ESSENTIAL READINGS IN MAGNESIUM TECHNOLOGY

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Edited by

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PREFACE

"Magnesium will lighten the tasks of man in countless ways as yet undreamed of, except in the minds of far-seeing engineers [...] who are already planning the future."

– 1942 Dow Chemical Advertisement

Due to their extraordinarily low densities, magnesium ("Mg") and its alloys have continued to be the focus of intensive research and development over the past century though widespread application has been restricted by property, cost, and performance limitations with respect to other metallic materials such as Al-alloys, Ti-alloys, and ferrous alloys. However, in light of Mg's availability and global efforts to reduce weight in the transportation sector, there has been a tremendous resurgence in research, development, and applications of these remarkable alloys.

Along with this renaissance came renewed interest from government, academia, and industry, and in the year 2000, the first Magnesium Technology Symposium was held at The Minerals, Metals & Materials Society (TMS) Annual Meeting and Exhibition in Nashville, Tennessee. A proceedings volume with 56 manuscripts was published in parallel with the new symposium, and the tremendous interest that was generated enabled the symposium to be held annually with the *Magnesium Technology* proceedings becoming the *de facto* publication for the magnesium industry.

In your hands (or perhaps on your screen), you have some of the most influential and impactful papers of the 1024 manuscripts published in the proceedings between 2000 and 2012. This single reference chronicles and condenses the major global advances made over the last decade. To select the best papers, a team of editors was selected based on their extensive experience with various aspects of Mg technology, with all editors having served as organizers and editors on *Magnesium Technology* proceedings published during the selected timeframe (Mathaudhu, '11–'12; Luo, '04,'06,'07; Neelameggham, '06–'12; Nyberg, '08–'10; Sillekens, '10–'12).

Manuscripts were comprehensively reviewed for prospective inclusion, and the final papers were selected based on the following three criteria:

1. *General Relevance*. Beginning in 2002, the symposium organizers and session chairs began selecting "best paper" awards for one student and one contributed manuscript. These papers, at the time, represented the latest scientific breakthroughs, and thus are included as "essential reading" (see Table 1 on page xv). Also included based on this criteria are a number of "review" type papers that summarize the state-of-the-art in Mg technology, and thus frame the true impact of recent advances.

2. *Scientific Relevance.* In the academic world, the largest indication of impact is based on citations. The *Magnesium Technology* proceedings are indexed by a number of databases, from which citation data were collected and analyzed and papers with a high number of citations were selected for inclusion.

3. *Industrial Relevance*. In 2007, a "best paper" award in application was added to the student and contributed awards. These manuscripts were selected for inclusion due to their representation of leap-forward advances and novel demonstrations of industrial applications.

Introductions to each part further frame the importance and significance of the selected manuscripts. The papers selected for inclusion were divided along nine topical thematic areas, with the papers arranged by subject area rather than chronologically to support the cohesiveness of subtopics within each theme. The nine themes are as follows:

1. Magnesium Technology History and Overview
2. Electrolytic and Thermal Primary Production
3. Melting, Refining, Recycling, and Life-Cycle Analysis
4. Casting and Solidification
5. Alloy and Microstructural Design
6. Wrought Processing
7. Modeling and Simulation
8. Joining
9. Corrosion, Surface Treatment, and Coating

A significant amount of time and resources have gone into this volume, and many thanks are owed to those who have donated their energy to its success. Primary thanks goes to the many authors whose work is presented in this volume, the many symposium organizers and participants who have continually maintained a high level of scholarship and ensured the continual growth of this discipline. The production team at TMS and Wiley, primarily Matt Baker, are acknowledged for their continual support and motivation to see this project to completion. It is our hope that this volume will provide a key resource for those "*far-seeing engineers"* who have, and will, dedicate their livelihoods to the advancement of this amazing metal.

