REWAS 2019

Manufacturing the Circular Materials Economy

EDITED BY

Gabrielle Gaustad
Camille Fleuriault
Mertol Gökelma
John A. Howarter
Randolph Kirchain
Kaka Ma
Christina Meskers
Neale R. Neelameggham
Elsa Olivetti
Adam C. Powell
Fiseha Tesfaye
Dirk Verhulst
Mingming Zhang

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The Minerals, Metals & Materials Series

Gabrielle Gaustad · Camille Fleuriault ·
Mertol Gökelma · John A. Howarter ·
Randolph Kirchain · Kaka Ma ·
Christina Meskers · Neale R. Neelameggham ·
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Fiseha Tesfaye · Dirk Verhulst ·
Mingming Zhang
Editors

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Editors
Gabrielle Gaustad
Alfred University
Alfred, NY, USA

Camille Fleuriault
Gopher Resource
Eagan, MN, USA

Mertol Gökelma
Norwegian University of Science
and Technology
Trondheim, Norway

John A. Howarter
Purdue University
West Lafayette, IN, USA

Randolph Kirchain
Massachusetts Institute of Technology
Cambridge, MA, USA

Kaka Ma
Colorado State University
Fort Collins, CO, USA

Christina Meskers
Umicore
Olen, Belgium

Neale R. Neelameggham
IND LLC
South Jordan, UT, USA

Elsa Olivetti
Massachusetts Institute of Technology
Cambridge, MA, USA

Adam C. Powell
Worcester Polytechnic Institute
Worcester, MA, USA

Fiseha Tesfaye
Åbo Akademi University
Turku, Finland

Dirk Verhulst
Reno, NV, USA

Mingming Zhang
ArcelorMittal Global R&D
Schererville, IN, USA

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Preface

More than ten years ago, in October 2008, I participated in my first REWAS event, giving two presentations on my doctoral dissertation work examining aluminum recycling. At that time REWAS was called the Global Symposium on Recycling, Waste Treatment, and Clean Technology and the conference was in Cancun, Mexico. Much has changed in the decade since that conference but one thing remains the same: the looming sustainability challenges the world faces. Resource consumption continues to rise driving increased waste, impacts of climate change are growing, and energy use is increasing exponentially as the world continues to develop. Fortunately, the minerals, metals, and materials science community has embraced these challenges as opportunities to drive ground-breaking work in these fields. These engineers, scientists, educators, and entrepreneurs are contributing to significant gains in our shared goal of a sustainable materials industry.

The focus of this year's REWAS conference is on *Manufacturing the Circular Materials Economy*. Our current linear economy involves a one-way street where materials are extracted, manufactured, used, and then thrown away. The idea behind a circular economy is to de-couple development and growth from resource consumption which have been historically correlated. Unlocking the potential for circularity in the materials life-cycle can actually enable economic opportunities. All this will require ingenuity in the materials science and manufacturing sectors as well as require trans-disciplinary work with the sustainability and industrial ecology communities. We are highlighting this work in REWAS 2019 in five main thematic sessions.

Disruptive Material Manufacturing: A Systems Perspective

The landscape of materials manufacturing has the potential for dramatic change as new design techniques (e.g., materials genome) and new technologies (e.g., additive manufacturing) begin to scale to industrial production levels. What is the environmental impact of additive manufacturing? How will disruptive technologies change the landscape of producing materials? What is the circularity potential for inputs and outputs of these new production routes? How can these systems be optimized? How does the massive scale-up of clean energy technologies affect process flow sheets and recycling? Many of these questions are being addressed by the proceedings from this session which is a partnership with the Additive Manufacturing Committee.

Secondary and Byproduct Sources of Materials and Minerals

As scarcity and criticality concerns grow, attention has turned to ore alternative sources of important materials, metals, and minerals. Circular economy techniques, industrial symbiosis, and urban mining are sustainability strategies for obtaining these materials from industrial byproducts, end-of-life wastes, and other secondary sources. This includes recycling of electronic waste, batteries of all chemistries, and agricultural byproducts. What extraction technologies will be needed to enable this material recovery? What are the economic and environmental impact implications of such alternative routes? What kinds of material flow analysis and/or metric standardization is needed for tracking circularity at multiple scales? As many of these issues are tackled via pyrometallurgy and hydrometallurgy, these TMS committees were supporting partners in this session.

