FINAL PROGRAM

Mg 2021

12th International Conference on

Magnesium Alloys and their Applications

JUNE 15–18, 2021 | VIRTUAL EVENT





Sponsored by: TMS

This conference is sponsored by the Light Metals Division and the Magnesium Committee.

www.tms.org/Mg2021

SCHEDULE

Monday, June 7, 2021		
Contributed presentations available to view in the Mg2021 virtual platform		On-demand
Tuesday, June 15, 2021		
8:00 AM - 9:30 AM EDT	Plenary Presentations with Webinar-style Q&A	Live
9:30 AM - 9:50 AM EDT	Break	
9:50 AM - 10:50 AM EDT	Breakouts: Invited Presentations with Webinar-style Q&A	Live
10:50 AM - 11:50 AM EDT	Breakouts: Video Discussions for Contributed Presentations	Live
12:00 PM - 1:00 PM EDT	Informal Networking: Forming and Thermo-mechanical Processing*	Live
Wednesday, June 16, 2021		
7:00 AM - 8:00 AM EDT	Informal Networking: Advanced Characterization and Fundamental Theories; Solidification and Casting Processes*	Live
8:00 AM - 9:30 AM EDT	Plenary Presentations with Webinar-style Q&A	Live
9:30 AM - 9:50 AM EDT	Break	
9:50 AM - 10:50 AM EDT	Breakouts: Invited Presentations with Webinar-style Q&A	Live
10:50 AM - 11:50 AM EDT	Breakouts: Video Discussions for Contributed Presentations	Live
12:00 PM - 1:00 PM EDT	Informal Networking: Primary Production; Other Manufacturing Process Development*	Live
Thursday, June 17, 2021		
7:00 AM - 8:00 AM EDT	Informal Networking: Modeling and Simulation I; Alloy Development*	Live
8:00 AM - 9:30 AM EDT	Plenary Presentations with Webinar-style Q&A	Live
9:30 AM - 9:50 AM EDT	Break	
9:50 AM - 10:50 AM EDT	Breakouts: Invited Presentations with Webinar-style Q&A	Live
10:50 AM - 11:50 AM EDT	Breakouts: Video Discussions for Contributed Presentations	Live
12:00 PM - 1:00 PM EDT	Informal Networking: Recycling and Environmental Issues; Modeling and Simulation II*	Live
Friday, June 18, 2021		
7:00 AM - 8:00 AM EDT	Informal Networking: Corrosion and Protection; Structural, Functional, Biomedical, and Energy Applications*	Live
8:00 AM - 9:30 AM EDT	Plenary Presentations with Webinar-style Q&A	Live
9:30 AM - 9:50 AM EDT	Closing and Award Ceremony	Live
9:50 AM - 10:50 AM EDT	Breakouts: Invited Presentations with Webinar-style Q&A	Live
10:50 AM - 11:50 AM EDT	Breakouts: Video Discussions for Contributed Presentations	Live
Wednesday, June 30, 2021		
Mg2021 virtual platform closes		On-demand

*Informal networking sessions will have limited capacity

The schedule is in Eastern Daylight Time (UTC-4:00).
Use the Time Zone Converter to translate event times into your local time zone.

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FINAL PROGRAM

Bienvenue!

The 12th International Conference on Magnesium Alloys and their Applications (Mg 2021) is an impressive showcase of work, carefully curated for the global magnesium community. Originally planned to be held in Montreal, the meeting pivoted to a virtual format to ensure participation from our scientists, engineers, and researchers who are facing a variety of challenges stemming from the COVID-19 pandemic. With a robust technical program and speakers who are leaders in their field around the world, Mg 2021 offers valuable opportunities to learn and network. Whether you have work to present, insight to share, or questions to ask, your participation is greatly appreciated.

Tips for Participating in the Virtual Event

1) **Remove Distractions.** Notify others that you are at a conference. Set your out-of-office message in your e-mail client. Actively listen and take notes during the presentations, as if you were attending in person.
2) **Attend in Real Time.** Whenever possible, listen to presentations at their scheduled time so that you are able to ask questions and engage in discussions.
3) **Relax, and Enjoy!** If you miss something, don't worry. After all, One of the benefits of a virtual event is the ability to access recordings of the presentations. You have access to the recordings and the proceedings through the end of June 2021.

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- **Ravi Verma**, Boeing, USA
- **Jonathan Weiler**, Meridian Lightweight Technologies, Canada
- **Michael Worswick**, University of Waterloo, Canada
- **Peidong Wu**, McMaster University, Canada
- **Bong Sun You**, Korean institute of Materials Science, Korea
- **Mikhail Zheludkevich**, Helmholtz-Zentrum Geesthacht, Germany
- **Zisheng Zhen**, Magontec Asia, China
- **Fan Zhongyun**, Brunel University, UK

Plenary and Invited Speaker Presentations

Plenary and invited speakers will give live presentations with webinar-style question-and-answer sessions. Refer to the schedule to participate.

Contributed Presentations

The contributed presentations are pre-recorded and available on demand. Access begins on June 7, 2021 and ends on June 30, 2021. Live discussions in Microsoft Teams are scheduled for breakout sessions. Access the link to join in each session's description in the platform.

Virtual Meeting Settings

The following practices are recommended for optimal participation:

- Google Chrome browser; use the latest version.
- Mute your audio settings before joining a session.
- Minimize distractions; consider an out-of-office response for e-mail.

For additional technical support, contact support@morressier.com. For questions about programming, contact programming@tms.org.

Informal Networking

Use the networking sessions in Morressier to access the informal networking sessions.

Closed Captioning

Access closed captioning by using Google Live Caption in the Chrome browser.

1) In the Chrome address bar, type: chrome://flags/
2) From the Experiments page, search for Live Captions. From Live Captions, select Enable. You will be prompted to restart Chrome for changes to take effect.
3) After restarting Chrome, open Settings >> Advanced >> Accessibility. Toggle Live Caption to On. Open a new tab with video content and play a video. Captions should appear once speaking begins.

To stop Live Caption, open Settings >> Advanced >> Accessibility and toggle Live Caption **Off**.

GETTING STARTED

To participate in Mg 2021, you will need to log on to the virtual conference platform. Upon registering, you will be e-mailed a link. Use the link to log on with your e-mail address and create a password. Enter your e-mail address and password to access the virtual platform.

TECHNICAL SUPPORT

Mg 2021 is hosted on the Morressier virtual event platform. If you need assistance using the virtual platform, contact the Morressier support team by using the chat tool in the bottom right corner of the screen or by emailing support@morressier.com.

DOWNLOAD MG 2021 PROCEEDINGS

All registrants receive free electronic access to the Mg 2021 proceedings publication until June 30, 2021.

To download the proceedings, go to the proceedings publications login page. Enter your name and your unique Confirmation ID number, found in your registration confirmation e-mail (format 21-xxxxx). Please remember to use the hyphen when entering your confirmation number.

John Allison,
University of Michigan, USA
Presentation Title: "Accelerating Predictive Understanding of Microstructural Evolution and Mechanical Behavior of Magnesium Alloys"

Friday | 8:00 AM | June 18, 2021

The Center for PRedictive Integrated Structural Materials Science (PRISMS) is creating and disseminating a unique open-source capability for accelerating the scientific understanding of magnesium alloys. A central component of this framework is a suite of high performance, open-source multi-scale computational tools for predicting microstructural evolution and mechanical behavior. These are used in conjunction with advanced experiments in integrated scientific "Use Cases" focused on topics such as predicting the evolution of precipitates in Mg-rare earth alloys, their subsequent influence on mechanical behavior and quantification of alloying effects on the evolution of deformation twins during monotonic and cyclic loading. A third thrust is providing this information to the community via an information repository called the Materials Commons. This talk will review the Center's progress and plans.

Irene Beyerlein,
University of California Santa Barbara, USA
Presentation Title: "Effects of Interfaces on Deformation Twinning Behavior at the Mesoscale"

Friday | 9:00 AM | June 18, 2021

There are a wide range of structural applications that desire advanced materials with high strength-to-weight ratios in combination with other outstanding mechanical properties. Mg alloys offer a potential solution, but successful incorporation of Mg alloys into engineering designs is, however, hindered by their limited plasticity. One of the important and puzzling underlying mechanisms governing their plastic behavior is deformation twinning, which form in these materials under straining. The development of twins both inside the crystal and at crystalline interfaces has mostly been addressed at the atomistic scale level. In our research, we employ crystal plasticity-based micromechanics model to establish and understand the effects of material interfaces, whether they arise from free surfaces, grain boundaries, phase boundaries, or precipitates, on the expansion of twin embryos, twin-tip propagation and twin boundary migration. In this talk, recent results from a number of modeling and experimental studies will be presented and discussed.

Nick Birbilis,
Australian National University, Australia
Presentation Title: "Breaking Expectations in Magnesium Alloys"

Thursday | 8:00 AM | June 17, 2021

Magnesium (Mg) alloys are remarkable materials, with several extremes in their properties (not always favourable). The opportunities from the low density of Mg are yet to be fully realised (in spite of increased year on year usage). Some of the challenges to Mg-alloy development have been economic and geopolitical, others from competitor action – with the rate of Mg-alloy development not as significant as that of other alloy systems. Recent years have seen unique step changes in the understanding of Mg-alloy behaviour - particularly in ductility and corrosion performance. Enhanced understanding, facilitates design opportunities, and the advent of more ductile magnesium, and corrosion-resistant Mg-alloys is emerging. Examples covering development of not-so-novel Mg-alloys, with very novel properties, are presented. Concepts are extended to Mg-alloys for use in batteries and as functional materials (highlighting how versatile Mg-alloys are).

Hamid Jahed,
University of Waterloo, Canada
Presentation Title: "Magnesium Structural Application: A Case Study"

Thursday | 9:00 AM | June 17, 2021

Attractive specific strength and fatigue properties, excellent machinability, and good dimensional tolerances in casting and forging of magnesium captured the attention of automotive companies as a potential candidate for weight reduction.

Lots of progress was made during past two decades in weight saving from 10% to 70% per part when original steel and/or aluminum parts were replaced with magnesium. Strong basal texture of wrought magnesium alloys limits active slip systems at room temperature. Activation of prismatic and pyramidal slip systems at temperatures above 225C, however, enables forming. Leveraging the hot temperature forming and fatigue properties, magnesium suspension parts manufactured through forging became the focus of a large-scale research and development project led by the University of Waterloo in collaboration with Multimatic, Canmet, Ford, and Centreline. The successful design, manufacturing, and testing of front lower arm suspension of a car with 37% weight saving is presented in this plenary talk.

Yoshihito Kawamura,
Kumamoto University, Japan
Presentation Title: "Research and Development Trends in LPSO Magnesium Alloys for Structural and Biomedical Applications"

Thursday | 8:30 AM | June 17, 2021

LPSO magnesium alloys with a duplex structure of alpha-Mg and LPSO phases exhibit a remarkable balance of properties of high strength, heat resistance, flame resistance and reasonable corrosion resistance. Their manufacturing technology and applications are becoming more robust in Japan. Recently, we've succeeded in developing incombustible LPSO Mg-Zn-Y alloys. The ignition temperature was improved from 1,150 K to 1,300 K. The LPSO Mg-Zn-Y alloys, produced by an RS P/M processing with optimized manufacturing conditions, have excellent fracture toughness, with 20 MPa m1/2 or higher in fracture toughness Klc and >400 MPa in yield strength y. We are now developing manufacturing technology of RS P/M LPSO Mg-Zn-Y alloys with excellent fracture toughness for aerospace application. Moreover, fine-gauge wires with 30 μm in diameter have been fabricated by drawing the RS/PM LPSO Mg-Zn-Y alloys. We are currently using these fine-gauge wires to design and develop bioabsorbable medical devices.

Michele Manuel,
University of Florida, USA
Presentation Title: "Processing Magnesium Metal Matrix Composites Using Electromagnetic Acoustic Transduction"

Wednesday | 9:00 AM | June 16, 2021

A grand challenge of metal matrix nanocomposites (MMNCs) lies in processing. Magnesium and its inherently reactive properties has virtually eliminated the ability to use conventional techniques such as powder metallurgy. A novel technology has been developed called Electromagnetic Acoustic Transduction (EMAT) to process bulk Mg-MMNCs. EMAT transforms electromagnetic energy into high intensity sonication to induce acoustic cavitation, with the goal of disrupting particle agglomeration. This plenary will explore the landscape of metal matrix nanocomposite fabrication techniques while introducing the EMAT technology and its inherent advantages. Furthermore, the physics of acoustic production and its connection to the resultant microstructure will be explained in the context of potential material property improvements.

Fusheng Pan,
Chongqing University, China
Presentation Title: "Development and Applications of High Plasticity Magnesium Alloys"

Tuesday | 8:30 AM | June 15, 2021

It is well known that magnesium has a typical close packed hexagonal structure with few movable slip systems. Compared with aluminum alloys and steels, low plasticity and poor formability of magnesium alloys seriously restricts their wide application. How to improve the plasticity without damaging strength or vice versa has become a research hotspot and focus for development of new types of magnesium alloys in the world. In the past decade, Chongqing University and other units have done a lot of work in the development of high plasticity magnesium alloy and proposed an alloy design theory of "solid solution strengthening and plasticizing (SSSD)."

It is found that the solid solution of some specific atoms in magnesium can not only improve the strength by hindering the slip of basal plane dislocation but also improve the plasticity by narrowing the slip resistance gap between the basal plane and the non-basal plane and thus promote the activation of non-basal slip. As a result, both strength and plasticity of the magnesium alloy are improved simultaneously. The development of SSSD theory provided a new way to balance and optimize the strength and plasticity of magnesium alloys in the past ten years. Based on this theory, Chongqing University has developed a variety of new high plasticity magnesium alloys, of which more than 10 alloys have been listed in the National Standard or International Standard. The elongation of ultra-high plasticity magnesium alloy can reach to over 65%, and the elongation of ultra-high strength wrought magnesium alloy with b > 500MPa can reach to more than 10%.

Maria Teresa Perez-Prado,
IMDEA Materials Institute, Spain
Presentation Title: "Dislocation-particle Interactions in Magnesium Alloys"

Friday | 8:30 AM | June 18, 2021

Precipitation constitutes a microstructural design tool that has been utilized successfully to strengthen metals such as, for example, aluminum alloys and nickel superalloys. However, particle hardening has proven significantly less effective in magnesium, thus severely limiting the possibilities for structural alloy design. Exploiting the hardening potential of precipitates in magnesium alloys requires a profound understanding of the interaction between dislocations and precipitates. Basal dislocations are usually the main strain carriers, although non-basal slip systems may also become active and play a key role. The relative contribution of each mechanism depends on testing conditions, composition, microstructure and texture. This lecture will review recent research on dislocation-particle interactions in magnesium alloys using a combined approach including micromechanical testing, slip trace analysis, and high resolution transmission electron microscopy. The interaction of basal and non basal dislocations with particles of different sizes and orientations with respect to the matrix will be discussed.

Anil Sachdev,
General Motors Company, USA
Presentation Title: "Advances in Magnesium Alloys for Automotive Applications"

Tuesday | 8:00 AM | June 15, 2021

Innovations in the aluminum and steel industries are providing significant challenges to widespread application of magnesium components in automotive applications. Key barriers are mechanical properties including strength and ductility and corrosion mitigation. Alloying with rare earth elements can improve mechanical properties but adds cost. This talk will demonstrate how multi-scale computational methods, including a recently funded program by the Department of Energy, are addressing the challenge of reducing cost and improving properties to make magnesium alloys competitive for high volume applications in the automotive industry. The talk will address the needs and challenges and provide examples of alloy development for sheet, castings and extrusions. A key driver is the need to reduce or eliminate the dependency on expensive rare-earth alloying additions without compromising properties. The discussion on sheet material will additionally include the need for warm stamping and judicious choice of lubrication, corrosion coatings, and joining techniques for large vehicle body components. Finally, the talk will touch upon advanced materials models and their validation to predict material composition and processing conditions for optimum use of magnesium for specific applications.

Kwang Seon Shin,
Seoul National University, Korea
Presentation Title: "Development of High Performance Magnesium Alloys"

Wednesday | 8:00 AM | June 16, 2021

The global market for magnesium alloys has steadily expanded in the past decade, stimulated by the strong demand for lightweight components from the automobile and electronic industries. It is important to develop new advanced magnesium alloys with enhanced formability, high strength, and improved corrosion resistance to expand the application of Mg alloys. Mg sheet formability is an important requirement for enclosure applications such as car doors, hoods, and decklids, and necessitates further improvement. In addition, the corrosion resistance of Mg alloys should be improved while maintaining high strength for automobile and bioimplant applications. This study examines various approaches for increasing the formability of Mg sheets and develops magnesium alloys with high corrosion resistance and strength using severe plastic deformation (SPD) processes such as multi-directional forging (MDF) and screw rolling (SR).

Jonathan Weiler, Meridian Lightweight, Canada
Presentation Title: "Contemporary Magnesium Die-casting Research and Technology: A Canadian Viewpoint"

Wednesday | 8:30 AM | June 16, 2021

For the last 20 years, Canada has been a world leader in magnesium die-casting research and development. The breadth of research faculty and facilities, presence of a strong industrial sector, and the participation of government funded programs and agencies have fueled significant developments. This paper provides an overview of the developments led by Canadian researchers in the field of magnesium die-casting in alloy development, property and microstructural characterization, development of ICME models, joining and corrosion technologies, and automotive product development with focus on developments funded by large-scale government funded research programs.

Michael Worswick, University of Waterloo, Canada
Presentation Title: "Characterization and Continuum Modeling of a Rare-earth Magnesium Alloy Leading to Full-scale Auto Parts"

Tuesday | 9:00 AM | June 15, 2021

This presentation provides an overview of material characterization and model development studies performed on a texture-modified rare earth magnesium alloy sheet (ZEK100). Wrought magnesium alloys are attractive for automotive industry applications due to their low density and high specific strength. However, commercial magnesium alloys, such as AZ31B sheet usually have poor formability at room temperature due to limited activity of slip systems. Additionally, due to the twinning deformation mechanism activated in specific loading directions, magnesium alloys exhibit an asymmetric stress-strain response in uniaxial tension and compression tests. The formability of magnesium alloys can be improved by deforming at elevated temperatures; however, warm forming of AZ31B requires a more complex heated tooling setup which increases the cost of the forming operation. Alternatively, the formability can be improved by the addition of rare-earth elements such as Ce, Nd, Y and Gd, for example, which have been shown to weaken the basal texture. Constitutive, formability and fracture characterization of both AZ31B and ZEK100 sheet is presented, considering both room and elevated temperature conditions over a wide range of strain rate. The mechanical behavior can be related back to the initial crystallographic texture in light of known deformation mechanisms operating at different orientations and strain rates. Extensive tensile and compressive constitutive characterization experiments were performed on both alloys, including characterization of anisotropy with strain and material strain rate- and temperature-sensitivity. Forming limit characterization was also performed at elevated temperatures using in situ digital image correlation (DIC) strain measurement. The ZEK100 alloy exhibits significantly higher formability at temperatures below 250°C, whereas the two alloys have similar formability in the 250-300°C range.

Yield criteria capturing the evolving anisotropy and asymmetry of magnesium sheet alloys are proposed to model the complex behavior of magnesium alloys at room and elevated temperatures. At room temperature, the material behavior of both alloys is highly anisotropic and asymmetric; however, the degree of asymmetry and anisotropy is diminished at elevated temperature. The proposed material model is validated against several laboratory-scale experiments: 3-point bending, limiting dome height (LDH) and limiting draw ratio (LDR) experiments. Full-scale forming trials are performed considering prototype door inner and roof outer tooling. AZ31B and ZEK100 blanks were formed with initial elevated temperatures, but with room temperature tooling. The AZ31B blanks failed during forming whereas the ZEK100 blanks were successfully drawn for temperatures above 250°C. Recent constitutive models suitable for warm forming conditions using commercial forming software (Autoform) and are shown to provide predictions in accord with the forming trials.

SPONSORSHIP

TMS would like to thank the following sponsors for their support of the event:

mag specialties

Headquartered in Denver, Colorado, MAG provides customers with local engineering, sales, and customer support. Our manufacturing facility located in Nuevo Laredo, Mexico utilizes advanced Dow extrusion technology complemented by intellectual capital accumulated over 75 years of business in the magnesium industry.

IMA® International Magnesium Association

Founded in 1943, the mission of the International Magnesium Association (IMA) is to promote the use of the metal magnesium in material selection and encourage innovative applications of the versatile metal. IMA's members consist of primary producers of the metal, recyclers, foundries, fabricators, end-users and suppliers. The global voice of the magnesium industry, IMA serves the industry and its membership through its Annual World Magnesium Conference, seminars, statistical programs, research and publications. Through IMA's efforts, manufacturers and consumers are increasingly aware of the numerous options and benefits the metal magnesium provides.