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Alan A. Luo, The Ohio State University
Neale R. Neelameggham, IND LLC
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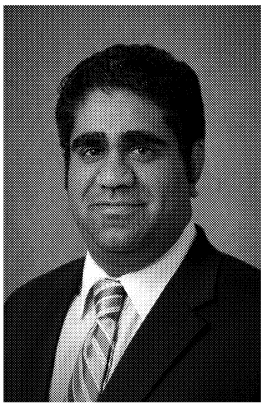
Table 1: Magnesium Technology Best Paper Award Winners

PART	AWARD	AUTHOR(S)	TITLE	PAGE
Part 1: Magnesium Technology History and Overview	2013 Best Application Paper	D'Errico F., Screnci A.	High-capacity hydrogen-based green-energy storage solutions for the grid balancing	77
Part 2: Electrolytic and Thermal Primary Production	2010 Best Student Paper	McLean K., Pettingill J., Davis B.	Cathode wetting studies in magnesium electrolysis	107
Part 3: Melting, Refining, Recycling, and Life-Cycle Analysis	2003 Best Student Paper	Aarstad K., Syvertsen M., Engh T.A.	Solubility of fluorine in molten magnesium	181
Part 4: Casting and Solidification	2004 Best Contributed Paper	St.John D.H., Dahle A.K., Abbott T., Nave M.D., Qian M.	Solidification of cast magnesium alloys	193
	2007 Best Student Paper	Lee S.G., Gokhale A.M.	Phenomena of formation of gas induced shrinkage porosity in pressure die-cast Mg-alloys	211
	2005 Best Student Paper	Moore A.R., Torbet C.J., Shyam A., Jones J.W., Walukas D.M., Decker R.F.	Fatigue behavior of thixomolded® magnesium AZ91D using ultrasonic techniques	227
	2010 Best Application Paper	Duygulu O., Ucuncuoglu S., Oktay G., Temur D.S., Yucel O., Kaya A.A.	Development of 1500mm wide wrought magnesium alloys by twin roll casting technique in Turkey	239
Part 5: Alloy and Microstructural Design	2007 Best Application Paper	Klösch G., McKay B.J., Schumacher P.	Preliminary investigation on the grain refinement behavior of ZrB_2 particles in Mg-Al alloys	255
	2006 Best Student Paper	Blake A.H., Cáceres C.H.	Solid solution effects on the tensile behaviour of concentrated Mg-Zn alloys	263
	2002 Best Contributed Paper	Powell B.R., Rezhets V., Balogh M.P., Waldo R.A.	The relationship between microstructure and creep behavior in AE42 magnesium die casting alloy	275
	2013 Best Fundamental Paper	Sasaki T.T., Ohkubo T., Hono K.	Age hardening behavior of Mg-1.2Sn-1.7Zn alloy containing Al	269
	2006 Best Contributed Paper	Suzuki A., Saddock N.D., Jones J.W., Pollock T.M.	Phase transformation and creep of Mg-Al-Ca based die-cast alloys	291
	2011 Best Student Paper	Lee J.-K., Kim S.K.	Fire-proof evaluation of CaO added Mg-3Al, Mg-6Al, and Mg-9Al Mg cast products	305
	2010 Best Fundamental Paper	Rosalie J.M., Somekawa H., Singh A., Mukai T.	Directionally controlled precipitation on twin-boundaries in Mg-Zn-Y alloys	319
	2012 Best Application Paper	Okamoto K., Sasaki M., Takahashi N., Wang Q., Gao Y., Yin D., Chen C.	Applicability of Mg-Zn-(Y,Gd) alloys for engine pistons	325
Part 6: Wrought Processing	2009 Best Student	Ebeling T., Hartig Ch., Laser T., Nürnberg M.R., Bormann R.	Deformation mechanisms of AZ31 magnesium alloy	333
	2008 Best Student Paper	Slooff F.A., Zhou J., Duszczyk J., Katgerman L.	Constitutive behavior of wrought magnesium alloy AZ61	339
	2011 Best Fundamental Paper	Chun Y.B., Davies C.H.J.	The evolution of in-grain misorientation axes (IGMA) during deformation of wrought magnesium alloy AZ31	345
	2012 Best Student Paper	Stutz L., Bohlen J., Letzig D., Kainer K.U.	Formability of magnesium sheet ZE10 and AZ31 with respect to initial texture	357
	2009 Best Application Paper	Mishra R.K., Gupta A.K., Rao P.R., Sachdev A.K., Kumar A.M., Luo A.A.	Influence of cerium on texture and ductility of magnesium extrusions	363
	2005 Best Contributed Paper	Kurz G.	Heated hydro-mechanical deep drawing of magnesium sheet metal	389
	2013 Best Student Paper	Sagapuram D., Efe M., Moscoso W., Chandrasekar S., Trumble K.P.	Non-basal textures in magnesium alloy strips produced by extrusion-machining	395
Part 7: Modeling and Simulation	2009 Best Fundamental Paper	Janz A., Gröbner J., Schmid-Fetzer R.	The Mg-Al-Zn-Mn-Ca-Sr alloy system: Backbone of understanding phase formation in AXJ alloys and modifications of AZ and AM alloys with Ca or Sr	437
	2008 Best Fundamental Paper	Schmid-Fetzer R., Gröbner J., Mirković D., Janz A., Kozlov, A.	Constitution of magnesium alloys	451
	2011 Best Application Paper	Turski M., Grandfield J.F., Wilks T., Davis B., DeLorme R., Cho K.	Computer modeling of DC casting magnesium alloy WE43 rolling slabs	457
	2007 Best Fundamental Paper	Lévesque J., Inal K., Neale K.W., Mishra R.K., Luo A.A.	Numerical modelling of large strain deformation in magnesium	467
	2012 Best Fundamental Paper	Solanki K.N., Moitra A., Bhatia M.	Effect of substituted aluminum in magnesium tension twin	479
Part 9: Corrosion, Surface Treatment, and Coating	2003 Best Contributed Poster	Tiwari B.L., Bommarito J.J.	A novel technique to evaluate the corrosion behavior of magnesium alloys	573
	2004 Best Student Paper	Mandagie M., Brandt M., Durandet Y., Jahedi M.	Parametric study of laser cladding of AS 21 magnesium alloy with aluminium silicon/tungsten carbide powder	617

