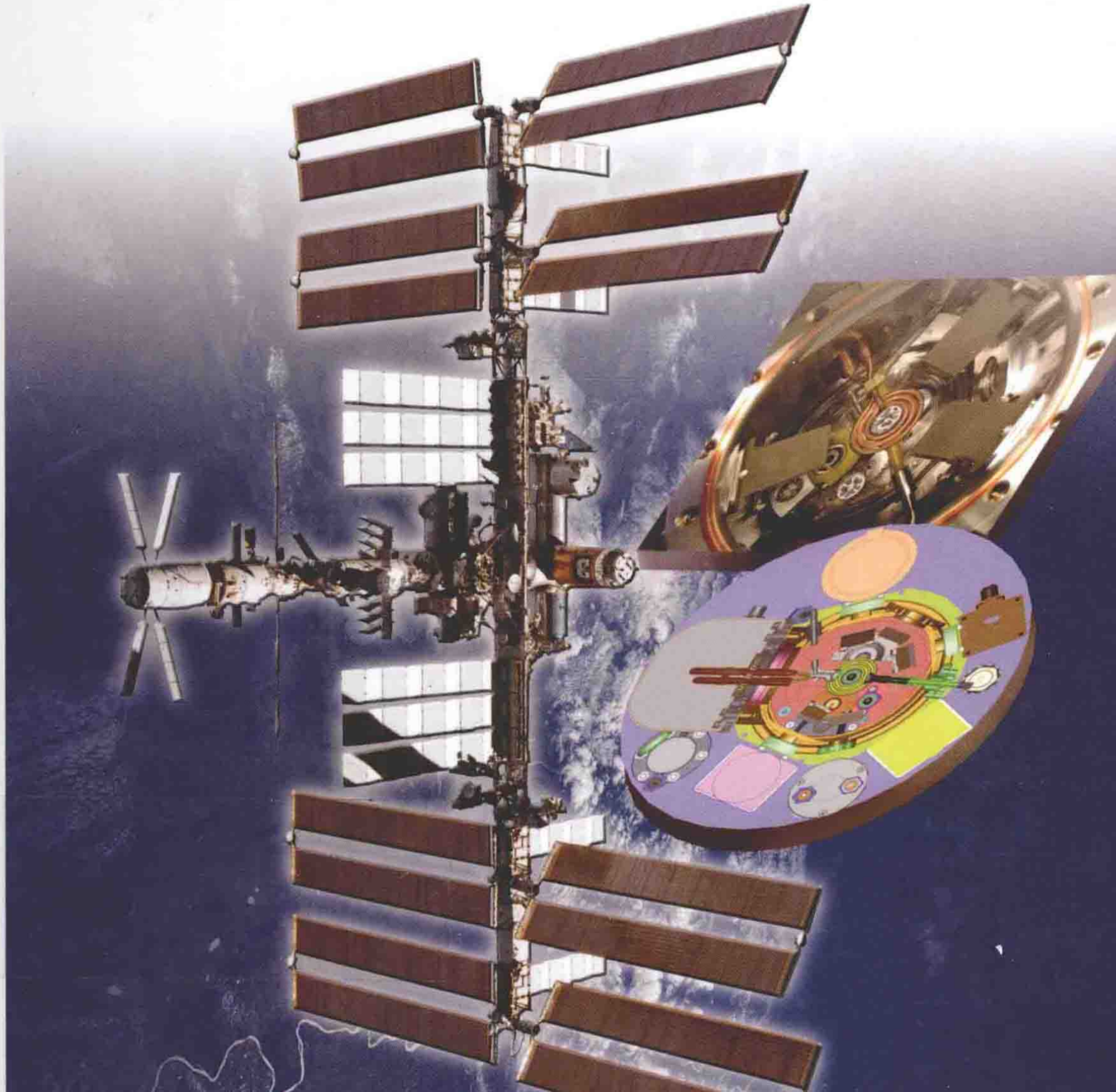
Dieter M. Herlach, Douglas M. Matson

WILEY-VCH

Solidification of Containerless Undercooled Melts



Edited by Dieter M. Herlach and Douglas M. Matson

Solidification of Containerless Undercooled Melts

WILEY-VCH

WILEY-VCH Verlag GmbH & Co. KGaA

The Editors

Prof. Dieter M. Herlach
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
51147 Köln
Germany