By registering for this meeting, attendees accept the terms of the TMS Privacy Policy and agree to abide by TMS policies, including the Meetings Code of Conduct and the TMS Anti-Harassment Policy. For additional information on policies related to TMS events, visit the TMS Meetings Policies page and the Code of Conduct portal. A complete listing of Society policies can be accessed through the Society Bylaws & Policies section of the TMS website.

Refunds

The deadline for all refunds was April 30, 2021. No refunds will be issued at the congress.

Time Zones

Unless otherwise noted, all times for this conference and related events will take place in the local time zone, EDT (UTC/GMT -4 hours). This is the local time for TMS headquarters in Pittsburgh, Pennsylvania, USA. Use a tool like the Time Zone Converter to translate event times into your local time zone.

Language

The meeting and all presentations and program materials will be in English.

Currency

All meeting fees are expressed in U.S. dollars (USD).

Access to Recorded Presentations and Proceedings after the Conference

Please note that registrants will have access to all recorded presentations from Mg 2021 through June 30, 2021. Log in to the conference platform at any time after the conference has ended to view content. Proceedings volumes will also be available for registrants to download through June 30, 2021. After that time, standard pricing will take effect.

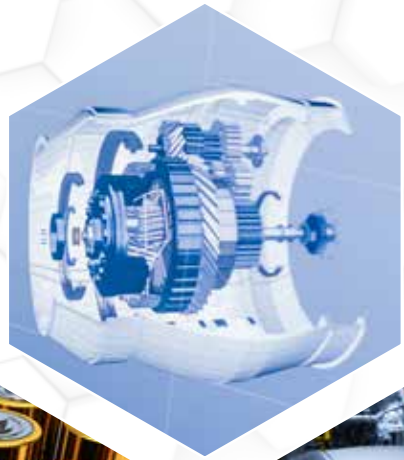
TECHNICAL PROGRAM

Mg 2021

12th International Conference on

Magnesium Alloys and their Applications

JUNE 15–18, 2021 | VIRTUAL EVENT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Applications

Tuesday AM | June 15, 2021

Session Chair: A. Luo, Ohio State University

8:00 AM Plenary
Advances in Magnesium Alloys for Automotive Applications: *A. Sachdev*[1]; [1]General Motors Company
Innovations in the aluminum and steel industries are providing significant challenges to widespread application of magnesium components in automotive applications. Key barriers are mechanical properties including strength and ductility and corrosion mitigation. Alloying with rare earth elements can improve mechanical properties but adds cost. This talk will demonstrate how multi-scale computational methods, including a recently funded program by the Department of Energy, are addressing the challenge of reducing cost and improving properties to make magnesium alloys competitive for high volume applications in the automotive industry. The talk will address the needs and challenges and provide examples of alloy development for sheet, castings and extrusions. A key driver is the need to reduce or eliminate the dependency on expensive rare-earth alloying additions without compromising properties. The discussion on sheet material will additionally include the need for warm stamping and judicious choice of lubrication, corrosion coatings, and joining techniques for large vehicle body components. Finally, the talk will touch upon advanced materials models and their validation to predict material composition and processing conditions for optimum use of magnesium for specific applications.

8:30 AM Plenary
Development and Applications of High Plasticity Magnesium Alloys: *F. Pan*[1]; [1]Chongqing University
It is well known that Mg has a typical close packed hexagonal structure with few movable slip systems. Compared with aluminum alloys and steels, low plasticity and poor formability of magnesium alloys seriously restricts their wide application. How to improve the plasticity without damaging strength or vice versa has become a research hotspot and focus for development of new types of magnesium alloys in the world. In the past decade, Chongqing University and other units have done a lot of work in the development of high plasticity magnesium alloy, and proposed an alloy design theory of "solid solution strengthening and plasticizing (SSSD)". It is found that the solid solution of some specific atoms in magnesium can not only improve the strength by hindering the slip of basal plane dislocation, but also improve the plasticity by narrowing the slip resistance gap between the basal plane and the non-basal plane and thus promote the activation of non-basal slip. As a result, both strength and plasticity of the magnesium alloy are improved simultaneously. The development of SSSD theory provided a new way to balance and optimize the strength and plasticity of magnesium alloys in the past ten years. Based on this theory, Chongqing University has developed a variety of new high plasticity magnesium alloys, of which more than 10 alloys have been listed in the National Standard or International Standard. The elongation of ultra-high plasticity magnesium alloy can reach to over 65%, and the elongation of ultra-high strength wrought magnesium alloy with s b > 500MPa can reach to more than 10%.

9:00 AM Plenary
Characterization and Continuum Modeling of a Rare-earth Magnesium Alloy Leading to Full-scale Auto Parts: *M. Worswick*[1]; T. Skszek[2]; S. Kurikuri[3]; C. Butcher[1]; A. Abedini[1]; M. Boba[1]; K. Omer[1]; [1]University of Waterloo; [2]Magna International Inc.; [3]National Research Council of Canada
This presentation provides an overview of material characterization and model development studies performed on a texture-modified rare earth magnesium alloy sheet (ZEK100). Wrought magnesium alloys are attractive for automotive industry applications due to their low density and high specific strength. However, commercial magnesium alloys, such as AZ31B sheet usually have poor formability at room temperature due to limited activity of slip systems. Additionally, due to the twinning deformation mechanism activated in specific loading directions, magnesium alloys exhibit an asymmetric stress-strain response in uniaxial tension and compression tests. The formability of magnesium alloys can be improved by deforming at elevated temperatures; however, warm forming of AZ31B requires a more complex heated tooling setup which increases the cost of the forming operation. Alternatively, the formability can be improved by the addition of rare-earth elements such as Ce, Nd, Y and Gd, for example, which have been shown to weaken the basal texture. Constitutive, formability and fracture characterization of both AZ31B and ZEK100 sheet is presented, considering both room and elevated temperature conditions over a wide range of strain rate. The mechanical behavior can be related back to the initial crystallographic texture in light of known deformation mechanisms operating at different orientations and strain rates. Extensive tensile and compressive constitutive characterization experiments were performed on both alloys, including characterization of anisotropy with strain and material strain rate- and temperature-sensitivity. Forming limit characterization was also performed at elevated temperatures using *in situ* digital image correlation (DIC) strain measurement. The ZEK100 alloy exhibits significantly higher formability at temperatures below 250°C, whereas the two alloys have similar formability in the 250-300°C range. Yield criteria capturing the evolving anisotropy and asymmetry of magnesium sheet alloys are proposed to model the complex behavior of magnesium alloys at room and elevated temperatures. At room temperature, the material behavior of both alloys is highly anisotropic and asymmetric; however, the degree of asymmetry and anisotropy is diminished at elevated temperature. The proposed material model is validated against several laboratory-scale experiments: 3-point bending, limiting dome height (LDH) and limiting draw ratio (LDR) experiments. Full-scale forming trials are performed considering prototype door inner and roof outer tooling. AZ31B and ZEK100 blanks were formed with initial elevated temperatures, but with room temperature tooling. The AZ31B blanks failed during forming whereas the ZEK100 blanks were successfully drawn for temperatures above 250°C. Recent constitutive models suitable for warm forming conditions using commercial forming software (Autoform) and are shown to provide predictions in accord with the forming trials.

Biomedical Applications I

Tuesday AM | June 15, 2021

Session Chair: M. Manuel, University of Florida

9:50 AM Invited
In-vivo Degradation and Hydrogen Gas Development in Low Alloy Content Magnesium Alloys: M. Dargusch[1]; N. Yang[1]; J. Venezuela[1]; N. Balasubramani[1]; S. Johnston[1]; K. Mardon[1]; C. Lau[1]; R. Allavena[1]; *D. St John*[1]; [1]University of Queensland
The in-vivo degradation rates of a range of low alloy content magnesium alloys suitable for the manufacture of medical implant devices has been explored and compared to the in-vivo corrosion rates of the commercial WE43 alloy. The degradation behaviour of the alloys was carefully measured using in-vivo weight loss measurements and the biocompatibility of each of the alloys has been evaluated using detailed histological analysis. Differences in the corrosion behaviour are explained in terms of alloy microstructure. Degradation behaviour was found to be associated with the development of hydrogen gas in the implanted specimens. The evolution of hydrogen with time and related histological effects were also examined in this study using CT scan information and related histological evaluation.

10:20 AM Invited
Effect of LPSO Phases on Crack Propagation in an Extruded Mg-Dy-Nd-Zn-Zr Alloy Influenced by Heat Treatment: *P. Maier*[1]; B. Clausius[1]; N. Hort[2]; [1]University of Applied Sciences Stralsund; [2]Helmholtz Zentrum Geesthacht
The effect of LPSO-phases on the crack propagation in different microstructures modified by heat treatment is investigated. Solution heat treatment on a hot extruded RESOLOY (Mg-Dy-Nd-Zn-Zr) has been done to change the initial fine-grained microstructure, consisting of lamellar LPSO structures within the matrix, into coarser grains of less lamellae but more bulk LPSO-phases. Crack initiation and propagation are of interest. Since the coarser microstructure tends to twin under plastic deformation, the crack propagation is also influenced by twin boundaries. The bulk LPSO-phases clearly hinder crack growth, either by increasing the energy to pass through the phase or along its interface. Twin boundaries and LPSO-phases are also responsible for crack initiation. The microstructural features were characterized by micro- and nanohardness as well as the amount and location of LPSO-phases in dependence on the heat treatment condition. Bulk LPSO-phases show a higher hardness than the grains with or without lamellar LPSO-phases.

New Applications

Tuesday AM | June 15, 2021

Session Chair: F. Pan, Chongqing University

9:50 AM Invited
The Research Progress of Magnesium and Alloys Based on Bibliometric Analysis: X. Peng[1]; *Y. Yang*[1]; [1]Chongqing University
Based on the bibliometric analysis of scientific articles published in the field of magnesium alloys during 2015-2019, it is aimed to reveal the emerging and important research hotspots and frontiers of basic research and technology development in magnesium alloy field, as well as the main countries/regions and research institutions. At the same time, it provides a prediction for the future research direction of magnesium alloys and applications. The analysis results show that significant progresses have been achieved in high-performance magnesium alloys, magnesium-based composites, processing technologies and functional magnesium materials. Corrosion resistance and coatings, texture and twinning, grain refinement and dynamic recrystallization, biocompatibility and biodegradability, rare earth and LPSO phases are the main research hotspots in the latest years. It is proved that the bibliometric analysis provides a new way for the research and discovery of the latest progress and development direction in the field of magnesium alloys.

10:20 AM Invited
Micro-alloying as a Novel Strategy for Developing High-performance Mg Anodes for Aqueous Mg-air Batteries: M. Deng[1]; L. Wang[1]; D. Hoeche[1]; S. Lamaka[1]; P. Jiang[1]; D. Snihirova[1]; N. Scharnagl[1]; *M. Zheludkevich*[1]; [1]Helmholtz Zentrum Geesthacht
Aqueous Mg-air batteries can be used in many fields like as power sources for marine equipment and as biodegradable batteries for implantable bioelectronics. Nevertheless, the applications of aqueous Mg-air batteries are still limited due to unsatisfactory practical performance mainly related to anode surface blockage by Mg(OH)2/MgO precipitates and severe self-corrosion during discharge. In the present work, we introduce micro-alloying as a novel strategy for developing high-performance Mg anodes. The preliminary results have demonstrated that lean binary Mg-Ca is a good anode material showing better discharge properties than high purity Mg and some commercial alloy anodes. Here we show that the Mg-Ca anode performance can be further enhanced via indium (In) micro-alloying. Mg-air battery exhibits simultaneously increased power and energy density adopting micro-alloyed Mg-Ca-In anodes. With addition of minor In, self-corrosion of the anode is suppressed and, at the meantime, chunk effect is limited.

Structural Applications

Tuesday AM | June 15, 2021

Session Chair: W. Poole, University of British Columbia

9:50 AM Invited
Elevated Temperature Formability of Texture-weakened Magnesium-sheet Alloys: Strain-rate Sensitivity Effects: *D. Klaumunzer*[1]; M. Imiela[1]; [1]Volkswagen Group Innovation
Recent work in the development of novel magnesium sheet alloys has been focussed extensively on improving the room-temperature stretch formability. In most alloy systems, such improvement is attributed to a texture-weakening effect by the addition of zinc in combination with either rare-earth elements or calcium. While such an improvement is significant compared to standard alloys showing a strong basal texture, such as AZ31, the formability enhancement is still insufficient to form real components, e.g. for the automotive industry, at room temperature. Additionally, some of the recently developed alloys show a retarded enhancement of formability at elevated temperatures making them inherently difficult to form into complex geometries. We can show that this can be attributed to a strain-rate sensitivity effect which attains low values at intermediate temperatures. Based on these findings, alloy design guidelines can be established that help to improve formability also in an industrially relevant context.

10:20 AM Invited
Process Map and Extrusion Properties of New ZAXEM11100 Alloy: T. Avey[1]; *J. Caris*[2]; A. Luo[1]; [1]The Ohio State University; [2]Terves LLC
Recently, a new magnesium alloy ZAXEM11100 (Mg-1.0Zn-1.0Al-0.5Ca-0.4Mn-0.2Ce, wt. pct.) has been developed for automotive sheet forming applications. In this collaborative work between Terves and OSU, ZAXEM11100 alloy has been evaluated for extrusion applications. CALPHAD (CALculation of PHAse Diagrams) modeling is used to design a simplified multi-stage solution treatment schedule (T4) and aging treatment (T6) after extrusion. A process map is generated for the new alloy based on Gleeble thermomechanical testing results at various temperature and strain rates. Room temperature tensile results will be presented in the T4 and post-extrusion T6 conditions with corresponding microstructures in comparison with the alloy sheet samples processed via hot rolling and heat treatment.

Wrought Alloys I

Tuesday AM | June 15, 2021

Session Chair: B. Williams, CanmetMATERIALS

9:50 AM Invited
Some Fundamental Questions on Wrought Mg Alloys: *J. Nie*[1]; [1]Monash University
Significant progress has been made in the past 20 years on wrought Mg alloys at fundamental and technological levels. At the fundamental level, textures formed in sheets and extrusions of different alloy compositions and produced under different strain paths or thermomechanical processing conditions are relatively well established, with the assistance of advanced characterisation techniques such as electron backscatter diffraction. At the technological level, room temperature formability of sheet has been improved, and tension-compression yield asymmetry of extrusion is also remarkably reduced. This presentation starts with some questions on dislocation dissociation, stacking faults, solute segregation, texture, and room temperature deformation behaviour of pure Mg and Mg alloys. With these questions, texture, grain size and deformation of sheets and extrusions produced under different processing conditions will be systematically examined and compared. Remaining and emerging scientific issues are then highlighted and discussed in the context of texture and grain size.

10:20 AM Invited
Strategies to Achieve Excellent Room Temperature Formability and High Strength in Wrought Magnesium Alloy Sheets: *T. Sasaki*[1]; M. Bian[2]; Z. Li[1]; T. Nakata[3]; S. Kamado[3]; K. Hono[1]; [1]National Institute for Materials Science; [2]National Institute of Advanced Industrial Science and Technology; [3]Nagaoka University of Technology
Heat treatable wrought magnesium alloy is promising as a strong and formable alloy sheet because Mg-Al-Zn-Ca-Mn and Mg-Zn-Ca-Zr alloys demonstrated comparable room temperature formability and strength with 6XXX series aluminum. This presentation will discuss strategies to achieve excellent room temperature formability and high strength in magnesium alloy sheets. The addition of Zn is beneficial in achieving good room temperature formability in the Mg-Ca-Al dilute alloy by texture weakening because the Zn addition facilitates the nucleation of weakly textured grains along twin boundaries during the solution treatment. However, the Zn content should be optimized to achieve satisfactory bake-hardenability, which is a unique feature that occurs in the dilute magnesium alloys strengthened by the precipitation of Guinier Preston (G.P.) zones. These bake-hardenable alloys exhibit high thermal conductivity. Therefore, the bake-hardenable magnesium alloy sheet is expected to broaden the application of wrought magnesium alloys.

Biomedical Applications II

Tuesday AM | June 15, 2021

Session Chair: M. Gupta, National University of Singapore

Towards Digital Manufacturing of Biodegradable Magnesium Implants: M. Salehi[1]; *V. Rudel*[2]; E. Berckmann[3]; S. Kaabi[4]; G. Ong[1]; J. Seitz[5]; J. Reisberg[2]; P. Ganser[2]; H. Seet[1]; S. Nai[1]; T. Bergs[6]; [1]Singapore Institute of Manufacturing Technology; [2]Fraunhofer Institute for Production Technology IPT; [3]ModuleWorks GmbH; [4]Syntellix Asia Pte Ltd; [5]Syntellix; [6]Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University
As the third generation of biomaterials, magnesium (Mg) is a promising candidate for biomedical applications. The traditional manufacturing methods are unable to produce complex geometries required for implants. Advancing manufacturing technologies could open a new window of opportunity for Mg alloys. This study aimed to develop an end-to-end manufacturing solution that enables the fabrication of customized porous Mg implants for craniomaxillofacial applications. Powder-bed inkjet 3D printing method followed by a sintering process was used to fabricate implant-like Mg components with an interconnected porous structure having more than 10 % of overall porosity. Then, clamping fixtures for a three-step machining process together with the adaptive CAM program for tool path planning and collision checking were successfully developed, enabling automated milling of the near-net-shape fabricated Mg implant. Overall, this combination of AM and the automatic post-machining process introduced in the current work will revolutionize the future of Mg alloys for implant applications.

Effect of Adding Zinc and Calcium Solute on Mechanical Properties in Magnesium Fine Wires: *H. Sannomiya*[1]; [1]Kobe University
In recent years, surgical sutures are made from bioabsrbable polymers due to the benefit for avoiding removal operation. Magnesium alloys are possible candidates for bioabsorbable sutures because of their biocompatibility and degradability. Since the drawing is suitable for manufacturing a metallic fine wire, we clarify the effect of additive elements, calcium or zinc, on mechanical properties of drawn magnesium wires. Binary alloys of Mg-Ca (0.1 to 0.3 at%) and Mg-Zn (0.1 to 0.3 at%) were cast followed by extrusion. The extrusions were drawn to fabricate a fine wire having a diameter of 0.2 mm. Tensile tests were conducted for the wires. As a result, yield stress increased with increasing the content of solute elements, while the work hardening rate and tensile ductility were varied with the kind of additive element. Inspect of the drawn microstructure revealed that the additive element plays an important role for microstructure evolution in magnesium.

New Materials / Processes; LPSO & MFS Structures

Tuesday AM | June 15, 2021

Session Chairs: M. Celikin, University College Dublin; K. Aizawa, Japan Atomic Energy Agency

Magnesium Hydride Slurry Aerospace Fuel with Net-zero or Net-negative Emissions: *Y. Wu*[1]; J. Scarponi[1]; N. Dexter-Brown[1]; J. Jayachandran[1]; A. Powell[1]; [1]Worcester Polytechnic Institute
Metals such as aluminum have been used in solid fuel systems for their high energy density. Magnesium has the advantage of low toxicity – indeed, it is a nutrient. The basicity of magnesium oxide in combustion exhaust can react with atmospheric CO2 and tie it up in precipitation. A slurry of magnesium hydride in a hydrocarbon with 1:1 Mg:C ratio has lower specific energy than jet fuel, but higher energy density which could lead to longer aircraft range. And the MgH2 can be produced from sea water and electricity with zero emissions. Thermodynamic calculations presented here indicate that this slurry fuel may burn with higher efficiency under engine conditions, particularly at high temperature, if combustion reaches equilibrium. Experiments were carried out to compare slurry droplet combustion kinetics with hydrocarbon fuel. Atmospheric equilibrium and condensation kinetics experiments estimate potential for carbon removal from the atmosphere.

Improving Adhesive Bonding of Explosive-welded Magnesium/Aluminum Joints by Interface Design: *M. Bian*[1]; X. Huang[1]; N. Saito[1]; I. Nakatsugawa[1]; Y. Chino[1]; [1]National Institute of Advanced Industrial Science and Technology

Multi-material lightweight materials have recently attracted considerable attention in the automotive industry, in particular where a trade-off between reduced weight and improved performances is required. Nevertheless, joining of dissimilar lightweight magnesium (Mg) and aluminum (Al) alloys is challenging due to the marked differences in their metallurgical and physical properties and the formation of brittle intermetallic compound layers: an Al3Mg2 layer on the Al alloy side and a Mg17Al12 layer on the Mg alloy side. In this study, the feasibility of improving adhesive bonding of an explosive-welded AZX611 (Mg-6Al-1Zn-1Ca-0.3Mn in wt.%)/A6N01 (Al-0.7Mg-0.5Si-0.3Cu in wt.%) joint was explored by conventional hot-rolling process. 7 mm thick plates were rolled to 1 mm thick sheets with different rolling temperatures and thickness reduction per pass to provide an in-depth understanding of the relationship between the rolling condition, adhesive bonding and interface microstructure of the AZX611/A6N01 joint sheet.