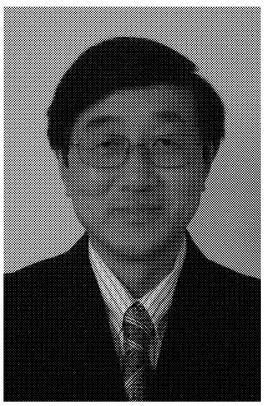
LEAD EDITOR



Suveen N. Mathaudhu

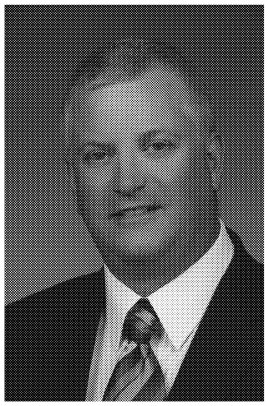
Suveen Mathaudhu serves as the Program Manager for Synthesis and Processing of Materials with the U.S. Army Research Office (ARO), Materials Science Division. He received his B.S.E. in Mechanical Engineering from Walla Walla University in 1998, and Ph.D. in Mechanical Engineering from Texas A&M University in 2006. In his current position, he manages programs that focus on the use of innovative approaches for processing high performance structural materials reliably and at lower costs. He also concurrently serves as an Adjunct Assistant Professor in the Department of Materials Science and Engineering at North Carolina State University, where his research interests include ultrafine-grained and nanostructured materials by severe plastic deformation, consolidation of metastable particulate materials and processing-microstructure-property relationships of refractory metals and lightweight metals, and thermally stable nanocrystalline materials. He has co-authored more than 60 technical publications in these areas. He is an active member of ASM, TMS, and MRS, and has served as the Chair of the TMS Magnesium Committee, and as organizer of the 2012 Magnesium Technology symposium.

EDITORIAL TEAM



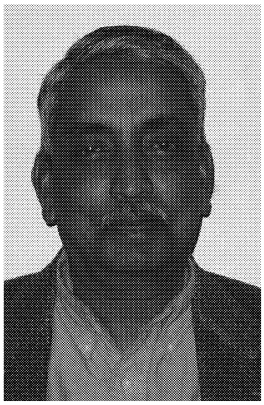
Alan A. Luo

Alan Luo is a Professor of Materials Science and Engineering and Professor of Integrated Systems Engineering (Manufacturing Group) at The Ohio State University (OSU) in Columbus, Ohio, USA. Prior to joining OSU in July 2013, Dr. Luo was a GM Technical Fellow at General Motors Global Research and Development Center (Warren, Michigan, USA) with 20 years of industrial experience. Dr. Luo won two John M. Campbell Awards for his fundamental research, and three Charles L. McCuen Awards for research applications at GM. He has 16 patents and more than 170 technical publications in advanced materials, manufacturing, and applications. Dr. Luo is an elected Fellow of ASM (American Society of Metals) International. He received the TMS (The Minerals, Metals & Materials Society) Brimacombe Medalist Award and SAE (Society for Automotive Engineers) International Forest R. McFarland Award in 2013, and USCAR (United States Council for Automotive Research) Special Recognition Award in 2009, and ASM Materials Science Research Silver Medal in 2008. Dr. Luo's research is also recognized by several Best Paper awards from TMS, SAE, and AFS (American Foundry Society). He is the Vice Chair of TMS Light Metals Division and SAE Materials Division and the Chair of SAE Non-Ferrous Metals Committee.



