	Product code
Friction Stir Welding and Processing	05112G

To order products from ASM International:

Online Visit www.asminternational.org/bookstore

Telephone 1-800-336-5152 (US) or 1-440-338-5151 (Outside US)

Fax 1-440-338-4634

Mail Customer Service, ASM International
 9639 Kinsman Rd, Materials Park, Ohio 44073-0002, USA

Email CustomerService@asminternational.org

In Europe American Technical Publishers Ltd.
 27-29 Knowl Piece, Wilbury Way, Hitchin Hertfordshire SG4 0SX,
 United Kingdom
 Telephone: 01462 437933 (account holders), 01462 431525 (credit card)
www.ameritech.co.uk

In Japan Neutrino Inc.
 Takahashi Bldg., 44-3 Fuda 1-chome, Chofu-Shi, Tokyo 182 Japan
 Telephone: 81 (0) 424 84 5550

Terms of Use. This publication is being made available in PDF format as a benefit to members and customers of ASM International. You may download and print a copy of this publication for your personal use only. Other use and distribution is prohibited without the express written permission of ASM International.

No warranties, express or implied, including, without limitation, warranties of merchantability or fitness for a particular purpose, are given in connection with this publication. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this publication shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this publication shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.