Understanding the Poor Hardening Potential of Nanoprecipitates in Highly Alloyed Magnesium Rare Earth Alloys: *X. Jin*[1]; W. Xu[2]; D. Shan[2]; B. Guo[2]; B. Jin[3]; M. Pérez Prado[1]; [1]IMDEA Materials Institute; [2]Harbin Institute of Technology; [3]University of Southern California

This work investigates the inefficiency of a dense distribution of nanoprecipitates to strengthen a weakly textured Mg-Gd-Y-Zr alloy by micropillar compression and analytical electron microscopy. The research shows that, in grains oriented favorably for basal slip, nanoprecipitation leads to pronounced slip localization due to dislocation shearing, resulting in a modest strengthening of basal systems. Additionally, in grains with the c-axis close to the compression axis, hard basal slip dominates deformation and nanoprecipitation promotes the activation of pyramidal slip, but also with a minor effect in the strength. Finally, in grains with the c-axis almost perpendicular to the compression axis, prismatic slip dominates deformation in the solid solution state and nanoprecipitation favors twinning due to solute depletion, leading to significant softening. The modest hardening response of the weakly textured alloy is mostly attributed to the softening associated to basal slip localization due to particle shearing.

The Effects of RE-RE Elements on the Phase Stability and Mechanical Properties of LPSO Phase in Mg-TM-RE-RE Quaternary Alloys: *K. Ikeda*[1]; S. Miura[1]; F. Miyakawa[1]; S. Takizawa[1]; T. Horiuchi[2]; S. Minamoto[3]; T. Itoi[4]; [1]Hokkaido University; [2]Hokkaido University of Science; [3]National Institute for Materials Science; [4]Chiba University

LPSO (Long-Period Stacking Ordered) phases in various Mg-TM-RE (TM: transition metals, RE: rare-earth elements) ternary alloys have attracted attention for high strength Mg alloys. In this study, it is attempted to confirm the existence of stable phases around the LPSO to substitution behavior of Mg-Zn-RE LPSO phase. Furthermore, the mechanical properties of each phase in Mg-Zn-RE-RE alloys are investigated by indentation tests. Quaternary alloys were prepared by melting Mg, Zn and several RE metal blocks in a high-frequency furnace under argon atmosphere, and casting in a mild steel mold. It was found that almost no Ce substitutes for Y in Mg-Zn-Y-Ce based LPSO, while Dy substitutes for Y in several Mg-Zn-Y-Dy based LPSO.

Classification of Oxide Films of Mg-X Binary Alloys and Application to LPSO-typed Multicomponent Mg Alloys: *S. Inoue*[1]; M. Yamasaki[1]; Y. Kawamura[1]; [1]Kumamto University

Mg alloys have high strength-to-weight ratios. However, Mg alloys easily burn and oxidize at high temperatures. To overcome the problem of flammability of Mg alloys, some reactive elements were added to Mg alloys. The reactive element oxide film formed on the Mg alloy surface may play an important role in improving incombustibility of the alloys. However, it is hard to find systematic investigation for the characterization of surface oxide film of Mg alloys in previous literatures. In this study, we have attempted to classify the oxide films of Mg-X alloys and multicomponent Mg alloys such as LPSO-typed ones. The proposed classification comprises three main types of oxides (MgO, XmOn, and XmOn/MgO) and two subgroups (thermally grown and thermal barrier) of each oxide type. The formation of thermal barrier type oxide film tends to improve non-flammability of Mg alloys regardless of sort of main oxide types.

Plastic Deformation Behavior of Lamellar-structured Mg-based Eutectic Alloys, as the "Mille-feuille Structured Material": *K. Hagihara*[1]; K. Miyoshi[1]; K. Hayakawa[1]; [1]Osaka University

LPSO phase is known to contribute to increase in both of strength and ductility of Mg alloys. As a deformation mode in it, kink-band formation is recently focused. However, its formation criteria have not yet been clarified. According to the study on the LPSO phase, its unique crystal structure which is constructed by the alternative stacking of soft and hard layers, called mille-feuille structure, are supposed as plausible factors to govern the formation of deformation kink bands. To confirm these assumptions, we examined the deformation behavior of several directionally solidified Mg-based two-phase eutectic alloy with lamellar microstructure as a model material, such as Mg/Mg17Al12, and confirmed the formation of kink-bands as expected. The details on this is discussed in the presentation.

Influence of Crystallographic Orientation on Corrosion Behavior of Mg-Zn-Y Alloys with Multimodal Microstructure: *M. Yamasaki*[1]; A. Furukawa[1]; Y. Kawamura[1]; Z. Shi[2]; A. Atrens[2]; [1]Kumamoto University; [2]The University of Queensland

Mg-Zn-Y alloys containing a long period stacking ordered (LPSO) phase have received a large amount of attention, due to its improved mechanical performance. With respect to the Mg/LPSO two-phase alloys, a heterogeneous multimodal microstructure develops during thermo-mechanical processing such as extrusion and rolling. The alpha-Mg matrix is bimodally grained; that is, it consists of fine dynamically recrystallized grains and strongly fiber-textured coarse grains. The former contributes to an improvement in ductility, while the latter contributes to mechanical strengthening of the alloy due to texture strengthening. Dispersion of LPSO phase is also effective for alloy strengthening. In other words, the extruded Mg-Zn-Y alloys involve electrochemical and geometrical heterogeneities. In this study, therefore, we have investigated influence of electrochemical and geometrical heterogeneities on corrosion resistance of extruded Mg-Zn-Y alloys with multimodal microstructure. Meticulous attention was paid to crystallographic orientation dependence of corrosion behavior of the extruded alloys.

Novel Applications / Processes / Materials

Tuesday AM | June 15, 2021

Session Chair: M. Pekguleryuz, McGill University

Physical, Chemical, and Mechanical Evaluations of Binder-jet Additive Manufactured Mg-Zn-Zr Alloy for Biomedical Applications: *M. Salehi*[1]; G. Ong[1]; H. Seet[1]; S. Nai[1]; [1]Singapore Institute of Manufacturing Technology

Magnesium (Mg) is one of the most challenging materials for additive manufacturing (AM). Near room temperature binder jetting of Mg powder shows great promise as an AM solution to fabricate green parts. However, a material-property evaluation of sintered parts is still lacking. This work aimed to provide an insight into the properties of sintered binder-jet printed Mg parts. Binder jetting was used to fabricate green parts made of Mg-5.9Zn-0.17Zr powder followed by sintering in an argon atmosphere. Micro-computed tomography and mercury porosimetry results exhibit interconnected porous structures with density > 87% and median pore diameter of 12.7 µm. Chemical analysis indicates that the evaporation of alloying elements is trivial (i.e., < 6%) compared to those observed in the laser powder bed fusion of Mg alloys. Finally, mechanical testing demonstrates that the sintered Mg parts provide comparable tensile strength, elastic modulus, and compressive properties to those seen for human cortical bone.

Linear Friction Welding of Magnesium and its Alloys: Overcoming Challenges: *L. Villegas Armenta*[1]; P. Wanjara[2]; I. Nakatsugawa[3]; Y. Chino[3]; J. Gholipour[2]; M. Pekguleryuz[4]; [1]McGill University, National Research Council Canada – Aerospace Research Center, Aerospace Manufacturing Technology Center; [2]National Research Council Canada – Aerospace Research Center, Aerospace Manufacturing Technology Center; [3]National Institute of Advanced Industrial Science and Technology, Multi-Material Research Institute, AIST Chubu; [4]McGill University

Weight reduction in the aerospace industry offers solutions to effectively address challenges of climate change and aircraft fuel consumption. Low-density magnesium (≈1.7 g/cm3) can provide a distinct advantage in weight reduction over denser light metals such as aluminum (≈2.7 g/cm3) or titanium (≈4.5 g/cm3). Developing effective techniques for joining magnesium parts to magnesium and other metals is needed to enable the widespread use of Mg in applications ranging from commercial aircraft seats to nano-satellite frames. Notably, magnesium poses liquid-phase joining challenges due to its low boiling point and high reactivity that result in welding defects and poor strength. Friction stir welding, a solid-state welding technique, has been tested on different magnesium alloys but poses difficulties in joining bulky or complex shapes and is therefore limited to joining plate components. Linear friction welding (LFW), another solid-state joining technique, is suitable for joining complex geometries and is a promising alternative for effective similar- and dissimilar-metal joining of magnesium. Our research aims at understanding the effect of LFW process parameters and alloying elements on the mechanical properties, ignition behavior, microstructure, texture, and corrosion resistance of welded Mg-to-Mg and Mg-to-Al welded sections. This work is a part of an international collaboration between the National Institute of Advanced Industrial Science and Technology, the National Research Council Canada Aerospace Research Center and McGill University, Materials Engineering.

Role of Zn on the Yielding Behavior in Mg-Al-Ca Based Dilute Alloys: *Z. Li*[1]; T. Sasaki[1]; S. Gao[2]; N. Tsuji[2]; K. Hono[1]; [1]NIMS; [2]Kyoto University

The low-cost Mg-Al-Ca based alloys have attracted considerable attention due to the potential for fulfilling the good formability and high strength concurrently. In this work, we investigate a yield point phenomenon caused by the Zn addition in a fully annealed Mg-1.2Al-0.5Ca-0.4Mn sheet alloy. The Lüders band deformation following yielding is clearly presented with the aid of digital image correlation during tensile tests. Meanwhile, this phenomenon becomes more prominent as the strain rate decreases. It is clarified that the initial yield drop is due to the enhanced dislocation locking and suppression of cross-slip by the Zn addition as revealed from (S)TEM and 3D atom probe analysis. The subsequent Lüders-type deformation is promoted by the dislocation multiplication and twinning transfer.

Wrought Alloys II

Tuesday AM | June 15, 2021

Session Chair: H. Jahed, University of Waterloo

Effect of Deformation Temperature on Microstructure and Texture Evolution in Cast AZ80 Magnesium Alloy: *P. Prakash*[1]; M. Wells[1]; B. Williams[2]; [1]University of Waterloo; [2]CanmetMATERIALS, Natural Resources Canada

This research studies the effect of deformation temperature on the microstructure and texture development in a cast AZ80 magnesium alloy within 300°C-400°C. The thermodynamic-stability of the Mg17Al12 phase greatly decreased with an increase in the deformation temperature. The precipitates were present in multiple morphologies in the material deformed at 300°C, while the different precipitate morphologies affected the occurrence of DRX in the material differently. Mg17Al12 precipitates in the lamellar morphology are suggested to have promoted DRX and texture randomization, while in the lath morphology restricted the occurrence of DRX. Mg17Al12 precipitates were not present in the material deformed at 400°C, while the DRX took place by the grain boundary bulging mechanism, and the DRXed grains preserved the deformation texture. The results indicate that the effect of deformation temperature on the microstructure and texture evolution is especially pronounced for this alloy owing to the changing thermal-stability of the Mg17Al12 precipitates.

Fatigue Characterization and Modelling of Forged AZ80 and ZK60 Magnesium: *A. Gryguc*[1]; S. Behravesh[1]; H. Jahed[1]; M. Wells[1]; B. Williams[2]; X. Su[3]; [1]University of Waterloo; [2]CanmetMATERIALS; [3]Ford Motor Company

The mechanical and fatigue properties of two commercially available Mg alloys (AZ80/ZK60) were investigated following a comprehensive forging development process to produce near-net-shape structural components. Characterization of the tension/compression and shear responses were done for a variety of different forging conditions to understand the structure-property relationship and optimize the key forging process parameters. The multiaxial fatigue response of the forged alloys were characterized, including the effects of phase angle and proportionality of the loading. The effects of the materials yield asymmetry and anisotropy in its cyclic behaviour was investigated in detail and phenomenologically linked to damage mechanisms. Strain, stress and variable amplitude fatigue experiments were carried out and energy based predictive models proved to provide a reliable life prediction for the forged Mg alloys. Full scale forging was successfully completed for both alloys producing defect free components with favourable properties that achieved a mass savings of 37% over the baseline.

Understanding Deformation Behaviour of AM50 AND AZ31 Magnesium Extrusions with Various Heat Treatments in Comparison with AA6063 and AA6082 Aluminum Extrusions: *B. Kara*[1]; A. Zeybek[1]; E. Kurtulus[1]; H. Aydin[2]; M. Atalay[2]; [1]Yesilova Holding; [2]Uludag University

The effect of the cooling methods after extrusion and subsequent heat treatment on mechanical properties of AM50 and AZ31 were studied. For each alloy, the influence of orientation of the specimen with respect to the extrusion direction was also investigated in comparison with 6063 and 6082 aluminum extrusions. The results obtained by hardness tests and charpy impact tests demonstrate that heat treatments have no significant effect on hardness and fracture energy values of AZ31 and AM50 alloys. Tensile test results also generally support this statement except that supersaturated solid solution (solution heat treatment followed by quenching in water) AZ31 plate shows significant loss in yield strength, but increase in elongation. However, the fracture energy obtained by charpy impact test and its tensile strength are similar to those under the different heat treatment conditions. AZ31 and AM50 extrusions exhibit highly anisotropic behaviour especially in terms of elongation values. AA6063 and AA6082 aluminum extrusions display low anisotrophy and provide high fracture energy values corresponding to their elongation values. However, AM50 and AZ31 alloys provide low fracture energy values regardless of their elongation values.

Investigation of the Effect of Extrusion Speed on Mechanical and Micro-structural Characteristics in a Tubular Profile Extruded from AM50 Magnesium Alloy: E. Kurtulus[1]; *I. Sapmaz*[1]; E. Özdogru[2]; [1]Yesilova Holding; [2]TRI Metallurgical Company

During the extrusion process of magnesium alloys, the extrusion speed has different effects on the microstructure and mechanical properties of the material. In this study; tubular extruded profiles produced from AM50 magnesium alloy were investigated. Extrusion production was carried out with 1 mm / s, 1.5 mm / s and 2mm / s ram speed, respectively. Tensile tests were carried out on the tensile test samples taken in the extrusion direction. As a result of these tests, yield strength, tensile strength and elongation values were achieved for different extrusion speeds were obtained and compared with each other. In addition, microstructure investigation was carried out including particle sizes and hardness measurements on tensile test samples via both optical and SEM analysis techniques. Finally; the fracture surfaces of the samples were examined by the SEM method and the differences were examined.

Aging Kinetics within GP-zone Forming, Dilute, Quaternary Alloys Containing Ca: *O. Ajiteru*[1]; S. Agnew[1]; [1]University of Virginia

Quaternary alloy systems Mg-Al-Ca-Mn (AXM) and Mg-Zn-Zr-Ca (ZKX) have emerged as promising candidates for application due to an attractive combination of properties, including good ductility and moderate strength as well as high extrusion limits. In order to achieve this good balance of properties, the alloys rely upon the formation of a dense population of ordered, Guinier-Preston (GP) zones which contain Al and Ca (AXM) or Zn and Ca (ZKX), respectively. It has already been shown that they exhibit attractive aging characteristics, such as a short aging times to obtain the peak-aged condition, and this has made them attractive for paint bake-hardening. In the present study, the focus is on over-aging. Samples are aged over a range of temperatures with the goal of determining if these alloys are vulnerable to "natural over-aging," that is over-aging at ambient temperatures, within a time frame that could jeopardize their usefulness in application.

Process Technologies

Wednesday AM | June 16, 2021

Session Chair: M. Pekguleryuz, McGill University

8:00 AM Plenary

Development of High Performance Magnesium Alloys: *K. Shin*[1]; [1]Seoul National University

The global market for magnesium alloys has steadily expanded in the past decade, stimulated by the strong demand for lightweight components from the automobile and electronic industries. It is important to develop new advanced magnesium alloys with enhanced formability, high strength, and improved corrosion resistance to expand the application of Mg alloys. Mg sheet formability is an important requirement for enclosure applications such as car doors, hoods, and decklids, and necessitates further improvement. In addition, the corrosion resistance of Mg alloys should be improved while maintaining high strength for automobile and bioimplant applications. This study examines various approaches for increasing the formability of Mg sheets and develops magnesium alloys with high corrosion resistance and strength using severe plastic deformation (SPD) processes such as multi-directional forging (MDF) and screw rolling (SR).

8:30 AM Plenary

Contemporary Magnesium Die-casting Research and Technology: A Canadian Viewpoint: *J. Weiler*[1]; [1]Meridian Lightweight

For the last 20 years, Canada has been a world leader in magnesium die-casting research and development. The breadth of research faculty and facilities, presence of a strong industrial sector, and the participation of government funded programs and agencies have fueled significant developments. This paper provides an overview of the developments led by Canadian researchers in the field of magnesium die-casting in alloy development, property and microstructural characterization, development of ICME models, joining and corrosion technologies, and automotive product development with focus on developments funded by large-scale government funded research programs.

9:00 AM Plenary

Processing Magnesium Metal Matrix Composites Using Electromagnetic Acoustic Transduction: *M. Manuel*[1]; [1]University of Florida

A grand challenge of metal matrix nanocomposites (MMNCs) lies in processing. Magnesium (Mg) and its inherently reactive properties has virtually eliminated the ability to use conventional techniques such as powder metallurgy. A novel technology has been developed called Electromagnetic Acoustic Transduction (EMAT) to process bulk Mg-MMNCs. EMAT transforms electromagnetic energy into high intensity sonication to induce acoustic cavitation, with the goal of disrupting particle agglomeration. This plenary will explore the landscape of metal matrix nanocomposite fabrication techniques while introducing the EMAT technology and its inherent advantages. Furthermore, the physics of acoustic production and its connection to the resultant microstructure will be explained in the context of potential material property improvements.

Corrosion I

Wednesday AM | June 16, 2021

Session Chair: M. Zheludkevich, Helmholtz Zentrum Geesthacht

9:50 AM Invited
Critical Issues in Magnesium Corrosion: Needs, Gaps and Opportunities: *J. Scully*[1]; [1]University of Virginia
Broader utilization of magnesium and magnesium alloys in corrosive environments requires further advances in corrosion science and engineering. Strategies to mitigate corrosion include either intrinsic improvements in alloy design to affect corrosion kinetics or extrinsic protective measures such as pretreatments, coatings and electrochemical protection. This talk focuses on the intrinsic attributes of magnesium alloys and surface films which control kinetic corrosion factors.

10:20 AM Invited
Galvanic Corrosion of AZX611 Magnesium Alloy / A6005C Aluminum Alloy Joint: *I. Nakatsugawa*[1]; Y. Chino[1]; [1]National Institute of Advanced Industrial Science and Technology
Galvanic corrosion between AZX611 (Mg-5.9wt.%Al-0.6wt.%Zn-1.0wt.%Ca) magnesium alloy / A6005C (Al-0.4wt.%Mg-0.6wt.%Si-0.2wt.%Fe) aluminum alloy joint in differently concentrated NaCl solutions was evaluated. The galvanic current showed a maximum at the initial stage and then decreased with time. H2 gas evolution was observed on both surfaces, which was accelerated in higher NaCl concentration. The weight loss measurement revealed that galvanic corrosion damaged not only AZX611 but also A6005C due to the surface alkalization caused by the cathode reaction. The Scanning Vibrating Electrode Technique (SVET) detected numerous local anodes on the AZX611 surface, which gradually disappeared and were replaced with passive areas. It was concluded that the galvanic corrosion of the AZX611 / A6005C joint was controlled by the depassivation behavior of the AZX611 anode, in which the NaCl concentration was critical.

Forming I

Wednesday AM | June 16, 2021

Session Chair: S. Yue, McGill University

9:50 AM Invited
Solid Phase Processing of Magnesium Alloys: *S. Whalen*[1]; N. Overman[1]; V. Joshi[1]; T. Varga[1]; D. Graff[1]; C. Lavender[1]; W. Frazier[1]; M. Rhodes[1]; T. Roosendaal[1]; E.[1]; R. Seffens[1]; T. Wang[1]; X. Ma[1]; J. Silverstein[1]; H. Das[1]; M. Pallaka[1]; A. Ortiz[1]; [1]Pacific Northwest National Laboratory
The Solid Phase Processing group at the Pacific Northwest National Laboratory is investigating the role of extreme deformation on the ability to extrude and join magnesium alloys. This presentation will highlight two emerging technologies currently being developed; Rotating Hammer Riveting (RHR) and Shear Assisted Processing and Extrusion (ShAPE), with examples given for their implementation of magnesium alloys. Magnesium alloy AZ31 has been joined to thermoplastic carbon fiber reinforced polymer (CFRP) by RHR. With RHR, the rivet head is mixed with, and metallurgically bonded to, the underlying sheets being joined to form a robust fastener. The RHR process, joint properties, and microstructural characterization will be discussed. Non-rare earth magnesium alloy ZK60 has been extruded by ShAPE to form thin-walled tubing with a highly refined microstructure and basal plane alignment away from the extrusion direction. These tubes have been slit and rolled into sheet and foil with anisotropic material properties.