Eric A. Nyberg

Eric A. Nyberg is a Chief Engineer at the Pacific Northwest National Laboratory (PNNL) in Washington state. Nyberg has conducted materials processing and characterization research of lightweight metals such as aluminum, magnesium, and titanium for more than 20 years. His research in magnesium has included producing rapidly solidified and extruded magnesium alloys, developing superplastically formed sheet panels, and developing high strain rate deformation models of magnesium for automotive applications. He has been recognized as an invited speaker at multiple international conferences for his work on lightweight automotive applications. He holds three U.S. Patents, an R&D 100 Award, and a Federal Laboratory Consortium Award for titanium injection molding. Both his B.S. and M.S. degrees are in Materials Science and Engineering from Washington State University. He has been actively involved with the TMS Magnesium Committee and TMS Magnesium Technology symposium since their inception in 2000.



Neale R. Neelameggham

Neale R. Neelameggham is "Guru" at IND LLC, involved in technology marketing and consulting in the field of light metals and associated chemicals, [boron, magnesium, titanium, lithium and alkali metals], rare earth elements, battery and energy technologies, etc. He has more than 38 years of expertise in magnesium production technology from the Great Salt Lake brine in Utah. He was involved in the Process Development of its startup company, NL Magnesium, through the presently known US Magnesium LLC, and was its Technical Development Scientist from where he retired. Dr. Neelameggham's expertise includes all aspects of the magnesium process, from solar ponds through the cast house including solvent extraction, spray drying, molten salt chlorination, electrolytic cell and furnace designs, lithium ion battery chemicals and byproduct chemical processing. In addition, he has an in-depth and detailed knowledge of alloy development as well as all competing technologies of magnesium production, both electrolytic and thermal processes worldwide. Dr. Neelameggham holds 13 patents and a pending patent on boron production, and has several technical papers to his credit. As a member of TMS, AIChE, and a former member of the American Ceramics Society, he is well-versed in energy engineering, bio-fuels, rare-earth minerals and metal processing, and related processes. Dr. Neelameggham has served in the TMS Magnesium Committee since its inception in 2000, chaired it in 2005, and has been a co-organizer of the Magnesium Technology Symposium since 2004. In 2007 he was made a permanent co-organizer for the Magnesium Technology Symposium. He has been a member of the Reactive Metals Committee and Recycling Committee, and a Programming Committee representative of the TMS Light Metals Division. In 2008, the TMS Energy Committee was created following the symposium on CO_2 Reduction Metallurgy initiated by him, and he was selected as the inaugural Chair for the committee. He received the Light Metals Division Distinguished Service Award in 2010 and has been a co-editor of the Energy Technology symposium proceedings volume. Dr. Neelameggham holds a doctorate in extractive metallurgy from the University of Utah.

Wim H. Sillekens

Wim H. Sillekens is a project manager in the New Materials & Energy Unit at the research and technology center of the European Space Agency (ESA–ESTEC), where he is currently acting as the coordinator of the European Community research project ExoMet. He obtained his Ph.D. from Eindhoven University of Technology, Netherlands, on a subject relating to metal-forming technology. He has been engaged in aluminum and magnesium research, among others on (hydromechanical) forming, recycling/refining, (hydrostatic) extrusion, forging, magnesium-based biodegradable implants, and as of late on light-metal matrix nanocomposites. His professional career includes positions as a post-doc researcher at his alma mater and as a research scientist / project leader at the Netherlands Organization for Applied Scientific Research (TNO). International working experience covers a placement as a research fellow at MEL (now AIST) in Tsukuba, Japan, and – more recently – shorter stays as a visiting scientist at GKSS (now HZG) in Geesthacht, Germany, and at PNNL in Richland, Washington, USA. He has authored or coauthored book chapters, journal papers, patents, conference papers, oral presentations (keynote/ invited/contributed), and so on (about 135 entries to date). Other professional activities include an involvement in association activities (among others, as the lead organizer of the TMS Magnesium Technology Symposium in 2011), international conference committees, and as a peer reviewer of manuscripts for scientific journals and conference proceedings as well as of research proposals. Research interests are in physical and mechanical metallurgy in general and in light-metals technology in particular.