Rethinking Production

Besides disruptive technologies, there are additional sustainability benefits with high potential in the production sector. In partnership with the Materials Characterization Committee, this session asks, How do we decrease emissions in production? How can we achieve sustainable process design? How will clean energy technologies be manufactured? How do we measure and quantify embodied energy (how do existing methods fall short and how do we align internationally)? How can we enable cost-effective and efficient collection and reprocessing of wastes? What are technologies and strategies for managing mixed materials? How can trace, tramp, and other unwanted contaminants be removed from secondary streams? What are opportunities for direct use of end-of-life products to make new products with minimal or no reprocessing? How do we reach zero-waste production?

Education and Workforce Development

Transitioning knowledge from the research and academic sectors into applied work is critical to realizing sustainability. Papers from this session address novel educational approaches like blended learning, flipped classrooms, and MOOCs, as well as approaches for integrating sustainability into traditional disciplinary curriculums like materials science. Technology transition, applied learning, and workforce development initiatives also will be highlighted. This session was in partnership with the TMS Education Committee and the Professional Development Committee.

In partnership with the Light Metals Division, REWAS 2019 also is showcasing work in the Cast Shop Technology symposium. Proceedings manuscripts from this joint session are featured in the *Light Metals 2019* publication, with abstracts appearing here on the next page. This session focuses on some of the unique challenges the aluminum industry faces in its transition to sustainability. Sustainable operations, life-cycle assessment, recycling impacts and awareness, charge materials, and other environmental issues relevant to cast shops are the focus of this session.

Looking back at the innovations since REWAS 2008 leaves me excited and hopeful for the next decade. Many thanks to the excellent team of organizers, committee chairs, reviewers, and session chairs who made this proceedings publication possible and most importantly, the researchers, authors, and presenters participating in REWAS 2019.

Gabrielle Gaustad
Lead Organizer

REWAS 2019: Cast Shop Recycling Technologies Abstracts

A Method for Assessment of Recyclability of Aluminum from Incinerated Household Waste
Mertol Gökelma, Ingrid Meling, Ece Soylu, Anne Kvithyld, Gabriella Tranell

Aluminum is widely used in daily household consumable goods such as food and drink packaging materials, storage containers, etc. The disposal of such goods into household waste means that this waste stream contains a significant amount of aluminum. Domestic waste is commonly sent to incinerator plants where the organics are combusted while the metallic content stays in the bottom ash, which is subsequently separated into various metal streams. Because of the importance of aluminum in the circular economy, there is a need for efficient recovery procedures for this metal source. This paper discusses the recyclability and the recovery rate of aluminum from the bottom ash through remelting with a molten salt. The remelting experiments were performed under a 50–50 wt% NaCl:KCl mixture with a 2 wt% CaF_2 addition to promote metal coalescence. The oxide thickness and trace element content of the starting metal and the composition of the resulting metal were characterized as these parameters largely determine the recovery rate and recyclability of these secondary metal streams. The laboratory results showed the coalescence efficiency up to 99.5% and the material yield up to 92%. High deviation in oxide content based on the oxide layer thickness measurements was observed which crucially affects the metal losses in recycling.

Aluminum Alloys in Autobodies: Sources and Sinks
Ayomipo Arowosola, Gabrielle Gaustad, Leslie Brooks

Emissions from the transportation industry combined with increasing consumption of materials have inspired the automotive industry to use lightweight materials in autobodies. A wide diversity of materials is being used, for example, aluminum, magnesium, and plastic composites. This lightweighting approach is a proven sustainability strategy improving fuel economy and thereby reducing greenhouse gas emissions. However, increasing the number of differing types of materials in cars is actually complicating recycling operations. Critical metals used as alloying additions are dissipatively lost in the recycling process and can also negatively impact recycling rates by accumulating as tramp elements. This work combines compositional characterization of automotive materials, material flow analysis, and techno-economic assessment to better understand this problem and inform solutions. Results show that both technical solutions like sensor-based sorting and operational solutions like compositionally based blending can decrease material losses, thereby reducing the negative impacts and inching closer to a circular economy.

Isothermal Hot Pressing of Skimmed Aluminium Dross: Influence of the Main Processing Parameters on In-house Molten-Metal Recovery
Varužan Kevorkijan

The Isothermal Hot Pressing (IHP) of skimmed aluminum dross, considered in this study, was performed under laboratory conditions using a cylindrical pressing model made from high-temperature stainless steel. The pressing model was inserted into an electrical furnace with a protective argon atmosphere. The temperature of the pressing was within the interval 650–900 °C, while the applied pressure varied between 5 and 50 bars. The laboratory results showed that when using IHP it is possible to reduce the remaining aluminum content in “pressed dross skulls” below 10%.