10:20 AM Invited
Eliminating Yield Anisotropy and Enhancing Ductility and Corrosion Resistance in Mg Alloys by Shear Assisted Processing and Extrusion: *V. Joshi*[1]; D. Zhang[1]; K. Solanki[2]; J. Darsell[1]; V. Beura[2]; N. Overman[1]; D. Herling[1]; [1]Pacific Northwest National Laboratory; [2]Arizona State University
Solid phase processing techniques such as friction stir welding, Shear assisted processing and extrusion (ShAPE)/ friction extrusion and cold spray have been successfully demonstrated as promising thermomechanical methods to produce metallic materials with enhanced performance. In this study, AZ series with and without silicon, ZK60 Mg alloys in as-received forms (as-cast or as-extruded) were processed using Shear Assisted Processing and Extrusion (ShAPE). Microstructural characterization was performed using EBSD and TEM and revealed that as compared to the feedstock materials/ billets, friction extruded Mg alloys had more uniform microstructure, equiaxed grains, finer and homogeneously distributed precipitates and chemical homogeneity. It was also observed that basal planes were not oriented parallel to extrusion axis. As a result, rod products exhibited significantly reduced (in some cases eliminated) yield asymmetry and achieved enhanced ductility, which were uncommon or difficult to attain using conventional processing techniques.

Primary & Recycling

Wednesday AM | June 16, 2021

Session Chair: M. Alderman, Luxfer MEL Technologies

9:50 AM Invited
A New Hydrometallurgical Process Combined with an Electrolytic Process for Magnesium Primary Production from Serpentine: *J. Fournier*[1]; [1]Alliance Magnesium
The primary production process developed by Alliance Magnesium Inc. is a hydrometallurgical process combined with an electrolytic process. It constitutes an improvement over the former Noranda Magnola Process and uses a combination of best in class technology to produce a high-quality magnesium for use in many applications, including the most demanding, namely the automotive market. It also introduces a radical breakthrough technological change by the production of some valuable by-products.The process allows processing and extracting magnesium from tailing, such as asbestos mine tailing, obtained after processing of magnesium-bearing ores and including a multi steps continuous line through the preparation and classification of the ores, the magnetic separation, a strong acid leaching, a liquid/ solid separation ans washing, a resin captation ans hydrolysis recovery, dehydration and electrolysis.

10:20 AM Invited
Thermodynamics on the Recycling Process of Mg Alloys Containing Ca, Sr and RE: *I. Jung*[1]; J. Cheon[1]; M. Kang[1]; [1]Seoul National University
The application of Mg alloys containing Ca, Sr and RE is expanding recently due to its good high temperature mechanical properties, formability and corrosion resistance. For the sustainable usage of these alloys, it is highly necessary to develop the proper recycling process of the Mg alloys. In the common melting recycling process of Mg alloys, molten salt of Na,K,Ca//Cl,F system is used to as refining flux. In the present study, the thermodynamic database for the Na,K,Mg,Ca,Sr,RE//Cl,F salt system was constructed and applied to the chemical equilibrium calculations between molten salts and liquid Mg alloys to investigate the refining recycling process of Mg alloys.

Solidification Processing

Wednesday AM | June 16, 2021

Session Chair: J. Weiler, Meridian Lightweight

9:50 AM Invited
Al11Mn4 Formation during the Solidification and Heat Treatment of AZ91: *C. Gourlay*[1]; J. Xian[1]; L. Peng[1]; G. Zeng[2]; D. Wang[1]; [1]Imperial College London; [2]Central South University
Manganese is commonly added to Mg-Al-based alloys to ameliorate against the negative effects of impurity Fe on corrosion, causing various AlxMny intermetallic compounds to form during solidification and/or heat treatment. Here we explore the conditions under which Al11Mn4 forms during casting and solution heat treatment of high purity AZ91 and AZ80. The crystallography of Al11Mn4 nucleation and growth are studied by EBSD and shown to be strongly linked with the formation of Al8Mn5. The intermetallic microstructures are discussed with respect to thermodynamic calculations in Thermo-Calc and Pandat.

10:20 AM Invited
MAXImolding: Vertical Semi-solid Magnesium Injection Molding Machine for Mega Volume Production: *A. Stone*[1]; E. Meyer[1]; [1]MAXImolding! Technology Germany
The four semisolid metal casting processes thixomolding, thixocasting, rheocasting and stress induced melt activation are very complex and highly maintenance intensive. The cold chamber die-casting, the hot chamber die-casting did not fulfill end user expectations for quality, energy savings, and environmental sustainability.We dedicated all our working life to solve two problems: production of high-integrity net-shape light metal parts, while reducing porosities in moldings (castings). We are fully committed to improving the non-sustainable current approach of molding - inspecting - separating and re-melting. MAXImolding Team invented and patented a new vertically oriented, environmentally friendly Semi-Solid Metal Injection Molding Machine (SSM-IMM). The Molding processing parameters are optimized without a human operator by closing a real-time x-ray feedback control loop based on parts quality indicators and proper AI algorithms. This is an intrinsically safe, energy and material efficient, environmentally sound magnesium-molding self-learning smart factory with no emissions outside of factory parameters limit.

Corrosion II

Wednesday AM | June 16, 2021

Session Chair: A. Eliezer, SCE

Effect of Microstructure on Corrosion Behavior of Cold-rolled Mg-Li-Al Alloy: *T. Morishige*[1]; H. Ikoma[1]; T. Takenaka[1]; [1]Kansai University
Mg-Li system alloy has excellent formability at room temperature due to their crystal structure. However, exfoliation corrosion appears during progress of corrosion. Therefore, it is difficult to apply for the actual metallic products without corrosion protection. Previously, the suppression of exfoliation could be attained by recrystallization of cold-rolled alloy. The microstructural characteristics were completely changed by recrystallization, so the detailed investigation is required for explanation of exfoliation corrosion origination. In this study, the origination of exfoliation corrosion of Mg-14 mass%Li-1 mass%Al alloy with various microstructures such as as-rolled, only recovered and recrystallized state. As the results, the induced strain during severe deformation is major factor of expression of exfoliation corrosion.

Oxygen Reduction during Degradation of Magnesium: C. Wang[1]; D. Mei[1]; M. Zheludkevich[1]; *S. Lamaka*[1]; [1]Helmholtz-Zentrum Geesthacht
Understanding fundamental mechanisms of magnesium degradation is vital for predicting its corrosion behaviour, developing new alloys and establishing reliable research methodologies. Hydrogen evolution reaction is widely regarded as the only cathodic process during corrosion of magnesium. Hence, tracing the amount of released hydrogen was thought to be a reliable measure of degradation rate. Recently, we have shown, by different methods, that oxygen reduction reaction (ORR) is important secondary cathodic reaction. In this work, we quantify rate of ORR for different grades of Mg.Contrary to expected, oxygen consumption was the highest during corrosion of ultra-high purity Mg, and slower for rapidly corroding commercial-purity Mg. This phenomena was linked with the growth rate, thickness, morphology and permeability of Mg(OH)2 layer that blocks the access of dissolved oxygen to electrochemically active Mg/MgO interface.

The Role of Native Oxides on the Corrosion Mechanism of Laves Phases in Mg-Al-Ca Composites: D. Zander[1]; *M. Felten*[1]; J. Nowak[1]; P. Grünewald[2]; F. Schäfer[2]; C. Motz[2]; [1]RWTH Aachen University; [2]Saarland University
Magnesium-Aluminum-Calcium composites are characterized by thermally stable Laves phases, which enable high-temperature material applications. Nevertheless, immersing the material into an electrolyte causes an increased corrosion rate as a consequence of micro galvanic effects among the Laves phases and the matrix. The Volta potential difference determined under atmospheric conditions on a freshly polished surface using Scanning Kelvin Probe Force Microscopy (SKPFM) is a valid measure for the micro galvanic coupling and the dynamic growth kinetics of a native oxide film.In the present study, the time-dependent native oxide film formation of Magnesium-Aluminum-Calcium alloys is analyzed via in situ SKPFM measurements. An inhomogeneous evolution of the Volta potential on the Laves phases compared to the matrix indicates heterogeneous native oxide formation. Dependent on the stability of the native oxide film in strongly alkaline electrolytes, the conducted measurements evaluate the corrosion behavior under these conditions.

Effects of Phase Fractions on Mechanical and Corrosion Properties of Mg-0.5Ca-0.5Mn-xZn Alloys: *T. Avey*[1]; A. Luo[1]; D. Dean[1]; [1]Ohio State University
Magnesium alloys have the potential to be used in new bioabsorbable medical devices because of their similar elastic response as bone, low toxicity, and lightweight. Current commercial Mg alloys are lacking in mechanical strength or corrosion resistance or contain harmful elements. Mg-Ca-Zn alloys have been of particular interest due to their balanced corrosion resistance and mechanical properties. By using a phase-based CALPHAD (CALculation of PHAse Diagrams) approach, microstructure with the most desirable mechanical properties and lowest corrosion rate can be designed. The three secondary phases that are under investigation are Mg2Ca, Ca2Mg6Zn3, and MgZn. Four compositions, Mg-0.5Ca-xZn (x=0, 0.5, 1.2, 2) were selected that were calculated through CALPHAD to contain different amounts of these phases. Corrosion rate is determined through weight loss measurements after immersion in SBF (Simulated Body Fluid). Mechanical properties are measured by ASTM E9 tensile and compression tests

Adjustable Corrosion Kinetic by Microstructure Design of Biodegradable ZX11: *V. Chaineux*[1]; S. Mergenthaler[1]; D. Zander[1]; [1]RWTH Aachen University

Biodegradable magnesium-calcium-zinc alloys are promising alloys for tailor made property design. It is well known that the corrosion kinetic of Mg-Ca-Zn is still subject of matter and needs to be improved. Therefore, controlling of corrosion mechanism by adjusting microstructure, alloying elements and impurities is still an important research focus.The present study therefore aims at a tailor-made adjustment of the local change of microstructural features by providing zones with different grain sizes, grain orientations and distributions of secondary precipitates to investigate their effects on the corrosion progress of biodegradable ZX11. The results were obtained by XRD, SEM and EBSD and correlated with ICP-MS analysis data of the used Hanks' balanced salt solution. A change of the corrosion kinetics and underlying mechanisms of ZX11 as a function of specific modifications of microstructures, as mentioned above, was observed and allows the adjustment of tailor-made corrosion kinetics by using an improved production process.

Deformation & Mechanical Behaviors I

Wednesday AM | June 16, 2021

Session Chair: D. Letzig, Magic-Magnesium Innovation Centre

A Micromechanics-based Modeling of Twin Evolution in Hexagonal Closed Packed Metals: *Y. Paudel*[1]; C. Barrett[1]; H. El Kadiri[1]; [1]Mississippi State University

Twin nucleation is an important phenomenon leading to anisotropy and damage in magnesium AZ31 alloy. The strain path anisotropy in magnesium AZ31 alloy results from profuse nucleation of {10-12} twinning under c-axis tension (tension twinning) or d-axis compression (extension twinning) while damage induces from various interactions between twins and other grain defects. This work demonstrates that micromechanical work field calculations can have great potential to guide laws for crystal plasticity to predict twin patterning. The study shows a minimum energy path of twinning evolution through twin nucleation, propagation, and growth. The investigated twinning behaviors include twin propagation to the neutral axis, nucleation of a second twin at a certain distance from the first one, and twin growth with the microstructure finally evolving to a favorable twinning pattern to accommodate the total bending strain. The twinning mechanisms observed from this analysis compare well with the experimental results.

Influence of the Manufacturing Process on the Formability at Room Temperature of Magnesium Flat Products: *M. Nienaber*[1]; J. Bohlen[1]; K. Kainer[2]; D. Letzig[1]; [1]Helmholtz-Zentrum Geesthacht; [2]Wroclaw University of Science and Technology

The development of flat products made of Mg-alloys with excellent formability at room temperature is of interest. Besides rolling, extrusion also offers the possibility of producing flat products. During extrusion, it is possible to produce a finished flat product in only one processing step by a high degree of deformation, which also results in different texture and microstructure development compared to the rolling of sheets. However, compared to the rolling process, the band width during extrusion is very limited due to the process layout. In this work, conventional rolled sheets as well as extruded flat bands of different alloy compositions will be investigated and compared. The influence on the texture and microstructure development as well as on the strain rate dependent mechanical properties and the forming behaviour will be shown and discussed. It can be shown that the manufacturing process has an important and alloy dependent influence on the formability.

The Influence of Recrystallization on the Temperature Dependence of Twinning in Magnesium Alloys: A. Brahme[1]; K. Inal[1]; R. Mishra[1]; A. Farzadfar[2]; *E. Martin*[3]; [1]University of Waterloo; [2]Corning Incorporated; [3]École Polytechnique

The nucleation of twin formation, an important mechanism in the deformation of magnesium alloys, is still an active topic of discussion. The twin formation is generally tied to the amount of shear stress resolved on the twin system. This work sheds light on the formation of twins by studying the deformation in 3 different Mg alloys. The alloys are deformed at 350C. The flow curves show the signature of dynamic recrystallization in all the alloys. The resultant microstructures are studied optically and using electron backscatter diffraction maps. The results clearly show the formation of dynamic recrystallized (DRX) grains are primarily located inside the twins. The volume fraction of DRX and twins is calculated using ASTM E562-02 standard from the optical micrographs. The volume fraction of DRX and twins thus calculated shows inverse correlation. Thus, indicating that the increase in the DRX leads to decrease in the amount of twinning by reduction in the conditions conducive for twin formation.

Characterization of Twinning and Dislocation Slip in Magnesium Single-crystals by High Spatio-temporal Resolution: *K. Máthis*[1]; P. Harcuba[1]; D. Ugi[2]; M. Knapek[1]; P. Ispánovity[2]; I. Groma[2]; [1]Charles University; [2]Eötvös Loránd University

A combination of in-situ scanning electron microcopy (SEM), acoustic emission (AE) technique and high-speed camera recording has been employed for study the mechanical behavior of Mg single crystals. The combination of these techniques enables to study the active deformation processes with exceptional spatiotemporal resolution. The kinetics of the twinning and dislocation slip is discussed in detail and compared with molecular dynamics and finite element method simulations. The causality of deformation mechanisms is revealed by statistical analysis of AE data.

Effect of Yttrium and Cerium on the Pyramidal Slip in Magnesium Single Crystals: *S. Ando*[1]; M. Sakamoto[1]; T. Hanada[1]; M. Tsushida[1]; H. KItahara[1]; [1]Kumamoto University

Tensile tests of Mg-Y and Mg-Ce single crystals at various temperature were carried out to investigate alloying effects on activity of pyramidal <c+a> slips. Both alloy single crystals were yielded by activation of {11-22}<11-23> second order pyramidal slips at low alloy concentration. In Mg-Y alloy, {10-11}<11-23> first order pyramidal slip appeared at high yttrium contents and the CRSS of the pyramidal slip increased. The CRSS of second order pyramidal in Mg-Ce was lower than that of pure magnesium. Effect of yttrium and cerium on the CRSS of pyramidal slips was discussed based on dislocation mechanism of pyramidal slip.

Forming II

Wednesday AM | June 16, 2021

Session Chair: B. You, Korea Institute of Materials Science

Influence of As-cast Microstructure on Forging Behaviour of Magnesium Alloy AZ80: *J. Uramowski*[1]; P. Prakash[1]; E. Azqadan[1]; A. Roostaei[1]; [1]University of Waterloo
The limitations of the internal combustion engine have driven alternate means of improving efficiency, such as using lightweight magnesium alloys for structural components. To meet structural strength and fatigue requirements the mechanical properties must be improved through forging, made difficult due to the crystal structure of magnesium. Research has shown that the mechanical properties of forged magnesium rely on the grain size, grain orientation, and internal defects of the as-cast starting material. This research focuses on the influence of the as-cast structure on the forging response and microstructure evolution of the AZ80 magnesium alloy. Flow stress is measured for samples cast with high and low cooling rates, and samples that were homogenized prior to deformation. The grain structure is analyzed at incremental strains during deformation for each starting material state. This knowledge will help to determine the optimal cast material structure that will enable structural components upon forging.

Effect of Caliber Rolling on Microstructure and Mechanical Properties of Wrought Mg-Bi Based Alloy: *H. Yu*[1]; [1]Hebei University of Technology
In this study, a Mg-1.32Bi-0.72Ca (BX11) alloy having bimodal grain structure was successfully fabricated by a new processing route of combining extrusion and 3 pass caliber rolling. This novel processing (E-CRed) demonstrates a necklace-like grain structure with ultrafine grains formed around the microscale deformed grains, which is remarkably different from the uniform microstructure of the as-extruded alloy. In addition, the E-CRed BX11 alloy exhibits strong basal texture which is mainly original from the large deformed grains. Furthermore, the E-CRed BX11 alloy represents excellent comprehensive mechanical properties, with an ultra-high yield strength of 351 MPa and a good elongation to failure of 13.2%. The significant strength improvement can be mainly attributed to the grain refinement and much stronger basal texture compared with the as-extruded sample.

Evolution of Texture and Microstructure in Mg-Zn-Ca Sheet Alloys during Thermomechanical Processing: *T. Berman*[1]; J. Allison[1]; [1]University of Michigan
The improved formability of advanced Mg sheet alloys has been attributed in part to their off-basal textures with a relatively low texture intensity. We have investigated the thermomechanical processing variables that produce these desirable textures in a systematic study of Mg-Zn-Ca alloys subjected to plane strain compression (PSC) using a Gleeble Thermomechanical Simulator. The PSC thermomechanical processing (TMP) route used consists of multiple compressive "hits" intended to simulate a multi-pass rolling process. This work utilizes microscopy and electron backscatter diffraction to track the evolution in microstructure and crystallographic texture that occurs during TMP at multiple stages in the processing path. We have demonstrated that the thermal soaks between passes and static recrystallization during the final annealing treatment play a particularly important role in determining the final texture. The effect of alloying and changes in processing conditions on the final texture are also important and will be discussed.

Cyclic Deformation Mechanisms and Fatigue Life Prediction of AZ31 Mg Alloy: A. Jamali[1]; M. Zhang[2]; A. Ma[2]; *J. Llorca*[1]; [1]IMDEA Materials Institute & Technical University of Madrid; [2]IMDEA Materials Institute
The low cycle fatigue behavior under fully-reversed cyclic deformation was determined in different orientations in an extruded AZ31 Mg alloy for different cyclic strain amplitudes. The shape of the cyclic stress-strain curves depended on the orientation due to the strong texture of the alloy and to the development of twinning under certain combinations of load and orientation. The mechanical response of the material under cyclic deformation was simulated by means of computational homogenization of a representative volume element of the microstructure of the alloy, The behavior of the Mg crystals followed a phenomenological crystal plasticity model which included all the different slip systems of Mg (basal, prismatic and pyramidal) as well as twinning and detwinning. The simulation results (in terms of the cyclic stress-strain curve and fraction of twinned material) were used to understand the cyclic deformation mechanisms and to predict the fatigue life from fatigue indicator parameters.

Texture Selection under the Influence of Solutes and Precipitates in Ternary Magnesium Rare Earth Alloys: *F. Mouhib*[1]; F. Sheng[2]; T. Al Samman[1]; S. Korte-Kerzel[1]; [1]Institute of Physical Metallurgy and Materials Physics, RWTH Aachen; [2]RWTH Aachen University
Magnesium-rare earth alloys have gained increasing academic and industrial attention due to very attractive properties. In particular, enhanced cold ductility caused by a softened deformation texture has triggered great research efforts to understand microstructure evolution under the influence of solutes. However, the underlying mechanisms responsible for the formation of unique textures with a basal pole spread in the transverse direction and the interaction of multiple solute species (e.g. Zn & RE) is yet to be clarified. This work retraces the formation of a pronounced TD-split texture observed in Mg-1%Zn-1%RE (RE= Er, Dy, Gd) considering synergetic effects of multiple solutes and precipitates. From the results, texture selection seems to originate from selective growth during recrystallization, depending on solute concentration and species, as well as precipitates. Understanding the interplay of these factors is key for a microstructure-informed alloy design.

Primary, Recycling, & Solidification Processing

Wednesday AM | June 16, 2021

Session Chair: P. Uguccioni, International Magnesium Association

Electro-chemo-mechanical Modelling of Corrosion Induced Material Damage: *D. Hoeche*[1]; N. Konchakova[1]; M. Zheludkevich[1]; C. Blawert[1]; W. Weber[2]; Z. Mir[1]; M. Shariati[2]; [1]Helmholtz-Zentrum Geesthacht; [2]Helmut-Schmidt University
Modelling and simulation of surface degradation and related material damage due to combination of aggressive environmental attack with mechanical loads is in the focus of this approach. A corrosion model is fully coupled to a mechanical model enabling the description of damage related system changes. The evolution of corrosion and its impact on the stress -strain relationship are analyzed numerically and compared with the experimental investigation on extruded cp-Mg. The aim of the study is to understand and to quantify the influence of corrosion related geometry and morphology changes on damage initiation and progress, and to devolop a numerical framework towards elimination of damage variables.

