Solidification Behavior in Reduced Gravity

DOUGLAS M. MATSON^{1,5} , ROBERT W. HYERS,² AMBER GENAU,³ and M. ASLE ZAEEM⁴

1.—Department of Mechanical Engineering, Tufts University, Medford, MA, USA. 2.—Mechanical and Industrial Engineering Department, University of Massachusetts, Amherst, MA, USA. 3.—Materials Science and Engineering Department, University of Alabama, Birmingham, AL, USA. 4.—Materials Science and Engineering Department, Missouri University of Science and Technology, Rolla, MO, USA. 5.—e-mail: douglas.matson@tufts.edu

Reducing gravitational effects such as thermal and solutal buoyancy enables the investigation of a large range of different phenomena in materials science. Reduced-gravity experiments can isolate phenomena otherwise obscured in ground-based experiments, leading to new discoveries that can improve materials and processes here on Earth. In addition to ground-based and short-term drop tower, reduced-gravity aircraft or sounding rocket facilities, long-term experiments in microgravity have a long history, from the early days of spaceflight to current experiments on the International Space Station (ISS). The *Materials Science in Reduced Gravity Symposium* was conducted as part of the 145th Annual Meeting in Nashville (TMS 2016). It involved three sessions composed of 29 presentations with contributions from more than 13 countries. The sessions concentrated on three different categories of topics related to ongoing reduced-gravity research: (1) Materials Science Research Rack (MSRR), (2) Ground-based/Parabolic Aircraft/Sounding Rocket Testing, and (3) Containerless Processing. Topics included particle engulfment, directional solidification, sintering, coarsening, influence of convection on solute and heat transport, metastable phase formation, phase selection, thermophysical property measurement, modeling activities for experiment control, and visualization of microstructural evolution. The symposium was sponsored by the TMS Materials Processing and Manufacturing Division and the TMS Solidification Committee. Although five papers were published as part of the TMS Supplemental Proceedings, the TMS Solidification Committee commissioned the organizers to produce a special topic for *JOM* to highlight the accomplishments from the meeting. These papers represent a broad summary of some of the exciting new solidification processing activities currently underway on the ground and in space to support reduced-gravity experiments.

SPECIAL TOPIC CONTENTS

Fecht and Wunderlich discuss molten alloy thermophysical property measurement in support of the modeling of solidification processes in “Fundamentals of Liquid Processing in Low-Earth Orbit: From Thermophysical Properties to Microstructure Formation in Metallic Alloys”. Advanced modeling of industrial processes on Earth requires property measurements of the highest fidelity. This paper discusses how space measurement techniques are being used to provide data for a broad range of liquid metal alloys to deeper undercoolings than can be achieved using conventional techniques. These advancements are attributed to the quiescent microgravity processing conditions accessible on the ISS.

Zimmerman et al. present a team review entitled “Columnar and Equiaxed Solidification of Al-7 wt.%Si Alloys in Reduced Gravity in the Framework of the CETSOL Project” that is currently running on the ISS. During directional solidification, the columnar to equiaxed transition (CET) significantly influences microstructural evolution and subsequent material properties in cast structures. Reduced gravity experiments show that grain-refined alloys exhibit CET while unrefined alloys show only columnar growth. Three different numerical modeling approaches successfully predict the position in the sample where the transition is expected to occur based on dendrite tip undercooling and growth rate predictions.

Directional solidification of a model transparent alloy system is presented in “Convection Effects During Bulk Transparent Alloy Solidification in DECLIC-DSI and Phase-Field Simulations in Diffusive Conditions” by Mota et al. Latent heat rejection at the growth interface through thermal diffusion is significantly different in space as compared to the ground during the dynamic oscillatory evolution of cellular and dendritic arrays. Recent modeling

activity on the development of morphological instabilities has been successful in predicting interface recoil, primary spacing, and macrosegregation.

“Macrosegregation During Re-melting and Holding of Directionally Solidified Al-7 wt.% Si Alloy in Microgravity” by Lauer et al. provides a review of the results of three recent directional solidification experiments using the ESA Low Gradient Furnace insert in the NASA Materials Science Research Rack (MSRR) on the ISS. Metallographic evaluations show how solidification structures evolve at different growth rates. Transient diffusion of the solute throughout the liquid and mushy-zone are successfully predicted using a mathematical model to track macrosegregation in the absence of buoyancy-driven convection.

The article by Lee and SanSoucie entitled “Experiments using a Ground-Based Electrostatic Levitator and Numerical Modeling of Melt Convection for the Iron-Cobalt System in Support of Space Experiments” discusses ground-based preparations required to support ongoing space investigations. The authors discuss how mathematical modeling is used to predict convection during flight experiments, thus allowing investigators to select appropriate run conditions to understand how flow regime (laminar/turbulent), stirring, and liquid shear influences solidification behavior. In parallel, electrostatic levitation is used to measure density to support flow calculations, while evaporation rates are quantified to define safe thermal cycle profiles that limit both facility damage and sample compositional changes on-orbit over time. This work illustrates how ground testing supports the development of reduced gravity solidification experiments.