LIBS Based Sorting—A Solution for Automotive Scrap
Georg Rombach, Nils Bauerschlag

The demand for automotive sheet shows the highest growth rates in the aluminum industry. Currently, the main alloys are from 5.xxx and 6.xxx series with a variety of approx. 40 different specifications. Such a mixed scrap quality cannot be used in an efficient way in cast houses, due to the divergent Mg and Si concentrations. Additionally, the ratios between 5.xxx and 6.xxx scrap are unpredictable. Today, the only technical possibility to distinguish between these alloys is sensor-based sorting using LIBS. Such a sorting machine has to produce two sorting fractions, which both fulfill the requirements of the new wrought alloys. In this case a high sorting efficiency is mandatory. First results show a purity of the sorted fraction above 95% as well as a high recovery of the sorted material also above 90%.

Manufacturing of Hydrogen on Demand Using Aluminum Can Scrap with Near Zero Waste
Jed Checketts, Neale R. Neelameggham

During the 1990s Powerball Industries, UT had demonstrated producing Hydrogen on demand machinery—where encapsulated sodium metal is reacted with water to release hydrogen gas under pressure. The hydrogen on demand has several applications. Here we discuss the ongoing research of making use of aluminum (recycled or newly produced) with anhydrous sodium sulfate—which will make sodium metal, sulfur oxides, and aluminum oxide. The thermodynamic analysis shows suitable physicochemical conditions for the reactions. Preliminary economics using aluminum scrap—recycled aluminum is shown.

Positive Material Identification (PMI) Capabilities in the Metals Secondary Industry: An Analysis of XRF and LIBS Handheld Analyzers
Leslie Brooks, Gabrielle Gaustad

Recycling is a critical part of obtaining a more circular economy. In the metals secondary industry, traditional equipment (a magnet, file, and/or grinding wheel) used to identify and sort materials at their end of life can aid in grouping metals (i.e., Al+Mg alloys, ferrous, high-temperature alloys, etc.), but they are incapable of identifying the alloy's elemental composition; a necessity for preventing downcycling and maximizing secondary utilization rates. Handheld analyzers that utilize X-ray fluorescence (XRF) and spectroscopy (LIBS) technology may offer technological assistance that is helpful for achieving this level of analysis, often referred to as Positive Material Identification (PMI). This work tests the performance of these units under the challenging conditions present in yards (contaminated, unpolished, rugged scraps). These instruments, with their increasing safety settings, ruggedness, ease of point-click use, and quick read times (for both XRF and LIBS) have significant potential, especially with ability to ID metal faster than cognitive recognition. Additionally, as unit costs of these instruments continue to decrease and the range of varying types of metal entering yards continues to widen, the return on investment becomes more immediate. However, extreme fluctuations of reported elemental compositions are being seen even when measurements have been taken in the same place consecutively; indicating that in their current state, they can inform content of material but are not necessarily reliable for reporting accurate and precise compositional percentages.

The Vertical Floatation Decoater for Efficient, High Metal Yield Decoating and Delacquering of Aluminum Scrap
Robert De Saro, Sam Luke

The Vertical Floatation Melter (VFD) has undergone pilot testing in removing organics from scrap aluminum. The VFD uses a vertical cone in which the scrap is dropped into the top and products of combustion at 1000 °F are introduced into the bottom, flowing countercurrent to the scrap. The gases float the scrap in the cone resulting in very high convective heat transfer which leads to rapid decoating with minimal metal loss.

Turnings, fines, Twitch, and UBC have been processed through a single unit. Decoating times are about one minute. Measured energy use varies from 78 to 854 Btu/lbm; measured preheat temperatures are 850 °F.

Decoat efficiency appears good with visually no oxidation present and no evidence of organics. Samples have been sent to a lab to confirm this.

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About the Editors

Gabrielle Gaustad recently became the Dean of the Inamori School of Engineering at Alfred University. For the prior ten years she was an Associate Professor in the Golisano Institute for Sustainability at the Rochester Institute of Technology. She holds a Ph.D. in Material Science and Engineering from MIT. The Gaustad group conducts research quantifying the economic and environmental trade-offs for materials at their end of life with a focus on recycling, resource recovery, and promoting a circular economy. Methodologies include a variety of systems modeling techniques such as dynamic material flow analysis, optimization, simulation, systems dynamics, economic modeling, process-based cost modeling, and life-cycle assessment, as well as traditional material characterization such as TGA, PSD, SEM, XRD, XRF, EDS, and ICP-MS. Specific projects include implications of material scarcity and criticality for clean energy technologies, aluminum and steel recycling technologies and compositional analysis, and environmentally benign and economically efficient recycling of lithium ion batteries, particularly those containing nanomaterials.