Microstructural and Mechanical Properties of Solid-state Additively Manufactured Friction Stir Deposited Magnesium AZ31: T. Robinson[1]; *M. Williams*[1]; H. Rao[1]; R. Kinser[1]; B. Jordon[1]; P. Allison[1]; [1]University of Alabama

This work examines a bulk deposition of additive friction stir deposition (AFS-D) of AZ31 Mg Alloy. The AFS-D process was used to fabricate a 4" by 4" by 1/4" tall deposition of AZ31 Mg alloy using a differentiating raster pattern. The effect of the bulk deposition on material properties was examined using microstructure characterization and mechanical testing. Electron Back-Scattered Diffraction (EBSD) was utilized to evaluate the microstructure of the AFS-D specimens at high interest areas in the raster pattern compared to the microstructure of the base material. Quasi-static tests at ambient temperature were performed to evaluate the mechanical performance of the AFS-D specimens compared to that of the base material. Post-mortem analysis via scanning electron microscopy (SEM) was used to elucidate the underlying factors of mechanical response of the AFS-D specimens.

A HAADF STEM Study on Nucleation and Growth Crystallography of Al8Mn5 on B2-Al(Mn,Fe) Intermetallic in AZ91 Alloy: *G. Zeng*[1]; W. Yang[2]; M. Kudo[2]; K. Nogita[3]; S. Matsumura[2]; C. Gourlay[4]; [1]Central South University; [2]Kyushu University; [3]The University of Queensland; [4]Imperial College London

Al-Mn-Fe compounds are important for providing corrosion resistance to magnesium alloys. Many Al8Mn5 particles contained a B2-Al(Mn,Fe) particle near their centre due to Al8Mn5 nucleation on B2 followed by an incomplete peritectic transformation. However, there is uncertainty about the crystallography and the nature of the interface structure at Al8Mn5 twin boundaries and Al(Mn,Fe)-Al8Mn5 boundaries. The present study has succeeded in direct observation of B2/Al8Mn5 intermetallics by aberration-corrected scanning transmission electron microscopy (STEM), including atomic-resolution imaging as well as elemental mapping by X-ray energy-dispersive spectroscopy (XEDS). We performed chemical mapping of atomic columns along <100>cubic to explore ordering in the B2-CsCl-type structure. We confirmed that Al8Mn5 is rhombohedral with the D810-Al8Cr5 structure type and R3m space group at the atomic scale. We also imaged the B2/Al8Mn5 interface to better understand the orientation relationship and atomic coherency between B2/Al8Mn5. We observed the interface of {2-201} twin boundaries along <1-102> with distinguished atomic-resolution.

Comparative Study of Structure Property Relationship of Extruded and Additively Manufactured WE43: R. Raghavendra[1]; *P. Upadhyaya*[1]; S. O'Halloran[1]; O. Mccarthy[2]; T. Kennedy[2]; [1]Waterford Institute of Technology; [2]Stryker Ireland

In recent years, bioresorbable materials have been considered as a viable option to replace temporary orthopaedic implants. Temporary orthopaedic implants are required for a relatively short time, just long enough to let bones heal. They are removed, during a second surgery. Bioresorbable materials eliminate the requirement for that invasive surgery.WE43 Magnesium alloy is a low density, biocompatible, metallic structure, which has mechanical properties similar to that of human cortical bone, which will biodegrade and absorbed by the body. Additive manufacturing (AM) can be used to produce implants with complex design providing new functionality compared with traditional manufacturing techniques. AM processing parameters for WE43 have been developed in this study and their relationship to component microstructural and mechanical properties investigated. Comparison to conventionally produced extruded WE43 is presented. Structure-property relationships obtained for both the manufacturing techniques were compared. This research is aimed at development of additively manufactured, bioresorbable magnesium implants.

Alloy Technologies

Thursday AM | June 17, 2021

Session Chair: K. Kainer, Wroclaw University of Science and Technology

8:00 AM Plenary

Breaking Expectations in Magnesium Alloys: *N. Birbilis*[1]; Z. Zeng[1]; [1]The Australian National University

Magnesium (Mg) alloys are remarkable materials, with several extremes in their properties (not always favourable). The opportunities from the low density of Mg are yet to be fully realised (in spite of increased year on year usage). Some of the challenges to Mg-alloy development have been economic and geopolitical, others from competitor action – with the rate of Mg-alloy development not as significant as that of other alloy systems. Recent years have seen unique step changes in the understanding of Mg-alloy behaviour - particularly in ductility and corrosion performance. Enhanced understanding, facilitates design opportunities, and the advent of more ductile magnesium, and corrosion-resistant Mg-alloys is emerging. Examples covering development of not-so-novel Mg-alloys, with very novel properties, are presented. Concepts are extended to Mg-alloys for use in batteries and as functional materials (highlighting how versatile Mg-alloys are).

8:30 AM Plenary

Research and Development Trends in LPSO Magnesium Alloys for Structural and Biomedical Applications: *Y. Kawamura*[1]; [1]Kumamoto University

LPSO magnesium alloys with a duplex structure of alpha-Mg and LPSO phases exhibit a remarkable balance of properties of high strength, heat resistance, flame resistance and reasonable corrosion resistance. Their manufacturing technology and applications are becoming more robust in Japan. Recently, we've succeeded in developing incombustible LPSO Mg-Zn-Y alloys. The ignition temperature was improved from 1,150 K to 1,300 K. The LPSO Mg-Zn-Y alloys, produced by an RS P/M processing with optimized manufacturing conditions, have excellent fracture toughness, with 20 MPa $m^{1/2}$ or higher in fracture toughness K_{Ic} and >400 MPa in yield strength σ_y. We are now developing manufacturing technology of RS P/M LPSO Mg-Zn-Y alloys with excellent fracture toughness for aerospace application. Moreover, fine-gauge wires with 30 μm in diameter have been fabricated by drawing the RS/PM LPSO Mg-Zn-Y alloys. We are currently using these fine-gauge wires to design and develop bioabsorbable medical devices.

9:00 AM Plenary

Magnesium Structural Application: A Case Study: *H. Jahed*[1]; [1]University of Waterloo

Attractive specific strength and fatigue properties, excellent machinability, and good dimensional tolerances in casting and forging of magnesium captured the attention of automotive companies as a potential candidate for weight reduction. Lots of progress was made during past two decades in weight saving from 10% to 70% per part when original steel and/or aluminum parts were replaced with magnesium. Strong basal texture of wrought magnesium alloys limits active slip systems at room temperature. Activation of prismatic and pyramidal slip systems at temperatures above 225C, however, enables forming. Leveraging the hot temperature forming and fatigue properties, magnesium suspension parts manufactured through forging became the focus of a large-scale research and development project led by the University of Waterloo in collaboration with Multimatic, Canmet, Ford, and Centreline. The successful design, manufacturing, and testing of front lower arm suspension of a car with 37% weight saving is presented in this plenary talk.

Alloy Development I

Thursday AM | June 17, 2021

Session Chair: E. Nyberg, Tungsten Parts Wyoming

9:50 AM Invited
Development of Corrosion Resistant Magnesium Alloy Containing Ca and Y: *B. You*[1]; Y. Kim[1]; H. Kim[1]; [1]Korea Institute of Materials Science
Corrosion behavior of Mg alloys containing Ca and Y was investigated. It was evaluated systematically depending on the casting process, heat treatment temperatures and surface coating for the wide application at different condition. In order to understand excellent corrosion resistance of Ca and Y containing alloys, we focused on the role of Y which makes the intermetallic compound easily with Al and Mn in commercial alloys during the melting. Also, it introduces field test results on several items which were made by die casting, billet making and extrusion processes for the application in railway, automotive and aerospace industries.

10:20 AM Invited
Development of Magnesium-Lithium Based Alloys for Space Applications:
The Relationship between Precipitation Hardening and Damping Capacity: F. Schott[1]; D. McKeown[1]; L. Jin[2]; *M. Celikin*[1]; [1]University College Dublin; [2]Shanghai Jiao Tong University
For developing lighter miniaturised satellite frame structures (CubeSat), which will allow additional payload as well as more design freedom, Magnesium-Lithium (Mg-Li) based alloys were investigated to potentially replace commonly used aluminium (Al) alloys. The effect of age-hardening treatment in comparison to Al-based alloys on damping performance were analysed using Dynamic Mechanical Analysis (DMA). Dynamic cantilever bending was performed for measuring viscoelastic properties and particularly the loss factor at varying temperatures under solution-treated, age-hardened and over-aged conditions. Moreover, thermally induced precipitates were characterized upon age-hardening treatment conducted at 150°C and 200°C. A direct link between the second phase formation and viscoelastic properties of the alloys was determined.

Cast Alloys I

Thursday AM | June 17, 2021

Session Chair: K. Sadayappan, CanmetMATERIALS

9:50 AM Invited
An Analysis of the Tensile Deformation Behavior of Commercial Die-cast Magnesium-aluminum-based Alloys: *M. Easton*[1]; H. Ang[1]; S. Zhu[1]; T. Abbott[2]; [1]RMIT University; [2]Magontec Ltd
Magnesium and its alloys have a complex progression of deformation mechanisms due to the hexagonal closed-packed crystal structure. Magnesium undergoes a series of different deformation modes as stress increases. The deformation behavior is marked by the commencement of elastic (Stage I), followed by basal slip and twinning (Stage II), prismatic slip (Stage III) and finally pyramidal slip (Stage IV). In this study, the deformation behavior of a range of commercial die-cast magnesium-aluminum-based alloys are analyzed. Four distinct stages of strain hardening can be seen in the tensile stress–strain curve and these are modeled according to the assumption that they correspond to the four deformation mechanisms. It is shown that both Stages I and III can be described by a linear equation while Stages II and IV follow a power-law relationship and fitted with Hollomon's equation. A semi-empirical equation is proposed to model the entire stress–strain curve.

10:20 AM Invited
Development of a Mg–RE Based Die-cast Magnesium Alloy for Elevated Applications: *X. Dong*[1]; L. Feng[1]; E. Nyberg[2]; S. Ji[1]; [1]Brunel University London; [2]Tungsten Parts Wyoming
Magnesium (Mg) alloys capable of operating at working temperatures above 200 °C and having the ability to be produced using high pressure die casting for high-volume manufacturing are developed. Such cost-effective methods are required for manufacturing critical parts for internal combustion (IC) engines such as those used in power tools. Here we introduce the variables in Mg–RE based alloys and the die-casting process. The new Mg–RE die-cast alloy shows excellent ambient and high temperature tensile strength and creep resistance. In addition, the new Mg–RE alloy also shows good stiffness and thermal conductivity, which are key advantages for alloys used at elevated temperatures.

LPSO & MFS Structures I

Thursday AM | June 17, 2021

Session Chair: Y. Kawamura, Kumamoto University

9:50 AM Invited
Disclination in Connecting Kink Bands Formed By Multiple Basal Slips: *T. Inamura*[1]; Y. Shinohara[1]; R. Matsumura[1]; [1]Tokyo Institute of Technology
The geometry of the kink band formed by multiple basal slips was formulated and the connection between the kink bands was examined using rank-1 connection. We proved that any two kink bands formed by any multiple basal slips can be rank-1 connected to each other. In addition to the wedge disclination, a mixed disclination at the junction of the two kink bands was found. The three-dimensional morphology of the connecting kink bands was sensitive to the mixing ratio of the basal slips in each kink band. Origin of the complexity of the kink microstructure is discussed based on the energy of disclinations that is inevitably formed in the connecting kink bands.

10:20 AM Invited
Highstrength Ductile Rapidly Solidified Mg-Zn-Y Alloys with Low Amount of LPSO Phase: *D. Drozdenko*[1]; M. Yamasaki[2]; K. Máthis[1]; P. Dobron[1]; P. Lukác[1]; N. Kizu[2]; S. Inoue[2]; Y. Kawamura[2]; [1]Charles University; [2]Kumamoto University
The present work is aimed at investigating dilute Mg-Zn-Y alloys prepared by the consolidation of rapidly solidified ribbons. The effect of the minor variation in composition (particularly, Zn and Y vary between 1-2 at. %) and the metal flow rate during extrusion (as a part of processing procedure) on the microstructure and resulting mechanical properties has been studied. Alloys have bimodal microstructure including non- and dynamically recrystallized grains with an overall average grain size of 1 µm. Mechanical performance is correlated to characteristics of the microstructure, such as dispersion of Zn- and Y-rich stacking faults and LPSO phase, grain size, etc. Inhomogeneous internal strain distribution in the bimodal microstructure was found to be of key importance. Digital image correlation technique was used to characterize the yielding behavior in detail. The investigated alloys have shown comparable tensile properties to the world record holders - Mg-Zn-Y alloys prepared by powder metallurgy.

Wrought Alloys III

Thursday AM | June 17, 2021

Session Chair: Z. Zhen, Magontec Asia

9:50 AM Invited
Highly Deformable Mg–Al–Ca Alloy with Al2Ca Precipitates: *L. Wang*[1]; G. Zhu[1]; X. Zeng[1]; [1]Shanghai Jiao Tong University
Magnesium (Mg) is the lightest structural metal. However, the poor formability of Mg alloys to great extent limits their applications in making structural parts. Formability is strongly correlated to both high tensile elongation and large work hardening capacity. Here, we report a new Mg-Al-Ca alloy in which a majority of deformable Al2Ca precipitates form while the formation of Laves phases of Mg17Al12 and Mg2Ca seems suppressed. Al2Ca precipitates imped dislocation motion, leading to large work hardening. Then, Al2Ca precipitates deform with dislocations and stacking faults under the enhanced flow stress, which relieve local stress concentration and improve tensile elongation. In addition, solutes Al and Ca suppress twin nucleation while promoting <c+a> dislocations in Mg. This new Mg-Al-Ca alloy demonstrates one of the highest combinations of tensile elongation and work hardening capacity among existing Mg alloys. Effect of Zn addition to this new alloy will also be discussed.

10:20 AM Invited
Microstructure and Mechanical Properties of Ultrahigh-strength Low-alloy Mg-Al-Ca-Mn Extrusion Alloys: *M. Zheng*[1]; X. Liu[1]; Z. Li[1]; X. Qiao[1]; [1]Harbin Institute of Technology
The development of high-strength wrought magnesium alloys are mostly based on strengthening from second phases. However, high number density of second phases reduces ductility and formability of Mg alloys. We developed new ultrahigh-strength low-alloy Mg-Al-Ca-Mn extrusion alloys by taking full advantage of fine-grain strengthening induced by ultrafine grains and grain boundary segregation-induced strengthening. The composition and extrusion parameters on microstructure and mechanical properties of low-alloy Mg-Al-Ca-Mn alloys were investigated. A Mg-1Al-1Ca-0.4Mn (wt%) alloy extruded at 200oC and extrusion rate of 1.5 mm/s exhibited TYS of 412 MPa, UTS of 419 MPa and elongation to failure of 12.0%, while a Mg-0.7Al-0.3Ca-0.4Mn (wt%) alloy extruded at 200oC and extrusion rate of 1.0 mm/s exhibited TYS of 412 MPa, UTS of 418 MPa and elongation to failure of 14.8%. The mechanism of microstructural evolution and strengthening mechanism of the ultrahigh-strength-low-alloy Mg-Al-Ca-Mn alloys were discussed.

Alloy Development II

Thursday AM | June 17, 2021

Session Chair: D. Sediako, University of British Columbia

Achieving Exceptionally High Strength in Mg-Al-based Magnesium Extrusions: *Z. Zeng*[1]; J. Nie[2]; N. Birbilis[1]; [1]Australian National University; [2]Monash University
Exceptionally high strength Mg-Al-Zn and Mg-Al-Ca-based alloys are demonstrated herein, revealing a yield strength of more than 380 MPa. In this study, AZ31 and Mg-Al-Ca-based alloys was extruded at different temperatures to reveal an exceptionally high strength with ultrafine grains. To reveal the origin of high strength in the developed alloy, the microstructure of Mg-Al-base alloys was compared with those of Mg-1Zn alloy and pure Mg with similar grain size and textures. The solute atoms were identified to be the key to alloy strengthening (~210 MPa). In contrast to grain boundary sliding and grain rotation that is observed submicron-grained pure Mg; the solute in submicron-grained Mg-Al-based alloys suppressed such intergranular deformation modes, with the grain boundaries in submicron-grained AZ31 providing significant strengthening (via the Hall-Petch relationship). The results herein reveal high strength Mg-alloys are readily achievable, the related concepts of which have implications for numerous Mg alloy systems.

Improving the Creep Resistance of Elektron21 by Adding AlN/Al Nanoparticles Using the High Shear Dispersion Technique: *H. Yang*[1]; Y. Huang[2]; K. Kainer[3]; H. Dieringa[2]; [1]Magnesium Innovation Centre; [2]Helmholtz-Zentrum Hereon; [3]Wroclaw University of Science and Technology
A novel high shear dispersion technique (HSDT) was used for the first time to effectively distribute AlN/Al nanoparticles (NPs) in Elektron21 (El21) magnesium alloy. Different high shearing speeds were adopted to investigate the optimum shearing speed for optimum daegglomeration of nanoparticles and enhancing the creep resistance of AlN/Al NPs reinforced El21 alloy. The results showed that the creep resistance of El21+0.5% AlN/Al nanocomposite increased with the increasing speed of HSDT. The individual/synergistic roles of AlN and Al were also systematically identified by comparing the microstructural evolutions and creep properties of El21, El21+0.25% Al, El21+0.75% AlN and El21+1% AlN/Al. The creep results showed that the mixture additions of AlN and Al NPs give a synergistic improvement on the creep resistance of El21 alloy compared to that with single addition of Al or AlN NPs.

The Influence of Ca on the Precipitation Behavior in a Mg-rare Earth Alloy: *Q. Shi*[1]; B. Williams[2]; A. Natarajan[3]; A. Van der Ven[3]; J. Allison[1]; [1]University of Michigan; [2]CanmetMATERIALS; [3]University of California, Santa Barbara
The potential effect of Ca for improving the precipitation strengthening of Mg-rare earth (RE) alloy system has not been well explored. In this study, a systematic characterization of precipitation behavior during the aging process was conducted for a Ca-containing Mg-Nd-Y alloy. In this quaternary alloy system, a very similar precipitation type and evolution sequence was observed compared to Mg-Nd-Y ternary alloy system. The clustered combination of ß'''' and ß' precipitates accounted for the aging peak at 200°C. Both TEM-EDS and APT characterization showed the Ca segregation in both ß'''' and ß' metastable strengthening phases. This indicates the positive effect of Ca to promote precipitation in Mg-RE alloys and thus enhance precipitation strengthening. The current results provide the possibility for using Ca as an alternative alloying element to reduce the level of RE elements and expand the commercial use of high strength Mg-RE alloys.

Understanding the DSA Phenomenon in Extruded Mg-Rare Earth Alloys throughout In-situ Synchrotron Diffraction and Acoustic Emission Experiments: *G. Garces*[1]; P. Pérez[1]; B. Chávez[2]; R. Barea[2]; K. Mathis[3]; K. Guan[4]; D. Egusa[4]; E. Abe[4]; P. Adeva[1]; [1]Cenim-CSIC; [2]Universidad Nebrija; [3]Charles University; [4]The University of Tokyo
To analyze and explain the phenomenon, in-situ synchrotron radiation and acoustic emission experiments during compression tests have been performed in a binary extruded Mg-RE (Y, Gd and Nd) alloy with the addition of transition metals. The compression tests have been carried out at temperatures between 25-300°C and strain rates in a range of 4×10-5 - 8×10-3 s-1, conditions in which the DSA phenomenon appears. The experiments of synchrotron radiation and acoustic emission indicate that serrations are associated with simultaneous competitive movement of diffusing solute atoms and mobile dislocations or twin boundaries taking place during plastic deformation. In addition to the pinning of mobile dislocation, the segregation of rare earth and transition metals atoms at twin boundaries results in an additional source of the serration flow.

Cast Alloys II

Thursday AM | June 17, 2021

Session Chair: A. Luo, Ohio State University

Effects of Impurity Fe on Intermetallics in AZ91: *L. Peng*[1]; J. Xian[1]; C. Gourlay[1]; [1]Imperial College London
In the Mg industry, Mg-Al alloys are commonly melted/held in steel crucibles and Fe can be picked up into the melt to form Al-Mn-(Fe) intermetallic compounds (IMC) which can be potent micro-galvanic cathodes for corrosion. In this study, AZ91 was held in small Fe-0.2C crucibles at a wide temperature range of 640 – 850 ˚C for 4 h to obtain a different level of impurity Fe in the melt, followed by cooling at rate ~4 K/s. It is found that the increasing Fe content led to an increasing volume fraction of two Fe-rich phases: B2-Al(Fe,Mn) and Al_5Fe_2, and caused a change in morphology of the Al_8Mn_5 and $Al_{11}Mn_4$ particles. Direct contact between B2-Al(Fe,Mn) and Mg, and Al_5Fe_2 and Mg was observed at higher Fe content. The nucleation and growth of these IMCs was measured and is discussed.