Prof. Douglas M. Matson
Tufts University
Dept. of Mechanical Eng.
200 College Avenue
Medford, MA 02155
USA

We would like to thank the DLR for the material used in the cover picture.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Composition Thomson Digital, Noida, India
Printing and Binding Markono Print Media Pte Ltd, Singapore
Cover Design Adam Design, Weinheim

Print ISBN: 978-3-527-33122-2
ePDF ISBN: 978-3-527-64793-4
ePub ISBN: 978-3-527-64792-7
mobi ISBN: 978-3-527-64791-0
oBook ISBN: 978-3-527-64790-3

Printed in Singapore
Printed on acid-free paper

Edited by
Dieter M. Herlach and
Douglas M. Matson

Solidification of Containerless Undercooled Melts

Preface

Metallic materials are prepared from the liquid state as their parent phase. The conditions under which the liquid solidifies determine the physical and chemical properties of the as-solidified material. In most cases time and energy consuming post-solidification treatment of the material is mandatory to obtain the final product with its desired properties and design performance. Therefore, efforts are directed towards virtual material design with computer assisted modelling. This can shorten the entire production chain - ranging from casting the shaped solid from the melt to the final tuning of the product in order to save costs during the production process. The goal is to fabricate novel materials with improved properties for specific applications. To date, metal production is the largest industry worldwide. In the European Union there are 417 700 enterprises with 5.1 Million employees. They correspond to 3.9% of the entire workforce and produce 244.4 billion EUR added value each year (*European business – Facts and figures Eurostat 2007*). Therefore, even small improvements in production efficiency for the metal industry may lead to large economic gains.

Computational materials science from the liquid state requires thermo-physical parameters measured with high accuracy and detailed knowledge of the physical mechanisms involved in the solidification process. In particular, these are crystal nucleation and crystal growth. Both of these processes are driven by an undercooling of the liquid below its equilibrium melting temperature to develop conditions where a driving force for the advancement of a solidification front is created. This gives access to non-equilibrium solidification pathways which can form metastable solids which may differ in their physical and chemical properties from their stable counterparts. Detailed modelling of solidification, both near equilibrium and far away from thermodynamic equilibrium, requires that the solidification process must be investigated in every detail.

In order to achieve the state of an undercooled melt, it is advantageous to remove heterogeneous nucleation sites which otherwise limit the undercoolability. The most efficient way to realize such conditions is containerless processing of melts. In such, the most dominant heterogeneous nucleation process, involving interaction with container walls, is completely avoided. Nowadays, electromagnetic and electrostatic levitation techniques have been developed for containerless undercooling and solidification of molten metals and alloys. A freely suspended drop gives the extra benefit to directly observe the solidification process by combining the levitation technique with proper diagnostic means. For instance, short range ordering as precursor of crystal nucleation has been investigated by using synchrotron radiation and neutron diffraction on containerless undercooled melts. Additionally, primary phase selection processes for rapid solidification of metastable phases has been observed in situ by energy dispersive X-ray radiation using synchrotron radiation of high intensity. Rapid growth of dendrites is observed on levitation undercooled melts by using video camera techniques characterized by high spatial and temporal resolution.