Camille Fleuriault is R&D Metallurgist at Gopher Resource in Eagan, Minnesota, USA. She is developing innovative and environmentally friendly recycling processes for the secondary metals industry. In particular, she is focusing on waste management and energy efficiency of high-temperature systems. She holds a B.S. in geological engineering and an M.Eng. in Mineral Engineering from the National School of Geological Engineering in Nancy, France, and a M.Sc. in Metallurgical Engineering from Colorado School of Mines, USA. She is *JOM* advisor for the TMS Pyrometallurgy Committee.

Mertol Gökelma is a postdoctoral researcher in the Department of Materials Science and Engineering at Norwegian University of Science and Technology (NTNU), Trondheim, Norway. He finished his B.Sc. degree at Dokuz Eylul University in Metallurgical Engineering and Materials Science, Turkey, and his M.Sc. and Ph.D. in Metallurgical Engineering at RWTH Aachen University, Germany. He worked as a research assistant for four years at the Institute of Process Technology and Metal Recycling (IME), RWTH. His research interests focus on process metallurgy of nonferrous metals and he has been involved in different R&D projects focused on recycling of magnesium black dross, recycling and refining of precious metals, powder synthesis of titanium alloys, and metallothermic reduction of oxides. The main focus of his research is recycling and refining of aluminum as well as the behavior of nonmetallic inclusions in Al-melts.

John A. Howarter is an Associate Professor in Materials Engineering at Purdue University with a joint appointment in Environmental and Ecological Engineering. His research interests are centered on synthesis, processing, and characterization of sustainable polymers and nanocomposites, value recovery through recycling and reprocessing of waste materials, and sustainable materials that can enable improved design for the environment.

John is the Chair of the TMS Public and Governmental Affairs committee and serves on the TMS Board of Directors. Since 2014 he has served as the chapter advisor for the Purdue University Material Advantage student organization. John earned a B.S. from The Ohio State University in 2003 and Ph.D. from Purdue

University in 2008, both in Materials Engineering. From 2009 to 2011 he was a National Research Council postdoctoral scholar in the Polymers Division of the National Institute of Standards and Technology in Gaithersburg, Maryland.

Randolph Kirchain's research and teaching aim to improve materials-technology decisions by characterizing the economic and environmental impact of those decisions. That impact may derive from changes in the performance of the products into which those materials are transformed and/or in the systems in which they are produced, used, and eventually discarded. Dr. Kirchain has authored over 200 publications in refereed journals and conferences. He has been awarded the American Iron and Steel Institute's Top Technical Achievement Award, the General Motors Technical Achievement Award, and the TMS Recycling Technology Award. Currently, Dr. Kirchain serves as the co-director of the MIT Concrete Sustainability Hub.

Kaka Ma received her B.S. in Materials Physics from University of Science and Technology of China in 2006 and earned her Ph.D. in Materials Science and Engineering from the University of California (UC), Davis in December 2010. She joined Colorado State University as a tenure-track assistant professor in August 2016 after several years of postdoctoral research at UC Davis and UC Irvine.

Dr. Ma's research interests sit at the interface of materials science, mechanical engineering, and sustainability. She is interested in fabrication and characterization of advanced materials that contain nanoscale microstructural features for high performance such as high specific strength, high ductility, improved reliability and lifetime. Her research also performs mechanical testing at small scales and in localized regions such as boundaries and interface using nanoindentation and nanoscratch techniques. She aims to discover new processing-structure-properties correlation and to manufacture advanced materials for next-generation structural, electronic, and energy components. Her previous research investigated nanostructured or ultrafine grained materials ranging from thermal barrier coatings, aluminum alloys to metal matrix composites. Her recent research activities focus on multiscale hierarchical structured materials, functionally graded materials, low-work-function electride materials, additive manufacturing (AM) and sustainability issues associated with metal AM. Dr. Ma serves on the editorial board for the journal *Materials Science and Engineering A* and is a reviewer for several other journals, including *Nature Communications*, *Metallurgical and Materials Transactions A*, *Journal of Materials Science*, *Surface and Coatings Technology*, and *Journal of Alloys and Compounds*.