Recent Studies on Grain Refinement of Magnesium Alloys: *S. Jung*[1]; Y. Son[1]; Y. Park[2]; Y. Lee[1]; [1]KITECH; [2]Pusan National University
Grain refinement of Mg alloys has been major research topic over the past decades, because it has been considered as one of the effective approaches to increase the strength and ductility, simultaneously. Among the various methods, superheating method is an effective grain refinement method of Mg-Al alloys. This process involves heating the melt to about 150~260 above the liquidus temperature, followed by a rapid cooling to the pouring temperature. With the simple control of the melt, a successful grain refinement can be achieved for grain refinement of Mg-Al alloys. However, a clear mechanism has not yet been identified yet. In this study, literatures of recent grain refinement studies were studied in detail, and experiments were performed to clarify the grain refining mechanisms of Mg–Al alloys by superheating. Grain size of Mg-Al alloys were analysed before and after superheating and intermetallic particles were thoroughly investigated using vacuum filtering technology.

Intermetallic Formation during Solidification of a Mg-Sn-Al-Zn-Mn Alloy: *Y. Deng*[1]; G. Zeng[1]; C. Gourlay[2]; [1]Central South University; [2]Department of Materials, Imperial College London
Multicomponent Mg-Sn-Al-Zn-Mn alloys involve the formation of multiple primary and eutectic intermetallics during the solidification process. Here, the formation of intermetallics in Mg-4Sn-3Al-1.5Zn-0.6Mn (TAZM4310) (wt.%) as-cast alloys was studied using thermodynamic calculations and analytical scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) detectors. The as-cast microstructure consists of Al-Mn intermetallics, \945-Mg, Mg_2Sn, tau-MgAlZn, and $Mg_{17}Al_{12}$ phases. Al-Mn phases were identified as Al_8Mn_5 and tau-AlMn with different morphologies, from both composition and crystal structure. We also found that most of the Mg-Al-Zn particles with >10 at.% Zn content were tau-MgAlZn phase in the alloy. Mg_2Sn often co-existed with $Mg_{17}Al_{12}$ and tau-MgAlZn phase, forming multi-phase particles. The results have implications for understanding microstructure evolution of Mg-Sn-Al-Zn-Mn alloys during the solidification process, especially the intermetallic phases involved.

Solute and Precipitate Effects on Recrystallization Kinetics of Ce-containing Mg Alloys: *G. Storey*[1]; S. Sutton[2]; D. Hartman[2]; A. Clarke[1]; K. Clarke[1]; [1]Center for Advanced Non-Ferrous Structural Alloys, Colorado School of Mines; [2]Mag Specialties Inc.
Recrystallization kinetics of magnesium alloys can vary greatly based upon precipitate and solute content. Rare earth alloying elements, such as Ce, have been shown to improve the elevated-temperature properties of magnesium alloys. Quantifying the effects of precipitate fraction and solute content can result in fundamental understanding that will enable optimized industrial processing pathways. The baseline composition for this study is ZK60, with modified zinc and cerium additions. These alloying modifications result in variations in second phase insoluble particle type, volume fraction and distribution that have strong effects on both grain size and recrystallization. Here, we present quantitative determinations of precipitate and solute content as a function of alloying and relate these aspects to recrystallization kinetics. These results provide further insights into mechanical and microstructural characteristics, such as grain size distribution, texture, and hot working flow stress, which are affected by enhanced or retarded recrystallization kinetics.

Deformation & Mechanical Behaviors II

Thursday AM | June 17, 2021

Session Chair: M. Barnett, Deakin University

The Role of Intermetallic Particle Morphology and Position in Twin Transmission across Grain Boundaries: *B. Anthony*[1]; V. Miller[1]; [1]University of Florida
Deformation twins in magnesium alloys contribute to early failure during room temperature forming by providing void nucleation sites and preferential crack pathways. This is particularly true for instances of twin transmission where the stress imposed at a grain boundary by a twin nucleates a new twin in the neighboring grain, leading to thicker twins and longer continuous twin boundaries. Many commercial alloys feature coarse intermetallic particles at the grain boundaries in their as-solidified state, but the role of these particles in modifying twinning behavior has only been studied computationally. Experimental validation via electron backscatter diffraction is used to perform a statistical analysis of twinning in thixomolded AM60 with varying particle volume fractions to determine their effect on twinning behavior and transmission frequency, particularly with respect to size, aspect ratio, and distance from the impingement site.

The Role of Dislocation Climb in the High Temperature Deformation of Mg alloys AZ31B and ZK10 and the Distinctions in the Activity of Dislocations with a c-type Burgers Vector: *M. Ritzo*[1]; S. Agnew[1]; [1]University of Virginia
Tensile samples of a Mg alloys AZ31B and ZK10 sheet were tested at a range of temperatures and strain rates designed to rather evenly probe a similar range of Zener-Hollomon (Z) parameter values. A version of the viscoplastic self-consistent (VPSC) code, which accounts for the kinematics of dislocation climb, is used to model the behavior. Both alloys exhibit a transition in the r-values and texture evolution at some value of Z. Below this critical value the constitutive response transitions to a power law and the modeling reveals that dislocation climb plays a significant role in strain accommodation. While the behavior of AZ31B does not demand activity of dislocations with a c-type Burgers vector, the ZK10 alloy does. TEM-based investigation of dislocations in samples deformed above and below the aforementioned transition is employed to provide an explanation for the distinct behavior of the two alloys.

Continuous ECAP Processing of Mg Alloys: *A. Griebel*[1]; C. Davis[2]; J. Schaffer[1]; T. Lowe[2]; [1]Fort Wayne Metals; [2]Colorado School of Mines
Nutrient metal implants designed to absorb into the body over time promise a future with fewer follow up surgical procedures and long-term complications. Alloys based on magnesium hold the most promise for widespread implementation in these applications. Absorbable magnesium devices generally benefit from materials with increased strength, ductility, and localized corrosion resistance. High shear deformation techniques like ECAP can improve properties in each of these three categories. Continuous ECAP processing offers ultrafine grain benefits of traditional ECAP, but on a production-level scale. This presentation will review the implementation to-date of continuous ECAP processing on Mg alloys.

An Investigation of the Mechanism of the Negative Strain Rate Sensitivity of Mg Alloys: *M. Shabana*[1]; L. Capolungo[2]; S. Agnew[1]; [1]University of Virginia; [2]Los Alamos National Laboratory
Many solute strengthened alloys exhibit dynamic strain aging (negative strain rate sensitivity and often serrated flow) at particular strain rates and temperatures, and Mg alloys are no exception. It has for some time been suggested that interactions between mobile and forest dislocations are required to explain these phenomena. In a seminal work published in 2004, Picu outlined a specific mechanism for the negative strain rate sensitivity of dilute solid solutions and performed a parametric investigation of the Lomer lock case relevant to FCC alloys. In the case of HCP Mg alloys, the interactions between basal and prismatic dislocations do not have any such locked configurations. Rather, annihilation and glissile junction formation are the relevant cases. A parametric study is performed in which mobile basal dislocations encounter prismatic forest dislocations and vice versa. Implications for dynamic strain aging in Mg alloys are discussed.

Effect of Gd and Nd Additions on the Mechanical Behaviors of Extruded Mg Alloys: *Y. Xu*[1]; S. Wang[2]; Y. Wang[2]; L. Xiao[2]; N. Hort[3]; [1]Chongqing Academy of Science and Technology; [2]Shanghai Spaceflight Precision Machinery Institute; [3] MagIC-Magnesium Innovation Center, Helmholtz-Zentrum Geesthacht
The influence of alloy elements and heat treatment on the microstructure and mechanical behaviors of four extruded Mg–Gd–Nd ternary alloys are discussed in this study. The grain sizes of extruded alloys decrease from 26 to 5 μm with alloy content increasing after extrusion. The mechanical test results show that both Gd and Nd have positive effect on the hardness, yield strength and Young's modulus. The ultimate tensile strength (UTS) is enhanced by Gd, but decreased with Nd content. The elongation of alloys is lower with higher alloy elements. Those extruded alloys were aged for 200 h in 200. The Young's moduli are decreased by ageing treatment. Combined with microstructure study, part of reinforcement which identified as Mg5(Gd,Nd) phase is solved in Mg matrix. On the other hand, the ß' precipitates were distributed in grains which leads the great improvements of yield strength.

Effect of Adding Third Element on Deformability of Mg-Al Alloy: *K. Senoo*[1]; T. Nakatsuji[1]; N. Ikeo[1]; M. Yamaguchi[2]; T. Mukai[1]; [1]Kobe University; [2]Japan Atomic Energy Agency
In recent years, magnesium is expected to be used as a structural material in vehicles. Since limited slip systems in magnesium induces marked yield anisotropy and poor deformability at room temperature, there is a certain demand for developing magnesium alloys having improved plastic anisotropy. In this study, we focused on the Mg-Al system alloy, which is widely used in commerce, and examined a third element that contributes to improve the plastic anisotropy. Generalized stacking fault energy (GSFE), which corresponds to the energy for sliding atomic layer along a slip plane, was calculated in the first-principles calculations to estimate deformability of ternary Mg-Al-X alloys adding the third element, X, to the Mg-Al binary alloy. As a result, it was suggested that the addition of zirconium contributes most to the reduction of plastic anisotropy. Mechanical characterization revealed the effect of the third element on the deformability at room temperature.

LPSO & MFS Structures II

Thursday AM | June 17, 2021

Session Chair: M. Itakura, Jaea

Atomic-resolution Characterizations of Deformation Twins in Mg-Gd Alloys: *K. Guan*[1]; D. Egusa[1]; G. Garces[2]; E. Abe[1]; [1]The University of Tokyo; [2]National Centre for Metallurgical Research (CENIM-CSIC)
As one of the important deformation mechanisms, twinning plays a crucial role in plastic deformation and eventually in controlling the formability and mechanical properties of Mg alloys. In this work, extruded Mg-Gd alloys were compressed at 150 \176C and 200 \176C, and the corresponding compression curves exhibit obvious serrations. We investigated twin boundaries in the samples compressed to 4 % plastic strain by atomic-resolution high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). The results indicate that numerous Gd atoms distinctly segregated at the interface between {10-12} twin and matrix, and the Gd-rich plane is always separated by steps. It is interesting to note that the average step height in samples with large serrations is greater than that in those with small serrations. Therefore, we deduce that the strong interaction between solute atoms and twin boundary leads to stress drops in serrated stress-strain curves.

Direct Observation of Solute Segregations at Kink Boundaries in LPSO-type Mg Alloys: *D. Egusa*[1]; K. Inoue[2]; Y. Nagai[2]; E. Abe[1]; [1]The University of Tokyo; [2]Tohoku University
Mg alloys containing long period stacking/order (LPSO) phase have gathering wide attention because of their excellent mechanical properties, which are believed to be derived from their unique deformation modes, "kinking". In the present study, we have investigated atomic structure of kink boundary (KB) in a hot-extruded Mg-Zn-Y alloy, based on scanning transmission electron microscopy (STEM) and atom-probe tomography (APT). STEM observations show that KBs are composed of arrays of extended basal dislocations that selectively locates on solute-enriched stacking faults (SESF) in the LPSO structure. Introduction of such dislocations on SESF causes structural reconstruction, forming local hexagonal close-packed Mg region within SESF. Atomic-scale STEM/APT observations reveal that a composition of such local hcp regions becomes as dilute as that of Mg matrix in this alloy. This significant reconstruction should enhance a thermal stability of kink microstructure, which is essential for understanding mechanical properties of the Mg-Zn-Y alloys at elevated temperature.

Attempt to Apply X-ray Fluorescence Holography to a Grain of Mille-Feuille Structure Mg Alloys: *K. Kimura*[1]; D. Egusa[2]; H. Miyazaki[1]; A. Ang[1]; S. Kashima[1]; Y. Yamamoto[1]; N. Happo[3]; T. Matsushita[4]; E. Abe[2]; K. Hayashi[1]; [1]Nagoya Institute of Technology; [2]The University of Tokyo; [3]Hiroshima City University; [4]Nara Institute of Science and Technology
Mg alloys containing Zn and rare earths (RE) have been received increasing attention owing to their superior mechanical properties. It has been reported that Zn and RE form clusters, which should play an important role in strengthening these alloys. X-ray fluorescence holography (XFH) is a powerful tool to visualize a three dimensional atomic arrangement around a selected element. XFH has been applied to Mg-Zn-Y alloys to characterize the $L1_2$-type Zn_6Y_8 clusters. However, XFH requires mm size single crystals, which has been restricted the range of application of this technique. In particular, almost all Mg-Zn-RE alloys can not be obtained in the single crystal form. In this study, we attempt to apply XFH technique to a grain of polycrystalline $Mg_{97}Zn_1Gd_2$ using a micro beam X-ray and a two dimensional detector to record Zn-Kα holograms. We will discuss the pattern of the obtained hologram in comparison with the calculated results.

Analysis of Local Elasticity in Mille-feuille Structured Magnesium Alloys: Y. Urakawa[1]; *D. Egusa*[1]; M. Itakura[2]; E. Abe[1]; [1]The University of Tokyo; [2]Japan Atomic Energy Agency

Mille-feuille structured (MFS) materials, in which hard layers and soft layers are alternately laminated, exhibit high strengths by hot working. Although their strengthening mechanisms are still unclear, the inhomogeneous properties between the hard layers and the soft layers is accepted to be playing a large part. In the LPSO structure, the elastic properties of hard/soft layers can be estimated by macroscopic investigations of nearly single crystalline specimens, however it is difficult for MFS owing to their low degree of order. In the present study, we have investigated the elastic property of solute enriched layers in the MFS of Mg-Zn-Y alloy, based on STEM direct observations, the linear elastic model and first-principles calculations. We estimated Young's Modulus of Zn/Y enriched layers, based on the linear elastic model, resulting to suggest that Zn/Y enriched layers are indeed behave as hard layers in MFS Mg alloys.

Evaluation of Residual Strain Distributions around Ridge-type Kinks in a Single-phase Mg-6at%Zn-9at%Y Alloy by Synchrotron X-ray Radiation: *T. Miyazawa*[1]; R. Namba[1]; T. Fujii[1]; S. Yamasaki[2]; M. Mitsuhara[2]; H. Nakashima[2]; [1]Tokyo Institute of Technology; [2]Kyushu University

Mg-Zn-Y alloys have a typical mille-feuille structure which is named long-period stacking ordered (LPSO) phase consisted of alternative stacking of hard and soft layers. It has been known that the LPSO phase can be plastically deformed with forming kinks during compressive deformation. In this study, to investigate the kink formation mechanism, residual strain distributions around ridge-type kinks in a compressively deformed LPSO single phase specimen were measured by the energy-dispersive X-ray diffraction microscopy with synchrotron white X-ray. Tensile strain remained locally near by the tips of ridge-type kinks after unloading. This is caused that grain boundaries inhibit bending of basal planes due to the formation of kinks. There were local residual strain distributions which were asymmetric with respect to the ridge-type kinks. This result is consistent with the asymmetric pre-kink formation mechanism before development of the ridge-type kinks.

In-situ Analysis on LPSO Formation from Amorphous Mg85Y9Cu6 Alloys: *H. Okuda*[1]; S. Lin[1]; M. Yamasaki[2]; Y. Kawamura[2]; S. Kimura[3]; [1]Kyoto University; [2]Kumamoto University; [3]JASRI

Effect of substitution of transition elements from Zn to other 3d elements on the formation and stability of LPSO structures is an interesting subject to understand microstructure control of the alloys. In the present work, phase transformation process in amorphous Mg85Y9Cu6 alloys during heating the sample at a constant rate of 10 K/min. has been analyzed by in-situ small- and wide- angle scattering/diffraction measurements. Results were compared with those previously obtained for Mg85Y9Zn6 alloys, which we have examined in detail[1]. Present results suggest that the tendency to form solute clusters in supersaturated hcp matrix is far less remarkable when compared with that for MgYZn alloys. Nucleation sites of the LPSO crystallites were found to be different when compare the path with the MgYZn alloy under the same heat treatments.[1] H.Okuda et al., Acta Mater. 194(2020)587.

Developments of Resonant Small-angle Scattering Mearuements for Contrast Control at the Mg K Absorption Edge: *H. Okuda*[1]; S. Lin[1]; R. Sakohata[1]; S. Kimura[2]; Y. Temenori[2]; Y. Kitajima[3]; [1]Kyoto University; [2]JASRI; [3]KEK-PF

Small-angle scattering is a useful approach for examining quantitative analysis of precipitation nanostructures, and also of compositional fluctuations in alloys. We would like to present our recent developments on resonant small-angle scattering measurements made at the K absorption edge of light metals, in particular, at Mg. Since the photon energy of such absorption edge are in the so-called tender X-ray region, i.e., around 1 keV, there are several experimental difficulties to overcome. By using the resonant scattering, control of contrast for Al3Mg nano precipitates in Al-Mg alloys and MgO nanoparticles supported on polymer membranes were confirmed.Present approach is expected to be useful in examining not only the precipitation nanostructures or Mg nanostructures such as nanoparticles and pillars, but also the average structure in multilayered microstructures having large distribution.

Kink Deformation Dynamics of LPSO Alloy in the Experimental View Point of Multilayer Structure Deformation: *K. Aizawa*[1]; W. Gong[2]; S. Harjo[1]; T. Kawasaki[1]; [1]Japan Atomic Energy Agency; [2]Kyoto University

We discuss a dynamics of kink deformation for Mg-based LPSO alloy, using neutron diffraction data and AE data. We treat the kink deformation of LPSO alloy as an example for multilayer structure deformation with large deflection, namely kink structure, chevron structure, etc. and try to characterize its dynamics features.

Fundamental Research

Friday AM | June 18, 2021

Session Chair: S. Agnew, University of Virginia

8:00 AM Plenary

Accelerating Predictive Understanding of Microstructural Evolution and Mechanical Behavior of Magnesium Alloys: *J. Allison*[1]; [1]University of Michigan

The Center for PRedictive Integrated Structural Materials Science (PRISMS) is creating and disseminating a unique open-source capability for accelerating the scientific understanding of magnesium alloys. A central component of this framework is a suite of high performance, open-source multi-scale computational tools for predicting microstructural evolution and mechanical behavior. These are used in conjunction with advanced experiments in integrated scientific "Use Cases" focused on topics such as predicting the evolution of precipitates in Mg-rare earth alloys, their subsequent influence on mechanical behavior and quantification of alloying effects on the evolution of deformation twins during monotonic and cyclic loading. A third thrust is providing this information to the community via an information repository called the Materials Commons. This talk will review the Center's progress and plans.

8:30 AM Plenary

Dislocation-particle Interactions in Magnesium Alloys: *M. Perez Prado*[1]; [1]IMDEA Materials Institute

Precipitation constitutes a microstructural design tool that has been utilized successfully to strengthen metals such as, for example, aluminum alloys and nickel superalloys. However, particle hardening has proven significantly less effective in magnesium, thus severely limiting the possibilities for structural alloy design. Exploiting the hardening potential of precipitates in magnesium alloys requires a profound understanding of the interaction between dislocations and precipitates. Basal dislocations are usually the main strain carriers, although non-basal slip systems may also become active and play a key role. The relative contribution of each mechanism depends on testing conditions, composition, microstructure and texture. This lecture will review recent research on dislocation-particle interactions in magnesium alloys using a combined approach including micromechanical testing, slip trace analysis, and high resolution transmission electron microscopy. The interaction of basal and non basal dislocations with particles of different sizes and orientations with respect to the matrix will be discussed.

9:00 AM Plenary
Effects of Interfaces on Deformation Twinning Behavior at the Mesoscale: *I. Beyerlein*[1]; [1]University of California, Santa Barbara
There are a wide range of structural applications that desire advanced materials with high strength-to-weight ratios in combination with other outstanding mechanical properties. Mg alloys offer a potential solution, but successful incorporation of Mg alloys into engineering designs is, however, hindered by their limited plasticity. One of the important and puzzling underlying mechanisms governing their plastic behavior is deformation twinning, which form in these materials under straining. The development of twins both inside the crystal and at crystalline interfaces has mostly been addressed at the atomistic scale level. In our research, we employ crystal plasticity-based micromechanics model to establish and understand the effects of material interfaces, whether they arise from free surfaces, grain boundaries, phase boundaries, or precipitates, on the expansion of twin embryos, twin-tip propagation and twin boundary migration. In this talk, recent results from a number of modeling and experimental studies will be presented and discussed.