The application of containerless processing on Earth is limited since large levitation forces are needed to compensate for the gravitational force acting on the samples. The large levitation forces cause undesirable effects like externally induced stirring of the liquid or deformation of the liquid sample from sphere-like geometry. These are overcome when utilizing the special environment of reduced gravity. Here, the forces to compensate for g-jitter, the small random accelerations associated with spacecraft operation, are about three orders of magnitude less than levitation forces on Earth. Based upon such consideration a facility for containerless electro-magnetic processing in space called TEMPUS (Tiegelfreies Elektro-Magnetisches Prozessieren Unter Schwerelosigkeit) has been developed by DLR, the German Space Agency. It was constructed by the German aerospace industry and tested during several parabolic flight campaigns to demonstrate technical functionality. In a cooperation between DLR Space Agency and the US National Aeronautics and Space Administration (NASA), TEMPUS had its maiden flight under real space conditions on board the shuttle Columbia during the NASA Spacelab mission International Microgravity Laboratory IML 2 in 1994. The German – USA cooperation was handled on the principle "no exchange of funds" meaning that the facility was provided by DLR and flight opportunity was offered by NASA. The total experiment time during the 14 days mission was shared between US and German investigator teams. The mission was successful not only by demonstrating technical functionality of TEMPUS in Space but also obtaining interesting scientific results including high accuracy measurements of thermophysical properties and investigations of gravity related phenomena in solidification of undercooled metals and alloys. Later on, TEMPUS was flown again on Columbia during NASA spacelab missions Microgravity Space Laboratory 1 (MSL-1) and Microgravity Space Laboratory 1 reflight (MSL-1R) in 1997. A broad spectrum of science return from the TEMPUS spacelab missions are published in Materials and Fluids Under Microgravity, Lecture Notes in Physics, eds.: L. Ratke, H. Walter, B. Feuerbacher (1995) and Solidification 1999, Proceedings of symposia at the TMS Fall Meeting 1998, eds.: W. H. Hofmeister, J. R. Rogers, N.B. Singh, S. P. Marsh, P. W. Vorhees (1999).

At present, an advanced Electro-Magnetic Levitator (EML) facility is under development by a common effort between the DLR Space Agency and the European Space Agency ESA. The EML is constructed by ASTRIUM and is scheduled for accommodation on board the International Space Station ISS in 2013. Meanwhile, several international investigator teams of scientists from the member states of ESA, USA and Japan are preparing experiments dedicated to be performed in Space using the EML multi-user facility on the ISS. In parallel to the experimental work, modelling and theoretical evaluation of solidification processes are planned. In particular, understanding the importance of gravity-driven phenomena like changes in heat and mass transport by forced convection is a central part of these solidification investigations.

These developments both on the experimental and on the theoretical side stimulated the editors of the present book to collect the state of solidification research as far as it is directly correlates to solidification of containerless undercooled melts. These attempts were supported by our colleagues who contributed to the scientific content of the present book. We appreciate their efforts and cooperation in delivering high quality articles to this book. Most of the authors of the book are members of an international Topical Team on Containerless Undercooling and Solidification of Melts (SOL-EML) sponsored by the European Space Agency. We thank ESA for this support and for their vision to bring together experts in this field from all over the world - with membership coming from Europe, North America, Japan and also from China and India. In these latter countries, enormous efforts are undertaken at present to set up a materials science programme in space. In particular, German partners and colleagues benefitted from priority programmes focused on solidification research on undercooled melts in the Earth laboratory, which were financed by the German Research Foundation DFG. This support is greatly appreciated as well. Last but not least the editors are very grateful to Dr. Martin Graf from WILEY – VCH for pleasant and efficient cooperation during the entire course of preparing and editing the present book.

Dieter Herlach and Douglas Matson

List of Contributors

Mark Asta
University of California
Department of Materials Science and Engineering
210 Hearst Memorial Mining Building, Room 384
Berkeley, CA 94720
USA

Sven Binder
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

Krishanu Biswas
Indian Institute of Technology
Department of Materials Science and Engineering
Faculty Building, Room 407
Kanpur 208016
India

Valdis Bojarevics
University of Greenwich
School of Computing and Mathematical Sciences
Old Royal Naval College
Park Row
London SE10 9LS
UK

Georg Ehlen
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

and

Institut für Festkörperphysik
Ruhr-Universität Bochum
Universitätsstraße 150
44780 Bochum
Germany