Christina Meskers is senior manager Open Innovation at Umicore's Group Research and Development where she is responsible for the development, management, and governance of the global portfolio of bilateral and multilateral research partnerships and (education) programs as well as the University—RTO—industry partner network. Furthermore she develops and implements the open innovation strategy. Christina serves on the Industrial Advisory Boards of among others the Sustainable Materials (SuMa) and Sustainable and Innovative Resource Management (SINReM) international M.Sc. programs and within EIT Raw Materials innovation community serves as member of the Education Committee and is vice-chair of Innovation Hub West steering committee.

With over 15 years' experience in the raw materials sector, her current focus is on the contribution of recycling and extractive technologies to the transition to sustainable cities and e-mobility. Christina co-authored the United Nations' International Resource Panel report "Metal Recycling—Opportunities, Limits, Infrastructure" (2012), among other publications. In 2008 she was a recipient of the Young Leaders Professional Development Award of The Minerals, Metals & Materials Society (TMS) Extraction and Processing Division. She was lead organizer of Sustainable Materials Production and Recycling 2010, REWAS 2013, and REWAS 2016 and connected these symposia to current societal and industrial trends. After volunteer roles in the TMS Recycling Committee, Materials and Society Committee, and Public and Governmental Affairs Committee she currently serves as Vice-chair of the Extraction and Processing Division.

Neale R. Neelameggham is “The Guru” at IND LLC, involved in international technology and management consulting in the field of critical metals and associated chemicals, thiometallurgy, energy technologies, soil biochemical reactor design, lithium ion battery design, and agricultural uses of coal. He was a visiting expert at Beihang University of Aeronautics and Astronautics, Beijing, China and a plenary speaker at the Light Metal Symposium in South Africa on the topic of low carbon dioxide emission processes for magnesium.

Dr. Neelameggham has more than 38 years of expertise in magnesium production and was involved in process development of the startup company NL Magnesium through to the present US Magnesium LLC, UT until 2011. He and Brian Davis authored the ICE-JNME award-winning (2016) article “21st Century Global Anthropogenic Warming Convective Model.” He is presently developing “stored renewable energy in coal” Agricoal™ for greening arid soils and has authored an e-book *Eco-stoichiometry of Anthropogenic CO2 That Returns to Earth* on a new discovery of quantification of increasing CO2 returns to Earth.

Dr. Neelameggham holds 16 patents and patent applications, and has published several technical papers. He has served in the Magnesium Committee of the TMS Light Metals Division (LMD) since its inception in 2000, chaired it in 2005, and in 2007 he was made a permanent co-organizer for the Magnesium Technology Symposium. He has been a member of the Reactive Metals Committee, Recycling Committee, and Titanium Committee, and was a Program Committee Representative for LMD.

Dr. Neelameggham was the inaugural chair, when in 2008, LMD and the Extraction and Processing Division created the Energy Committee, and he has been a coeditor of the Energy Technology symposium through the present. He received the LMD Distinguished Service Award in 2010. While he was the chair of Hydrometallurgy and Electrometallurgy Committee he initiated the Rare Metal Technology symposium in 2014. He is coeditor for the 2019 symposia on Magnesium Technology, Energy Technology, Rare Metal Technology, REWAS 2019, and Solar Cell Silicon.

Elsa Olivetti is the Atlantic Richfield Associate Professor of Energy Studies in the Department of Materials Science and Engineering at the Massachusetts Institute of Technology (MIT). Her research focuses on improving the environmental and economic sustainability of materials using methods informed by materials economics, machine learning, and techno-economic analysis. She has received the NSF Career award for her experimental research focused on beneficial use of industrial waste materials. Dr. Olivetti received her B.S. degree in Engineering Science from the University of Virginia. Her Ph.D. in Materials Science and Engineering from MIT was focused on development of cathode materials for lithium ion batteries.

Adam C. Powell joined the faculty at Worcester Polytechnic Institute (WPI) in August 2018 as an Associate Professor in the Mechanical Engineering Department. His field is materials processing, and his research focuses on validated mathematical modeling of metal process development for clean energy and energy efficiency. His research group is developing new projects whose goals are to reduce vehicle body weight, lower solar cell manufacturing cost with improved safety, reduce or eliminate environmental impact of aerospace emissions, and improve grid stability with up to 100% renewables.

Dr. Powell's research has resulted in 67 publications across materials classes: metal extraction/refining and product development, thin films, ceramic coatings, polymer membranes, batteries, and electromagnetic propulsion. He is the author of nine open source computational tools in materials processing, microstructure and thermodynamics modeling.