Deformation

Friday AM | June 18, 2021

Session Chair: M. Perez Prado, IMDEA Materials Institute

9:50 AM Invited
Effect of Phase Morphology on Microscopic Deformation Behavior of Mg-Li-Gd Dual-phase Alloys: J. Li[1]; *L. Jin*[1]; J. Dong[1]; W. Ding[1]; [1]Shanghai Jiao Tong University
Three dual-phase Mg-6Li-2Gd, Mg-7Li-2Gd and Mg-8Li-2Gd (wt.%) alloys, with different morphology of ß-Li and a-Mg phases, were fabricated by hot extrusion and then in-situ tension tested at room temperature (RT). Digital image correlation (DIC) technique and slip trace analysis were utilized to investigate the effect of phase morphology, including the size and configuration of ß-Li and a-Mg phases, on the microscopic deformation behavior of Mg-Li-Gd dual-phase alloys. The small a-Mg phase enclosed in a three-dimensional continuously connected network of ß-Li phase in Mg-8Li-2Gd (wt.%) alloys was observed to be distributed homogeneously by fine slip traces and triggered a large amount of deformation. The different microscopic deformation behaviors were thus discussed.

10:20 AM Invited
Quantification of Cyclic Twinning-detwinning Behavior During Low-cycle Fatigue of Unalloyed Mg and a Mg-Al Alloy Using High Energy X-ray Diffraction: *A. Murphy-Leonard*[1]; D. Pagan[2]; A. Beaudoin[3]; M. Miller[4]; J. Allison[5]; [1]Ohio State University; [2]Pennsylvania State University; [3]University of Illinois-Urbana Champaign; [4]Cornell University; [5]University of Michigan
The cyclic twinning and detwinning behavior of unalloyed Mg and a Mg-Al alloy was investigated using in-situ high energy X-ray diffraction (HEXD) under displacement controlled, fully-reversed low cycle fatigue conditions. Measurements were conducted at three levels of applied strain. At strain amplitudes greater than 0.5%, tension-compression asymmetry was observed during cyclic loading and related to cyclic twinning and detwinning. The twinning and detwinning behavior were characterized by monitoring the evolution of X-ray diffraction peaks associated with the basal {0002} planes throughout selected cycle. At strains greater than 0.5%, in-situ HEXD results show that twinning occurs during the compression portion of the cycle and, at early stages of fatigue, most twins are detwinned under reversed loading during the tensile portion of the cycle. After a number of fatigue cycles, the detwinning process was observed to be incomplete and residual twins remained throughout an entire cycle.

Formability

Friday AM | June 18, 2021

Session Chair: D. Klaumunzer, Volkswagen AG

9:50 AM Invited
How Useful is Grain Refinement for Improving the Ductility of Magnesium Alloys?: *M. Barnett*[1]; [1]Deakin University
This presentation discusses the failure of magnesium alloy AZ31 during tension, compression and bending. The aim is to determine how useful grain refinement is for extending the room temperature ductility. The ductility of a series of test samples is examined using X-ray microtomography. Using this approach enabled us to characterize void nucleation, growth and linkage during tensile loading. We conclude the impact of grain size on void growth is the critical factor. Voids grow faster in coarse grained samples and this hastens failure. The mechanism seems unique to tension and so some statements can be made regarding the impact of grain size on other deformations. The extent to which the conclusions can be generalized is also considered.

10:20 AM Invited
Controlling Deformation Twinning Through Microstructural Engineering: B. Anthony[1]; *V. Miller*[1]; [1]University of Florida
The stress states surrounding twin-boundary interactions have been widely studied in Mg and other hcp metals, but primarily for single phase alloys. In reality, many commercial Mg alloys contain a substantial volume fraction of hard micron-sized intermetallic particles, primarily located at grain boundaries. These hard particles alter the local stress state, but the role in twinning behavior had not been systematically explored. In this work, we use an elastoplastic fast fourier transform polycrystal plasticity code to systematically interrogate the role that grain boundary particles play in twin propagation, thickening, and transmission across the boundary. The implications for microstructural engineering for enhanced mechanical performance will be discussed.

Mechanical Behaviors

Friday AM | June 18, 2021

Session Chair: N. Hort, Helmholtz-Zentrum Hereon

9:50 AM Invited
Design of Ductile Mg Alloys by Tuning Hard <c+a> Dislocations into Easy Ones: *B. Li*[1]; Y. Shen[1]; Q. An[1]; [1]University of Nevada, Reno
Mg presents low strain to failure in c-axis compression, due to the fact that pyramidal dislocations, aka <c+a> dislocations, are hard to activate. Recent in-situ transmission electron microscopy study revealed that single crystal Mg could present very large plasticity (> 25%) in c-axis compression as a result of activation of high density, mobile <c+a> dislocations. It follows that if alloying elements that are able to lower the energy barrier to activating <c+a> dislocations can be identified, ductile Mg alloys can then be designed and processed. In this talk, we show that these alloying elements can be found by performing first principles high-throughput screening. In this approach, how alloying elements influence the generalized stacking fault energy on the pyramidal planes is calculated. Those elements that are able to reduce the unstable stacking fault energy, i.e. the energy barrier to dislocation nucleation and glide, are identified by combing through the Periodic Table.

10:20 AM Invited
The Indentation Size Effect in Mg Alloys: *W. Poole*[1]; S. Li[1]; G. Nayyeri[1]; [1]University of British Columbia
Instrumented indentation tests have received considerable recent attention for measuring the activity of slip systems in magnesium alloys. This approach has the advantage that single crystals are not required as tests can be conducted on polycrystalline samples. In this study, a range of magnesium alloys has been studied using instrumented indentation with a range of indenter tip radii from 1-250 μm. The indentation force-displacement curves were converted to indentation stress-strain curves using the approach of Kalidindi and co-workers. It was observed that there was a strong dependence of the indentation yield stress on the radius of indenter tip. A dislocation theory based model was developed to analyze the size effect. It was found that by extrapolating to an infinite indenter radius and calculating the resolved shear stress under the indenter, the critically resolved shear stress values obtained were in strong agreement with experimental results from single crystal.

Modeling I

Friday AM | June 18, 2021

Session Chair: J. Allison, University of Michigan

9:50 AM Invited
Atomistic Modeling in Mg and its Alloys: How does it help?: *W. Curtin*[1]; Z. Wu[2]; R. Ahmad[1]; B. Yin[3]; M. Stricker[4]; X. Liu[1]; [1]École Polytechnique Fédérale de Lausanne; [2]City University of Hong Kong; [3]Zhejiang University; [4]Ruhr University, Bochum
The strength and ductility in Mg and its alloys are controlled by phenomena that are fundamentally atomistic in nature, associated with the detailed behavior of the various dislocations in the hcp Mg crystal structure. This suggests that direct atomistic modeling and theory of atomistic deformation mechanisms can be useful for guiding the creation of new higher-performance alloys that are needed to make Mg technologically more useful. Here, we show a suite of simulations and/or theories demonstrating the specific dislocation phenomena that largely control Mg deformation. Examples include (i) the intrinsic transformation of the Pyramidal II <c+a> dislocation to a lower-energy, sessile, basal-dissociated structure, (ii) a Pyramidal cross-slip mechanism that enables ductility in alloys leading to a design map for achieving ductility in Rare-Earth-free alloys, (iii) solute strengthening of basal slip to decreasing plastic anisotropy, and (iv) the unusual observed features of prism slip revealed at the atomistic scale.

10:20 AM Invited
Mathematical Modeling of Multiple Effect Distillation of Magnesium: A. Telgerafchi[1]; M. Rutherford[1]; G. Espinosa[1]; *A. Powell*[1]; [1]Worcester Polytechnic Institute
Gravity-driven multiple-effect thermal system (G-METS) is a new method for potentially reducing both the cost and energy use of industrial magnesium distillation by as much as 90%. It uses gravity pressure head in standpipes to create pressure differences between effects, creating a cascade of multiple evaporations using heat of condensation. This talk will describe a detailed mathematical model of G-METS magnesium distillation including kinetics of alloy evaporation. Aspects of the model describe counter-flow evaporators and condensers which can separate volatile alloying elements such as zinc. Validating experiments include one- and two-effect batch distillation of Mg alloys including Zn, Al, Mn, Fe, Ni and Cu. Finally, a new primary production flowsheet using G-METS distillation can potentially reduce the cost of magnesium below that of aluminum. And this can in turn potentially enable new uses of magnesium for grid energy storage and transportation.

Corrosion III

Friday AM | June 18, 2021

Session Chair: L. Villegas Armenta, McGill University

Improvement in the Corrosion Resistance of AZ31 Magnesium Alloy via a Composite Ccoating of the Zn-Ce LDH/Oxide: *V. Zahedi Asl*[1]; J. Zhao[1]; Y. Palizdar[2]; [1]Beijing University of Chemical Technology; [2]Materials and Engineering Research Center
The pH values of the solution, ratios of the cations, intercalated compounds, and hydrothermal conditions are the main parameters that influenced the LDH efficiency. In this paper, the composite of the Oxide/LDH coatings, containing Zn2+ and Ce3+/Ce4+ as metal cations, were prepared on the AZ31 substrate by a combined co-precipitation and hydrothermal processing method for the first time. To investigate the effect of Ce ions on the deposition of the suitable coating on AZ31, the LDHs with different ratios of the cations were synthesized. The comprehensive characterizations of the morphology, composition, structure, of the synthesized coatings, were investigated by SEM, XRD. PDP and EIS measurements were conducted to compare the corrosion behaviors of the coatings. The self-healing ability of the scratched samples was investigated. The finding of this study proves that a composite coating composed of the uniform scaffold-like clusters of the oxides incorporated with the LDH plates is successfully produced which can retard the corrosion of the AZ31 effectively.

Efficient Corrosion Potential Measurement Technique for Mg Alloy: Coupling of Scanning Micro Droplet Capillary Method and Alloy Diffusion Couple: *M. Kim*[1]; S. Gateman[2]; J. Mauzeroll[2]; I. Jung[1]; [1]Seoul National University; [2]McGill Univerisity
Corrosion behavior of Mg alloy is one of key factors to determine the applicability of Mg alloys to automotive and other electronic components. However, the corrosion measurement for Mg alloys is time-consuming and highly dependent on the sample preparations and other experimental environmental factors. In order to build up the corrosion map data for various Mg alloys depending on the alloy composition and microstructure, more efficient novel corrosion measurement technique is required. In this study, we would like to present new efficient corrosion measurement technique coupling scanning electrochemical microscopy (SECM) and diffusion couple of Mg alloys. Using 250-nm diameter micropipette tip in contact with the surface of Mg sample, SECM can allow to measure the variation of corrosion potential of Mg alloy across the diffusion couple in a single scan. As an example of new novel method, the corrosion potential data of the Mg/Al diffusion couple will be demonstrated.

Corrosion Protection of AZ80 and ZK60 Forged Magnesium Alloys with Micro-arc Oxidation and Composite Coating: *Y. Xue*[1]; X. Pang[2]; S. Luo[1]; X. Zhang[1]; J. Hamid[3]; [1]Xi'an Shiyou University; [2]CanmetMATERIALS, Natural Resources Canada,; [3]University of Waterloo

Wrought Mg alloys have attracted increasing attention for automotive applications due to their homogeneous microstructure and enhanced mechanical properties compared to as-cast alloys. However, in real service conditions Mg structural components are susceptible to early failures due to the synergistic effects of corrosion and mechanical loading, which severely hinder their high penetration in automotive industry. Therefore, the corrosion protection of Mg structural components is of crucial importance. In this work, AZ80 and ZK60 Mg alloys were forged under different temperatures, and then treated with micro-arc oxidation (MAO) and micro-arc composite coating (MCC) which is the MAO plus E-powder coating. The effects of forging processing parameters on the microstructure and corrosion properties of the alloys were analysed, and the corrosion performances of the MAO, MCC coated Mg alloys were characterized through salt spray corrosion test. Experimental results demonstrated that the MCC coating provided robust corrosion protection for the wrought Mg alloys.

Deformation & Mechanical Behaviors III

Friday AM | June 18, 2021

Session Chair: P. Wu, McMaster University

Influence of Extrusion Rate on Microstructure and Mechanical Properties of Magnesium Alloy AM60 and an AM60-based Metal Matrix Nanocomposite: *D. Giannopoulou*[1]; H. Dieringa[1]; N. Ben Khalifa[2]; J. Bohlen[1]; [1]Helmholtz-Zentrum Hereon; [2]Leuphana University Lüneburg

Metal matrix nanocomposites are attracting attention because of their great potential for improved mechanical properties or possible functionalization. These hybrid materials are often produced by casting processes, but they can also develop their property profile after hot working, e.g. by forging or extrusion. In this paper a commercial cast magnesium alloy AM60 is enriched with 1 wt.% AlN nanoparticles and extruded into round bars with varied extrusion rate. The same is carried out with the unreinforced AM60 in order to be able to determine the influences of the AlN nanoparticles in direct comparison. The influences of extrusion speed on the recrystallization behavior as well as of nanoparticles on the microstructure evolution and particle induced strengthening are discussed and assessed with respect to the resulting mechanical performance.

Comparison of Effects of Heat Treatment on Mechanical Properties and Microstructural Behavior of Extruded AZ31 and AM50 Magnesium Alloys: *I. Sapmaz*[1]; E. Kurtulus[1]; E. Özdogru[1]; A. Zeybek[1]; [1]Yesilova Holding

Magnesium alloys provide wide application areas due to their low density, high specific strength, and stiffness. However, HCP (Hexagonal Close Pack) crystal lattice structure of the magnesium can limit its formability. Thermomechanical processes like extrusion provide refined microstructure, better mechanical properties, and higher ductility than casting. Heat treatment is an effective way to enhance mechanical properties by means of precipitation hardening. In this study, tubular extruded profiles produced from AZ31 and AM50 Magnesium alloys were investigated. Profiles were artificially aged to get T5 condition. Tensile and hardness tests were carried out with the longitudinal specimens that were taken out parallel to extrusion direction. The effect of the heat treatment was presented associated with microstructural investigation via both optical microscopy and Scanning Electron Microscopy analysis of fracture surfaces. As a result, the effect of heat treatment process on the mechanical properties and microstructural behaviors of AZ31 and AM50 will be revealed.

Disproof of Pyramidal <c+a> Slip in Magnesium: *Y. Huang*[1]; [1]Brunel University London

The current studies and understanding of magnesium deformation related to non-basal pyramidal <c+a> dislocations are critically discussed. The atomic configurations and crystallographic features in association with non-basal pyramidal <c+a> dislocations 1/3<11-23>{11-22} and 1/3<11-23>{10-11} have been unambiguously revealed for the first time using computer software, demonstrating that possible <c+a> dislocation core structures would involve too many atoms on multiple lattice planes and the dislocations are physically impossible. Magnesium single crystals were compressed along its hexagonal c-axis and the deformation mechanisms and fracture behaviour were fully characterized. Experimental results showed no evidence of <c+a> slip during deformation and fracture over the full range of temperatures tested from 20 deg C to 500 deg C.

Understanding Plastic Instability in Mg-Mn-based Alloys: *S. Woo*[1]; R. Pei[2]; T. Al-Samman[2]; S. Yi[1]; [1]Helmholtz-Zentrum Geesthacht; [2]RWTH Aachen

Plastic instability, commonly known as the Portevin–Le Chatelier (PLC) effect, manifests itself as an unstable plastic flow during tensile tests of structural materials such as steels, Al, Cu and Mg-based alloys. This phenomenon has a strong influence on diverse material properties, especially ductility, which degrades as the strain sensitivity coefficient and fracture toughness decrease, leading to unexpected vulnerabilities in the service environment. However, respective mechanisms are not yet clearly identified, especially in magnesium alloys, and this phenomenon is controlled by more complicated and various factors depending on the material. This study aims to identify the micromechanical mechanisms of PLC effect in newly developed Mg-Mn-based alloys under variation of the temperatures and strain rates. Based on the tensile tests under various conditions, the conditions in which the PLC effect clearly occurs were selected, and the correlation with microstructural factors was examined.

LPSO & MFS Structures IV

Friday AM | June 18, 2021

Session Chair: H. Okuda, Kyoto University

Effects of Pre-straining and Heat Treatment on Room Temperature and Creep Strength in a Long Period Stacking Ordered Type Mg-Zn-Y Alloy: *M. Suzuki*[1]; T. Yamaguchi[1]; K. Hagihara[2]; [1]Toyama Prefectural University; [2]Osaka University

Long period stacking ordered (LPSO) type magnesium alloys have been investigated by many researchers because of their excellent mechanical properties and unique crystalline structures. In the present investigation, the effects of kink density and subsequent heat treatment have been investigated on compression strength in a directionally solidified (DS) Mg-Y-Zn based LPSO alloys. Kink boundaries were introduced heterogeneously in DS alloys and many dislocations are introduced within grains after room temperature pre-straining. Both of room temperature compression strength and creep strength increases with increasing the value of the pre-strain. Mechanical properties of pre-strained specimens improved by high temperature heat treatment at 750 K, whereas their strength was decreased by the heat treatment at 650 K. EBSD analysis revealed that some recovery/re-arrangement of kink bands were occurred during heat treatment at 750 K. This microstructural change was affected significantly by both of kink density and subsequent heat treatment conditions.

Tensile Strengthening of a Mg Alloy Containing 25-vol% LPSO by Hot Extrusion Revealed by Neutron Diffraction: *S. Harjo*[1]; W. Gong[2]; K. Aizawa[1]; T. Kawasaki[1]; M. Yamasaki[3]; Y. Kawamura[3]; [1]Japan Atomic Energy Agency; [2]Kyoto University; [3]Kumamoto University
Interesting mechanical properties changes were found in Mg97Zn1Y2 alloy containing about 25-vol% long-period stacking ordered phase (LPSO) in the HCP structured a matrix (aMg), by hot-extrusion. In situ neutron diffraction measurements during tensile loading were conducted on three Mg97Zn1Y2 alloys with different processes: as-casted, and after hot-extrusion at 623 K with extrusion ratios of 5.0 and 12.5, to elucidate the relation between the changes in microstructure by hot-extrusion with the changes in mechanical property. The yield strength of aMg increased by the hot-extrusion, but when the extrusion ratio increased the aMg yield strength ironically decreased. LPSO was found to be strengthened monotonically as the extrusion ratio increased. Detailed results of neutron diffraction will be discussed to explain the mechanical properties changes of Mg97Zn1Y2 alloy by hot-extrusion.

Mechanical Properties of Hot-compressed Mg-Y-Zn Alloys with LPSO Phase: Y. Nakasuji[1]; *M. Yuasa*[1]; H. Miyamoto[1]; H. Somekawa[2]; [1]Doshisha University; [2]National Institute for Materials Science
Wrought-processed Mg-Y-Zn alloys with long-period stacking ordered (LPSO) phase have exhibited high strength. The high strength is suggested to be related to the deformation kink bands formed by the wrought process. In the present study, hot compression tests were carried out on four types of cast Mg-Y-Zn alloys with the different volume fraction of the LPSO phase. After compression tests, deformation kink bands were observed in the LPSO phases, and the morphology differed depending on the compression temperature and the volume fraction of the LPSO phase. As the results of the hardness tests, the hardness shows a tendency with the increase of compressive strain or decrease of compression temperature. We discussed the microstructure including the morphology of the deformation kink band and the hardness.

Experimental Aspects of Kink and Pre-kink Formation Process in Mg-Zn-Y Alloy with LPSO Phase: *M. Mitsuhara*[1]; T. Tokuzumi[1]; S. Yamasaki[1]; H. Nakashima[1]; K. Hagihara[2]; T. Fujii[3]; [1]Kyushu University; [2]Osaka University; [3]Tokyo Institute of Technology
The kink band formation process in Mg-6%Zn-9%Y alloy with the long-period stacking ordered (LPSO) phase was investigated in detail by in-situ compressive test and observation by SEM, and it succeeded in capturing the microstructural change with no surface relief which should be called as the pre-kink band. Using the SEM and the TEM analysis, it clearly founded that the pre-kink band involves the mobile and angle-variable terminated-subgrain-boundaries which consists of edge dislocation arrays. We are now developing the formation model of the pre-kink and kink band based on the disclination motion.