Jan Fransaer
University of Leuven
Department of Metallurgy and Materials Engineering (MTM)
Kasteelpark Arenberg 44 - box 2450
3001 Heverlee
Belgium

Peter K. Galenko
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

and

Institut für Festkörperphysik
Ruhr-Universität Bochum
Universitätsstraße 150
44780 Bochum
Germany

Charles-André Gandin
MINES ParisTech
CEMEF UMR 7635, CNRS
06904 Sophia Antipolis
France

Jianrong Gao
Northeastern University
Key Laboratory of Electromagnetic Processing of Materials
P.O. Box 314
3-11 Wenhua Road
Shenyang 110004
China

László Gránásy
BCAST
Brunel University
Uxbridge
Middlesex UB8 3PH
UK

and

Research Institute for Solid State Physics and Optics
P.O. Box 49
1525 Budapest
Hungary

Alain Lindsay Gree
University of Cambridge
Department of Materials Science and Metallurgy
Pembroke Street
Cambridge CB2 3QZ
UK

Tsuyoshi Hamada
Yokohama National University
Graduate School of Environment and Information Sciences
79-7 Tokiwadai
Hodogaya-ku
Yokohama 240-8501
Japan

Hani Henein
University of Alberta
Department of Chemical and Materials Engineering
7th Floor, Electrical & Computer Engineering Research Facility (ECERF)
91017-116 Street
Edmonton, Alberta T6G 2V4
Canada

Dieter M. Herlach
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

Dirk Holland-Moritz
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Linder Höhe
51170 Köln
Germany

Jürgen Horbach
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und
Raumfahrt (DLR)
Linder Höhe
51170 Köln
Germany

and

Heinrich Heine-Universität Düsseldorf
Institut für Theoretische Physik der
Weichen Materie
Universitätsstraß e 1
40225 Düsseldorf
Germany

Jeff J. Hoyt
McMaster University
Department of Materials Science and
Engineering
1280 Main Street
Hamilton, Ontario L8S4LS
Canada

Robert W. Hyers
University of Massachusetts
Mechanical and Industrial Engineering
160 Governors Drive
Amherst, MA 01003-2210
USA

Arash L. Ilbagi
University of Alberta
Department of Chemical and Materials
Engineering Department
7th Floor, Electrical & Computer
Engineering Research Facility (ECERF)
91017-116 Street
Edmonton, Alberta T6G 2V4
Canada

Yuko Inatomi
Institute of Space and Astronautical
Science, JAXA
3-1-1 Yoshinodai, Sagamihara
Chuo-ku
Kanagawa 229-8510
Japan

Andrew Kao
University of Greenwich
School of Computing and Mathematical
Sciences
Old Royal Naval College
Park Row
London SE10 9LS
UK

Alain Karma
Northeastern University
Department of Physics
360 Huntington Ave
Boston, MA 02115
USA

Kenneth F. Kelton
Washington University in St. Louis
Department of Physics
One Brookings Drive
St. Louis, MO 63130-4899
USA

Matthias Kolbe
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und
Raumfahrt (DLR)
Linder Höhe
51147 Köln
Germany

Mikhael Krivilyov
Udmurt State University
Department of Physics
Laboratory of Condensed Matter Physics
Universitetskaya 1
426034 Izhevsk
Russia

Philipp Kuhn
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Linder Höhe
51170 Köln
Germany

Kazuhiko Kuribayashi
Japan Aerospace Exploration Agency
The Institute of Space & Astronautical Science
3-1-1 Yoshinodai, Sagamihara
Chuo-ku
Kanagawa 229-8510
Japan

Wolfgang Löser
Leibniz-Institut für Festkörper und Werkstoffforschung, IFW
Helmholtzstraße 20
01069 Dresden
Germany

Douglas M. Matson
Tufts University
Department of Mechanical Engineering
200 College Avenue
Medford, MA 02155
USA