Dr. Powell is fluent in Japanese, and as a University of Tokyo Foreign Collaborative Researcher, gives technical talks in Japanese to industry, government, and academic audiences.

Fiseha Tesfaye is a Senior Researcher and project manager working in the Johan Gadolin Process Chemistry Centre (PCC) of Åbo Akademi University, Finland. He received his Master's degree in materials processing technology in 2009 from Helsinki University of Technology and Ph.D. degree in metallurgy in 2014 from Aalto University, Finland. During his Ph.D. period, he focused his research on the electrochemical investigation of the thermodynamic properties of sulfide and intermetallic materials.

After a postdoctoral position in the Laboratory of Inorganic Chemistry at Åbo Akademi University from 2015 to 2017, which focused on the sulfosalts and sulfates characterizations, he attracted a large research project related to thermodynamic investigation of complex inorganic material systems in the renewable energy and metals production processes. From September 2017 onward, his research activities have been focused mainly on the sulfate-oxide systems database development with the FactSage software package, as well as rigorous theoretical and experimental investigations for promoting improved recovery of values from waste streams. Dr. Tesfaye was also appointed as a Visiting Research Scientist at Seoul National University, South Korea, for 6 months between March and August 2018. Dr. Tesfaye's current research interests are also within the scope of materials science, recycling technology, circular economy, and metallurgical engineering.

Dr. Tesfaye is a regular contributor and member of TMS, and is the 2018 TMS Young Leaders Professional Development Award winner. He has served on TMS committees including Recycling and Environmental Technologies, Energy, and Young Professionals, and was a member of the scientific committee of Materials San Diego 2018. His personal achievements include significant improvement of experimental research applying the solid-state EMF technique for thermodynamic studies, as well as contribution of new experimental thermodynamic data of several chalcogenide materials. Dr. Tesfaye has published more than 35 peer-reviewed articles in his research areas.

Dirk Verhulst spent the last 40 years in practical process metallurgy research on both sides of the Atlantic, bringing a number of projects from the laboratory to the pilot scale, and a few to industrial implementation. He is presently an independent consultant in process metallurgy and energy efficiency. Until the end of 2008, he was Director of Research at Altairnano in Reno, Nevada. He participated in the development of the Altair Lithium–ion Battery and was involved in the design and procurement of the manufacturing plant for the ceramic materials. Over the period 2003–2008, he worked extensively on the Altair Hydrochloride TiO_2 Pigment Process and the operation of its pilot plant. The complex flow sheet included both hydrometallurgical and pyrometallurgical steps. Optimization of energy use was a key factor to make this new approach competitive. From 1995 to 2000, he was Senior Development Engineer in BHP's Center for Minerals Technology at the same location in Reno. It is at BHP that the development of the hydrochloride TiO2 pigment process was initiated. Other BHP projects included novel processes for nickel, cobalt, zinc, and copper. Prior to 1995, he worked for 17 years in the research department of Umicore in Hoboken, Belgium. He was active in lead refining and in the hydrometallurgy of minor metals (indium, tellurium, selenium), but was mostly involved in the introduction of electric furnaces in lead smelting and slag cleaning. He tackled mathematical models and lab-scale experiments, ran pilot plants, and participated in the start-up of industrial operations. He has a doctor of engineering science degree in extractive metallurgy from Columbia University, and a chemical engineering degree from the Free University of Brussels. He has written and presented publications in the areas of hydrometallurgy, pyrometallurgy, nanomaterials, and environmental science. He holds several patents and patent applications.

Mingming Zhang is a lead research engineer at ArcelorMittal Global R&D at East Chicago, Indiana. Dr. Zhang has over 15 years of research experience in the field of mineral processing, metallurgical, and materials engineering. He obtained his Ph.D. degree in Metallurgical Engineering from The University of Alabama and his master's degree in Mineral Processing from the General Research Institute for Non-ferrous Metals in China. Prior to joining ArcelorMittal, he worked with Nucor Steel in Tuscaloosa, Alabama where he was a metallurgical engineer leading the development of models for simulating slab solidification and secondary cooling process. Dr. Zhang has conducted a number of research projects involving mineral beneficiation, thermodynamics and kinetics of metallurgical reactions, electrochemical processing of light metals, metal recycling, and energy-efficient and environmentally cleaner technologies. He has published over 50 peer-reviewed research papers and he is the recipient of several U.S. patents. Dr. Zhang also serves as editor and reviewer for a number of prestigious journals including *Metallurgical and Materials Transactions A and B*, *JOM*, *Journal of Phase Equilibria and Diffusion*, and *Mineral Processing and Extractive Metallurgy Review*. Dr. Zhang has made more than 20 research presentations at national and international conferences including more than 10 keynote presentations. He was the recipient of 2015 TMS Young Leaders Professional Development Award. He has served as conference/symposium organizer and technical committee chair in several international professional organizations including The Minerals, Metals & Materials Society (TMS), the Association for Iron & Steel Technology (AIST), and the Society for Mining, Metallurgy & Exploration (SME).