Ground-based and reduced-gravity containerless processing used to study alloy solidification and experimental techniques include atomization facilities, drop-tube experiments, and levitation processing on parabolic flights, sounding rockets and the ISS. Results using these techniques are compared in the article by Herlach et al. entitled “Solidification of Undercooled Melts of Al-Based Alloys on Earth and in Space.” Convection using electromagnetic levitation processing significantly influences dendrite growth kinetics, segregation, and microstructural evolution.

“Use of Thermophysical Properties to Select and Control Convection During Rapid Solidification of Steel Alloys Using Electromagnetic Levitation on the Space Station” by Matson et al. discusses how the unique attributes of reduced-gravity testing allow for an expansion of the accessible range of melt stirring conditions compared to ground-based testing. Convection becomes a controlled test parameter spanning the laminar–turbulent transition for studies of the transformation from ferrite to austenite near the alloy melt temperature. Levitation tests on the ISS show that both undercooling and melt stirring reduce the incubation time between successive nucleation events.

UPCOMING FUNDING OPPORTUNITIES

Readers are encouraged to seek additional sponsorship opportunity information from the forthcoming yearly NASA research announcement (NRA) “Use of the NASA Physical Sciences Informatics System” leading to new evaluations of existing space research data. The recent “MaterialsLab” NRA added 16 funded investigators in seven science definition team reference experiments in 2016. Future NRAs include “FluidsLab” and “CombustionLab” focused solicitations which are scheduled to be released starting as early as next year.

The following papers are published under the topic “Solidification Behavior in Reduced Gravity” in the August 2017 issue (vol. 69, no. 8) of *JOM* and can be accessed via the *JOM* page at <http://link.springer.com/journal/11837/69/8/page/1>.

- “Fundamentals of Liquid Processing in Low-Earth Orbit: From Thermophysical Properties to Microstructure Formation in Metallic Alloys” by Hans-Jörg Fecht and Rainer Wunderlich.
- “Columnar and Equiaxed Solidification of Al-7 wt.%Si Alloys in Reduced Gravity in the Framework of the CETSOL Project” by G. Zimmermann, L. Sturz, H. Nguyen-Thi, N. Mangelinck-Noel, Y.Z. Li, C.-A. Gandin, R. Fleurisson, G. Guillemot, S. McFadden, R.P. Mooney, P. Voorhees, A. Roos, A. Ronaföldi, C. Beckermann, A. Karma, C.-H. Chen, N. Warnken, A. Saad, G.-U. Grün, M. Grohn, I. Poitault, T. Pehl, I. Nagy, D. Todt, O. Minster, and W. Sillekens.
- “Influence of Convection During Directional Solidification of a Bulk Transparent Alloy: Comparison of 1 g and μ g Eperformed in the DECLIC-DSI and Phase-Field Simulations in a Diffusive Growth Regime” by F.L. Mota, Y. Song, J. Pereda, B. Billia, D. Tourret, J.-M. Debierre, R. Trivedi, A. Karma, and N. Bergeon.
- “Macroscopic Segregation During Re-melting and Holding of Directionally Solidified Al-7 wt.% Si Alloy in Microgravity” by M. Lauer, M. Ghods, S.G. Angart, R.N. Grugel, S.N. Tewar, and D.R. Poirier.
- “Experiments using a Ground-Based Electrostatic Levitator and Numerical Modeling of Melt Convection for the Iron-Cobalt System in Support of Space Experiments” by Jonghyun Lee and Michael P. SanSoucie.
- “Solidification of Undercooled Melts of Al-Based Alloys on Earth and in Space” by Dieter M. Herlach, S. Burggraf, Peter Galenko, Charles-André Gandin, Asuncion Garcia-Escorial, Hani Henein, Christian Karrasch, Andrew Mullis, Markus Rettenmayr, and Jonas Valloton.
- “Use of Thermophysical Properties to Select and Control Convection During Rapid Solidification of Steel Alloys Using Electromagnetic Levitation on the Space Station” by Douglas M. Matson,

Xiao Xiao, Justin E. Rodriguez, Jonghyun Lee, Robert W. Hyers, Olga Shuleshova, Ivan Kaban, Stephan Schneider, Christian Karrasch, Stefan Burggraff, Rainer Wunderlich, and Hans-Jörg Fecht.

ACKNOWLEDGEMENTS

Funding was provided by National Aeronautics and Space Administration (Grant No. NNX16AB 59G).