Hideaki Nagai
National Institute of Advanced Industrial Science and Technology
AIST Tsukuba Central 5
Tsukuba, Ibaraki 305-8565
Japan

Ralph E. Napolitano
Iowa State University
Division of Materials Science and Engineering
3273 Gilman Hall
Ames, IA 50011-2300
USA

Takeshi Okutani
Yokohama National University
Graduate School of Environment and Information Sciences
79-7 Tokiwadai
Hodogaya-ku
Yokohama 240-8501
Japan

Shumpei Ozawa
Tokyo Metropolitan University
Department of Aerospace Engineering
Hino-shi
Tokyo 1901-065
Japan

Koulis Pericleous
University of Greenwich
School of Computing and Mathematical Sciences
Old Royal Naval College
Park Row
London SE10 9LS
UK

Tamás Pusztai
Research Institute for Solid State Physics and Optics
P.O. Box 49
1525 Budapest
Hungary

Roberto E. Rozas
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Linder Höhe
51170 Köln
Germany

and

Heinrich Heine-Universität Düsseldorf
Institut für Theoretische Physik der Weichen Materie
Universitätsstraß e 1
40225 Düsseldorf
Germany

Sumanta Samal
Indian Institute of Technology
Department of Materials Science and Engineering Faculty Building
Kanpur 208016
India

Olga Shuleshova
Leibniz-Institut für Festkörper- und werkstoffforschung, IFW
Helmholtzstr. 20
01069 Dresden
Germany

György Tegze
Institute for Solid State Physics and Optics
Wigner Research Centre for Physics
P.O. Box 49
1525 Budapest
Hungary

Gyula I. Tóth
Institute for Solid State Physics and Optics
Wigner Research Centre for Physics
P.O. Box 49
1525 Budapest
Hungary

Damien Tourret
MINES ParisTech
CEMEF UMR 7635, CNRS
06904 Sophia Antipolis
France

and

Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

Thomas Volkmann
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Germany

Chao Yang
Northeastern University
Key Laboratory of Electromagnetic Processing of Materials
P.O. Box 314
3-11 Wenhua Road
Shenyang 110004
China

Hideyuki Yasuda
Osaka University
Graduate School of Engineering
Department of Adaptive Machine Systems
Suita
Osaka 565-0871
Japan

Yikun Zhang
Northeastern University
Key Laboratory of Electromagnetic
Processing of Materials
P.O. Box 314
3-11 Wenhua Road
Shenyang 110004
China

Zongning Zhang
Northeastern University
Key Laboratory of Electromagnetic
Processing of Materials
P.O. Box 314
3-11 Wenhua Road
Shenyang 110004
China

Related Titles

Barsoum, M.

MAX Phases

Properties of Machinable Ternary Carbides and Nitrides

2013

ISBN: 978-3-527-33011-9

Bathias, C., Pineau, A. (eds.)

Fatigue of Materials and Structures

E-Book

ISBN: 978-0-470-39401-4

Dubois, J.-M., Belin-Ferré, E. (eds.)

Complex Metallic Alloys

Fundamentals and Applications

2011

ISBN: 978-3-527-32523-8

Jackson, K. A.

Kinetic Processes

Crystal Growth, Diffusion, and Phase Transitions in Materials

Second edition

2010

ISBN: 978-3-527-32736-2

Krzyzanowski, M., Beynon, J. H., Farrugia, D. C. J.

Oxide Scale Behavior in High Temperature Metal Processing

2010

ISBN: 978-3-527-32518-4

Slezov, V. V.

Kinetics of First-order Phase Transitions

2009

ISBN: 978-3-527-40775-0

Blondeau, R. (ed.)

Metallurgy and Mechanics of Welding

2008

ISBN: 978-1-84821-038-7

Scheel, H. J., Capper, P. (eds.)

Crystal Growth Technology

From Fundamentals and Simulation to Large-scale Production

2008

ISBN: 978-3-527-31762-2

Contents