Part I
REWAS 2019: Disruptive Material Manufacturing—Scaling and Systems Challenges

From Recycled Machining Waste to Useful Powders for Metal Additive Manufacturing

Blake Fullenwider, Parnian Kiani, Julie M. Schoenung and Kaka Ma

Abstract To fulfill the growing demand for alternative and sustainable feedstock production for metal additive manufacturing, a novel dual-stage ball milling strategy was proposed to effectively convert recycled stainless-steel machining chips to powder with desirable characteristics for metal additive manufacturing. A theoretical analysis was performed to evaluate the impact of ball size on the chips-to-powder evolution and the consequent powder morphology. To verify the viability of using the ball milled powder created from machining chips in metal additive manufacturing, single tracks have been successfully deposited via laser engineered net shaping deposition and compared to the single tracks made from gas atomized powder using identical deposition conditions. The microstructures of these single tracks exhibited adequate adhesion to the substrate, a uniform melt pool geometry, continuity, and minimal splatter. Minimal differences in grain structure were observed between the single tracks made from ball milled powder and those made from gas atomized powder.

Keywords Metal additive · Manufacturing · Stainless steel · Sustainability · Ball milling

Powder metallurgy processing techniques, such as additive manufacturing, thermal spray, spark plasma sintering, and hot isostatic pressing, are widely used to fabricate bulk samples from metal powders. Metal additive manufacturing, one of the advanced powder metallurgy techniques, has attracted extensive research interest in recent decades, because of its capability to create near-net-shape parts in one step [1]. Additive manufacturing (AM) is regarded as a more sustainable process compared to conventional processing such as casting, as it significantly reduces the need of subtractive machining processes and thereby results in less material waste and less use of hazardous cutting fluids [2–4]. The properties of the bulk components

B. Fullenwider · K. Ma (✉)
Department of Mechanical Engineering, Colorado State University, Fort Collins, CO 80523, USA
e-mail: Kaka.Ma@colostate.edu

P. Kiani · J. M. Schoenung
Department of Chemical Engineering and Materials Science, University of California, Irvine, CA 92697, USA

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created through AM processes depend on both the processing method and the feedstock powder properties [5]. Despite the progresses in processing optimization and product property improvement that have been achieved, metal AM still faces several challenges due to low feedstock utilization efficiency and the availability of ideal feedstock powders [3]. Gas atomized (GA) powders are the most common feedstock for current metal additive manufacturing techniques because of their spherical morphology and controllable particle size distribution [1]. However, one environmental challenge of using GA powder in metal AM is the high energy consumption required to produce the powder through atomization, leading to high costs and limited availability in alloy compositions [6, 7]. To fulfill the growing demand for alternative and sustainable feedstock production for metal additive manufacturing, the present work aimed to explore a mechanical milling strategy to fabricate powders from recycled machining waste chips. In addition, the feasibility of using the powders created from machining chips in metal AM was proved by successful deposition of single tracks and multiple layers via laser engineered net shaping (LENS®).

304L stainless steel was selected as the model material due to its wide use in AM for various structural materials [8]. The desirable characteristics of feedstock powder for AM include a near-spherical morphology and particle sizes of 38–150 μm. The machining chips used in the current study were provided by AK steel (West Chester Township, Butler County, Ohio, OH). The individual chips exhibit a length of 5–20 mm, as shown in Fig. 1a. The surface of the chips contains serrations (Fig. 1c) due to the previous machining operation. To effectively convert the machining chips with dimension of several millimeters to powders with particle size on the micron scale, both modeling and experimental work were conducted. A theoretical analysis combining Gusev's model [9] and Hertz's model [9, 10] was performed to evaluate the impact force and stress on the particle, as well as the resultant maximum deformation depth into the particle. Two different types of balls are used as the milling media: Φ-20 balls (ball diameter = 20 mm) and Φ-6 balls (ball diameter = 6 mm). Experimentally, various ball milling procedures were implemented to investigate the effect of ball diameter on the powder morphology evolution and particle size refinement. A novel strategy of changing ball diameters during the ball milling was applied.

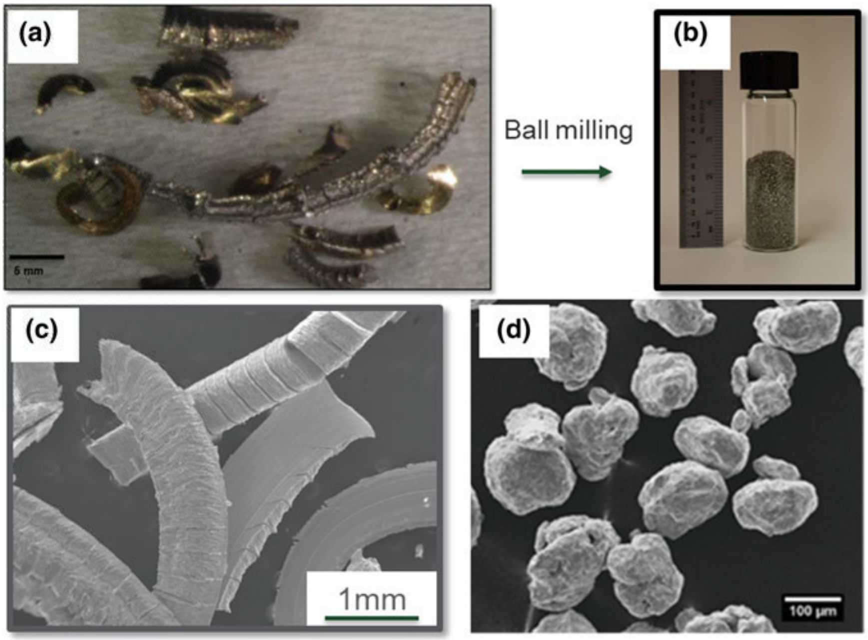

Fig. 1 **a** Optical image of the machining chips; **b** picture of the powders created by ball milling of machining chips; **c** SEM image of the machining chips; **d** SEM image of the powders created by ball milling of the machining chips

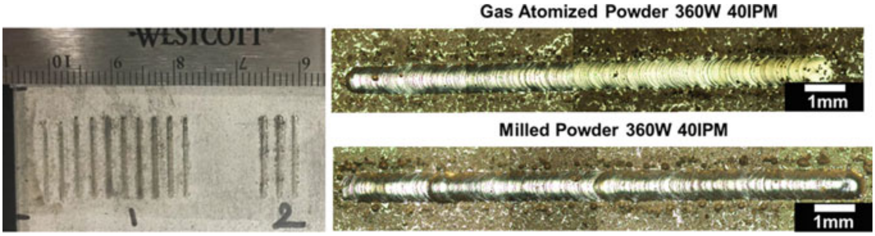

Fig. 2 Picture of the single tracks that were deposited using the ball milled powder created from the recycled machining chips and the representative optical image of ST-BM and ST-GA

The modeling results show that Φ-20 balls effectively reduce the powder particle size while Φ-6 balls effectively change the powder morphology to spherical or near-spherical. Based on the findings from the modeling, a novel dual-stage ball milling strategy was proposed to convert the machining chips to powders. Figure 1a, b exhibits the success of generating powders from the recycled machining waste. The powders created from the machining chips via dual-stage ball milling exhibit near-spherical morphology with particle sizes of 38–150 μm (Fig. 1d), which is suitable for metal additive manufacturing. The ball milled powders created from the machining chips also exhibit a higher hardness than GA powder, based on nanoindentation testing.

In addition, single tracks (ST) have been successfully deposited via LENS® using the ball milled powder created from the recycled machining chips. Single tracks were also made from GA powder (ST-GA) using identical deposition conditions. Figure 2 shows the single tracks that were deposited on the same substrate and the representative optical image of the single tracks made from ball milled powder (ST-BM) and ST-GA. The microstructures of these single tracks exhibited adequate adhesion to the substrate, a uniform melt pool geometry, continuity, and minimal splatter. Minimal differences in grain structure were observed between ST-BM and ST-GA. However, the average nanoindentation hardness of ST-BM is approximately 21% higher than that of ST-GA. The present research has discovered a sustainable approach to fabricate powders from recycled machining chips and has proved it is feasible to utilize these powders as feedstock in metal additive manufacturing.

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