Deconvolution Analysis of AE Due to Kinking in Mg-Y-Zn Alloy: *T. Shiraiwa*[1]; N. Hamada[1]; F. Briffod[1]; M. Enoki[1]; [1]University of Tokyo
Compression tests of directionally-solidified (DS) Mg-Y-Zn alloys with long-period stacking ordered (LPSO) phase were conducted to observe the kinking behavior by a combination of a high-speed camera and acoustic emission (AE) method. The formation and propagation of kink bands were successfully captured at a sampling rate of 5M FPS. The kink bands were generated in a time of several microseconds. In-situ observations of twinning in pure Mg were also performed for comparison. The formation speed of the kink bands was almost constant regardless of its length in DS Mg-Y-Zn alloy, whereas the formation speed of the twin band is correlated with its band sizes in pure Mg. In order to evaluate the dynamic behavior of kinking quantitatively, deconvolution analysis was conducted for AE waveforms corresponding to kink band formation. Based on the results of deconvolution analysis, the statistics of the dynamic behavior of kinking will be discussed.

Effect of Deformation Path on Work-hardening Behavior in Long-period Stacking Ordered Phase of Mg-Zn-Y Alloys: *N. Adachi*[1]; Y. Todaka[1]; I. Fukuoka[1]; H. Somekawa[2]; D. Ando[3]; M. Yuasa[4]; [1]Toyohashi University of Technology; [2]National Institute of Materials Science; [3]Tohoku University; [4]Doshisha University
Magnesium alloys with long-period stacking ordered phase are well known to have superior work hardening rate comparing with conventional magnesium alloys. Plastic deformation of long-period stacking ordered phase occurs though kink deformation with suppressing formation of twins. It is generally believed that kink-interfaces act as obstacles against slip deformation resulting in high work hardening rate. Therefore, it is important to control the fraction of kink-interfaces in the alloy during production process to achieve excellent mechanical properties. In this study, we have employed high-pressure torsion process which can switch a direction of shear strain during deformation, and the effect of deformation path on the formation of kink-interfaces has been investigated.

Fatigue and Fracture Behavior of Extruded Mg-Y-Zn Alloys Containing LPSO Phase: *F. Briffod*[1]; W. Yin[1]; T. Shiraiwa[1]; M. Enoki[1]; [1]University of Tokyo
The present study investigates the fatigue and fracture behavior of extruded Mg-Y-Zn alloys containing various amount of long-period stacking order (LPSO) phase. To this end, strain-controlled low-cycle fatigue, load-controlled high-cycle fatigue, and three-point bending tests are carried out. The results reveal a decrease in the fatigue life against the plastic strain amplitude with the increase in LPSO phase volume fraction but also an increase in the high-cycle fatigue limit. The latter one is associated with the decreasing presence of coarse equiaxed grains due to a higher recrystallization rate with the increase in LPSO content. Finally, bending tests reveals a shift in the fracture behavior from ductile to brittle with the increase in the LPSO phase volume fraction resulting in a decrease in fracture toughness. The present results are discussed in view of the different microstructural features of the a-Mg and LPSO phases.

In-situ Observation on the Formation Process of LPSO Structure in Mg Alloy by X-ray Absorption Spectroscopy: K. Ninomiya[1]; K. Itamoto[1]; K. Fujino[1]; *M. Nishibori*[1]; [1]Kyushu University
Long-period stacking (LPSO) type Mg alloy has the structure modulation and concentration modulation of the atomic arrangement in a long period. The LPSO structure has a hierarchical structure, which is composed of L_{12} clusters regularly arranged in-plane and out-of-plane. However, the formation mechanism of the LPSO structure has not yet been clarified.In this study, we have established the analysis method for the local structure of the L_{12} cluster by X-ray absorption spectroscopy and spectral simulation and considered the LPSO structure formation mechanism for $Mg_{97}Zn_1Gd_2$ alloys. In-situ observations of the X-ray absorption fine structure spectra at the Zn-K and Gd-K absorption edges were performed under isothermal conditions of 673K. As a result, it was found that the spectral change with the heat treatment time was successfully observed and that the 14H-LPSO structure of the $Mg_{97}Zn_1Gd_2$ alloy was formed in several steps.

Modeling II; LPSO & MFS Structures III

Friday AM | June 18, 2021

Session Chairs: J. Nie, Monash University; K. Hagihara, Nagoya Institute of Technology

Numerical Modeling of the Forging Response of a Magnesium Alloy Control Arm: *B. Williams*[1]; T. Kodippili[2]; J. McKinley[1]; S. Lambert[2]; H. Jahed[2]; [1]Canmetmaterials, Natural Resources Canada; [2]University of Waterloo

The pronounced temperature and strain-rate sensitivity of magnesium alloys were apparent during full-scale forging of control arm components. To achieve the required fatigue resistance of ZK60 and AZ80 control arms, it was necessary to forge at a low temperature of 300 °C. At this temperature, a slow strain-rate was used to ensure the force required for forging was within the available load capacity of the equipment. The final forging sequence required to achieve complete material fill of the component was determined through a combination of experimental forging and numerical simulations. The temperature and rate sensitivity of the alloys and the material model utilized in the simulations will be detailed. Differences between adaptive remeshing, Adaptive-Lagrangian-Eulerian (ALE) and Combined-Eulerian-Lagrangian (CEL) FEA methods for predicting large deformation under isothermal conditions will be discussed. The challenges of forging a complex shaped magnesium component are highlighted.

First-principles Study on the Stability of Vacancy Formation in a Mg-Zn-Y Alloy with Long-period Stacking Ordered Structure: *T. Tsumuraya*[1]; H. Momida[2]; T. Oguchi[2]; [1]Magnesium Research Center, Kumamoto University; [2]Institute for Science and Industrial Research, Osaka University

A dilute Magnesium (Mg) based alloy with a nominal composition of $Mg_{97}Zn_1Y_2$ exhibit a remarkable high tensile yield strength of 600MPa. This strength is coupled with a unique atomistic structure where a concentration of solute atoms (Zn, Y) appears on the (0001) plane in a few hcp Mg matrix layers. Shockley's partial dislocations occur in the concentrated solute atom layers. The stacking sequence is relatively long along the c-axis, and it refers to as long-period stacking ordered (LPSO) structure. In this study, to clarify the microscopic origin of the phase stabilities of LPSO structures, we calculate heats of formation and electronic structure of an Mg-Zn-Y alloy using first-principle calculations. We show how the geometry of solute clusters embedded in the Mg matrix affects electronic structure near the Fermi level that determines the structural stabilities. We also discuss the possible realization of vacancy formation in Mg-Zn-Y alloy using a convex hull.

Density Functional Theory Study of Solute Cluster Growth Processes in Mg-Y-Zn LPSO Alloys: *M. Itakura*[1]; M. Yamaguchi[1]; D. Egusa[2]; E. Abe[2]; [1]Jaea; [2]University of Tokyo

To predict the distributions of interstitial atoms in the solute clusters in LPSO alloys, and to determine the kind of elements present, it is necessary to identify mechanisms by which interstitial atoms are created. In the present work, we use density functional theory calculations to investigate growth processes of solute clusters, in order to determine the precise atomistic structure of its solute clusters. We show that a pair of an interstitial atom and a vacancy are spontaneously created when a certain number of solute atoms are absorbed into the cluster, and that all full-grown clusters should include interstitial atoms. We also demonstrate that interstitial atoms are mostly Mg, while the rest are Y; interstitial Zn atoms are negligible. This knowledge greatly simplifies the atomistic modelingof solute clusters in Mg-Y-Zn alloys.

Mesoscale Modeling of Kinks: *P. Cesana*[1]; [1]Kyushu University

Mg-based long-period stacking ordered (LPSO) alloys have attracted considerable attention over recent years due to their high strength, corrosion resistance and ignition temperature. Superior mechanical properties of LPSO depend strongly on a complex plastification pattern under loading and, in particular, on the formation of kinks, a mechanism that is yet to date largely elusive. In this talk we present recent advances in the modeling of kinks in the framework of non-linear elasticity. Our model consists of a Landau-type energy that is invariant under the full symmetry group of 2D (hexagonal or square) lattice. We perform FEM computations for rectangular (single-crystal) domains. We find the plastification pattern depends on the lattice symmetry and domain aspect ratio. Our results are in good agreement with a number of experimental observations of kinks both in LPSO structures and in single-crystals. This is a collaboration with G. Zanzotto (Padua) and E. Arbib (Milan).

FTMP-based Attempts Toward Kink Formation and Strengthening in MFS-Mg: *T. Hasebe*[1]; Y. Nawa[1]; [1]Kobe University

Identification of the kink formation/strengthening mechanisms in LPSO-Mg systems is attempted based on Field Theory of Multiscale Plasticity, where FTMP-incorporated FE simulations are conducted aiming at reproducing kinking processes and the attendant strengthening. The incompatibility-based relevant underlying microscopic degrees of freedom for kinking are introduced, by projecting it on to that manifested as a variable crystallographically compatible condition for additional shear deformation, i.e., R-1 connectivity, in addition to that for the slip modes. The targeted phenomena also include scale-free-like energy release characteristics together with the specific return maps based on the combined ND–AE technique. The simulated results successfully reproduce not only the kink morphologies but also the energy-releasing characteristics. Further examinations about the choice of the measure for driving the R-1 connectivity relationship lead us to conclude that non-uniform formation of the kinking regions can play pivotal roles in raising the flow stress, in addition to the other features.

Higher-order Gradient Crystal Plasticity Analysis of LPSO-structured Magnesium Using Meshfree Approach: *Y. Tadano*[1]; D. Kamura[1]; [1]Saga University

Magnesium alloys with the long period stacking order (LPSO) structure show the superior strength and are expected as the next generation structural material. In the LPSO materials, kink deformation is an important deformation mechanism as well as slip deformation in the crystalline scale and may be the origin of the material strengthening. In this study, a higher-order gradient crystal plasticity analysis is conducted to evaluate the stress field around kink band to understand the strengthening mechanism due to kink. The finite element method sometimes provides an improper solution in the higher-order gradient crystal plasticity analysis; therefore, the reproducing kernel particle method, which is a kind of meshfree method, is introduced into the higher-order gradient crystal plasticity analysis. A numerical analysis of a specimen with kind band is demonstrated using the present method, and it is shown that kind band increases the macroscopic flow stress of material.

Numerical Evaluation of Kink Banding in Mg-based LPSO Single Phase Alloy: *T. Mayama*[1]; K. Hagihara[2]; T. Ohashi[3]; Y. Mine[1]; M. Yamasaki[1]; Y. Kawamura[1]; [1]Kumamoto University; [2]Osaka University; [3]Kitami Institute of Technology

Kink banding in magnesium (Mg)-based long-period stacking ordered (LPSO) single phase alloy is studied by crystal plasticity finite element analysis, where basal and prismatic slip systems are taken into account. The numerical analysis reproduces formation processes of kink bands in single- and poly-crystals under various loading history including tensile, compressive or shear loading. While dominant kink-mode slip localization is developed by accumulation of basal slip, prismatic slip also produces slight kink bands under the conditions where basal slip system is hardly activated. Based on the numerical results, development mechanism of kink bands in LPSO is discussed in terms of lattice rotation and non-uniform deformation.

A Neural Network Approach for Approximating Simulation Predicted State Variables in a Preform Optimization Process: *T. Kodippili*[1]; S. Lambert[1]; A. Arami[1]; [1]University of Waterloo

An artificial neural network (ANN) assisted optimization framework is developed to improve the preform design process of a cast-forged magnesium AZ80 I-beam component. An entirely simulation-based optimization process would be computationally expensive and resource-intensive, limiting the searchable design space. A set of ANNs are trained – using finite element method (FEM) simulation data – on a subset of preform designs that are intelligently sampled from an optimized design space to predict state variable responses throughout spatially varying regions of the forging. The prediction accuracy of the ANNs will be discussed and compared with FEM simulations. The influence of the preform design on the material flow behavior will also be addressed.

Poster Session

Acoustic Emission Characteristics of Aqueous Corrosion in Mg-Zn-Y Alloys with Long-period Stacking Ordered Phase: *A. Furukawa*[1]; M. Yamasaki[1]; D. Drozdenko[2]; K. Mathis[2]; Y. Kawamura[1]; [1]Kumamoto University; [2]Charles University

Wrought Mg-Zn-Y alloys with long-period stacked ordered (LPSO) phase show excellent mechanical properties due to formation of multimodally heterogeneous microstructure during thermo-mechanical treatments such as extrusion and rolling. The multimodal microstructure in alpha-Mg/LPSO two-phase Mg-Zn-Y alloys consists of three regions: that is, dynamically recrystallized fine alpha-Mg grain region, hot-worked coarse alpha-Mg gain region, and LPSO phase grain region. The LPSO phase acts as alloy strengthening component. However, from viewpoint of corrosion engineering, it works as cathodic site, resulting in occurrence of Galvanic corrosion between alpha-Mg and LPSO phases. In previous studies, it has been attempted to unveil their complexed corrosion behavior using electrochemical measurements, but their corrosion processes have not been clarified yet. Therefore, in this study, corrosion processes of the alpha-Mg/LPSO two-phase Mg-Zn-Y alloy has been investigated by combination of electrochemical measurements and modern in-situ method – acoustic emission technique.

Development of Precipitation-hardenable Mg–Ag–Ca Sheet Alloys: *M. Bian*[1]; X. Huang[1]; Y. Chino[1]; [1]National Institute of Advanced Industrial Science and Technology

Precipitation-hardening, also known as age-hardening, is one of the most effective ways to strengthen Mg alloys. Recent studies have demonstrated that Mg–Ag–Ca system has good room temperature stretch formability, high strength and excellent flame-resistance. If precipitation-hardenability can be obtained by artificial aging, this alloy system is expected to attract more attention. In this study, attempts were made by the present authors to develop precipitation-hardenable alloys from the Mg–Ag–Ca system. A newly developed Mg–12Ag–0.1Ca (wt.%) alloy sheet shows moderate tensile yield strengths of 193 MPa, 130 MPa, 117 MPa along the rolling direction (RD), 45° and transverse direction (TD) in a solution treated condition. Subsequent artificial aging increases the tensile yield strength along the RD, 45° and TD to 236 MPa, 163 MPa and 143 MPa, respectively. This improvement in yield strength by the T6 treatment is associated with a dense distribution of Ag-enriched precipitates.

Effect of Ca Addition on Microstructure of AZ61 Magnesium Alloy during High Temperature Deformation: *K. Kim*[1]; J. Lee[1]; K. Kim[1]; [1]Pukyong National University

Magnesium alloys have been paid attention as lightweight materials in various industrial fields. However, their use is limited by poor formability at room temperature which was caused by the limited number of slip systems. The texture control plays an important role in plastic workability of magnesium. Addition of Ca as alloying element is known to improve the general corrosion resistance and mechanical integrity of magnesium alloys in chloride environment. In order to investigate the Ca concentration on microstructure formation behaviors, Ca addition on AZ magnesium alloy were experimentally investigated by high-temperature uniaxial compression. Uniaxial compression test was conducted at 673K and 723K with a strain rate of 5.0×10-2s-1. The working softening was observed and the main component of texture and the sharpness of basal texture in two kinds of specimens varies depending on the deformation conditions.

Effect of Cation Species in the Electrolyte on the Oxidized Film on the Anodizing of Mg-Li-Al Alloys: *Y. Ichigi*[1]; T. Morishige[1]; T. Takenaka[1]; [1]Kansai University

Mg-14mass%Li-3mass%Al (LA143) alloy has high corrosion resistance than previous Mg-Li alloys such as Mg-14mass%Li-1mass%Al (LA141). However, the corrosion properties of the alloy are not enough to apply for practical use without corrosion protection coatings. The anodization for Mg alloys is an effective technique to prevent metal surface from exposure to corrosion environment. Phosphoric acid-based solution containing metal cation are useful electrolyte to form thick oxide layer on Mg surface. In this study, the effect of cation species on the oxidized film was investigated.The film formed by each electrolytic solution was mainly composed of $Mg_3(PO_4)_2$, $AlPO_4$, $MgAl_2O_4$, and the phosphate and oxide containing each additive element were slightly present. Particularly, in the electrolyte containing Ca, the dissolution of LA143 was suppressed about twice as much as other electrolyte, and the most uniform and thick film was formed.

Effect of Pre-sintering in Silicothermic Reduction of MgO and Reduction Using Ca2SiO4 instead of CaO: *T. Saimura*[1]; T. Takenaka[1]; T. Morishige[1]; [1]Kansai University

Our laboratory has been researching Mg production using bittern-derived materials to develop an innovative Mg production process with lower environmental load. In previous studies, it was suggested that the contact condition between MgO, CaO and Si was very important to reduce bittern-derived material efficiently. In this study, the contact condition of MgO, CaO and Si was changed by sintering and the effect of the sintering condition on Si thermal reduction was investigated. A short-term sintering improved the reduction rate, but a longer sintering worsened the rate. Sintering seems effective in the improvement of contact condition, but cases the surface oxidation on Si. In this study, Si reduction with Ca_2SiO_4 instead of CaO was also attempted to reduce CaO consumption, but it was shown that MgO was lost by $CaMgSiO_4$ formation.

Effects of $MgCl_2$ and NaCl on Si-thermic reduction of MgO in Recycle of Mg-air Battery: *A. Hayashida*[1]; T. Takenaka[1]; T. Morishige[1]; [1]Kansai-University

The effects of the chlorine content used as electrolyte should be controlled in the recycle process of Mg-air battery. The influence of $MgCl_2$ and NaCl in Si-thermic reduction of MgO has been studied in this study. The mixture of MgO with $MgCl_2$ or NaCl was reduced by metallic Si at 1150C° for 3h, and the reduction rate was estimated. The reduction rate without $MgCl_2$ or NaCl addition was about 55% under our reduction condition, and 1mol% addition of $MgCl_2$ rarely affected the reduction rate. However, the reduction rate decreased with added amount of $MgCl_2$. and became about 15% in 10mol% addition. Even 1mol% addition of NaCl worsened the reduction rate, and the reduction rate decreased with the addition amount. It is confirmed that the chlorine content should be removed before Si-thermic reduction in the recycle of Mg-air battery.

First-principles Calculations of Phonon States in LPSO Magnesium Alloys: *D. Matsunaka*[1]; [1]Shinshu University

Several magnesium alloys include long period stacking ordered (LPSO) structures which consist of periodic arrangement of basal stacking faults and enrichment of solute atoms in the vicinity of the stacking faults. The solute-enriched layers give rise to a significant mass change as well as local stiffness due to the L12-type solute clusters, which affect the lattice vibration properties of the LPSO structures. Our previous study showed that for a heavy enough mass change, a phonon-mediated interaction of the solute-enriched layers is attractive and stabilizes the periodic stacking of the solute-enriched layers. In this study, we analyze phonon states of LPSO magnesium alloys, using first-principles calculations. We calculate phonon density of states and phonon dispersion based on the density functional perturbation theory.

Improvement of Corrosion Resistance by Zn Addition to Mg Alloy Containing Impurity Ni: *K. Ezumi*[1]; T. Morishige[1]; T. Kikuchi[2]; R. Yoshida[2]; T. Takenaka[1]; [1]Kansai University; [2]Chuo-Kosan., Ltd.

There is the deleterious influence of corrosion resistance of Mg alloy by contaminant of impurity element Ni during Mg recycling. Mg_2Ni precipitates trigger the galvanic corrosion between Mg matrix phase. Zn addition into Mg alloy may reduce the detrimental impact of impurities. A small amount of Ni element is dissolved into Mg-Zn intermetallic phase. Therefore, the microstructure and corrosion behavior were investigated by changing the amount of Zn in Mg alloy with a trace amount of Ni. From the results of the microstructural observation, Ni element existed in $MgZn_2$ intermetallic phase when the Zn content exceeded 6 mass%, to change the existing state of Ni whereas Mg_2Ni phase was dispersed in Mg-Zn alloy with a few percent of Zn.

Influence of Heat Treatment on the Stretch Formability of Age-hardenable Mg-Al-Ca-Mn-Zn Sheets: *M. Imiela*[1]; T. Sasaki[2]; K. Hono[2]; D. Klaumunzer[1]; [1]Volkswagen Group Innovation; [2]National Institute of Materials Science

In this work the influence of heat treatment on the stretch formability of an age-hardenable Mg-Al-Ca-Mn-Zn alloy sheet is investigated utilising Erichsen cupping tests within a temperature range from room temperature to 200°C. In contrast to traditional age-hardenable materials, such as Aluminium 6000 series sheets, the results show a lower stretch formability for the solution treated (T4) than for the peak aged (T6) condition, especially at intermediate temperatures (100-200°C). Uniaxial tensile tests reveal a significantly lower strain-rate sensitivity in the T4-condition within the same intermediate elevated temperature regime. These results have a direct implication on an envisioned industrial processing route such that forming of lightweight components should preferably be carried out on peak aged (T6) blanks.

Investigation of Microstructural Factors Affecting the Plane-strain Fracture Toughness of Mg-Zn-Y-Al Alloys Processed by Consolidation of Rapidly Solidified Ribbons: *S. Nishimoto*[1]; S. Inoue[1]; M. Yamasaki[1]; Y. Kawamura[1]; [1]Kumamoto University

Recently, high strength and ductile nano-crystalline Mg-Zn-Y-Al alloys with LPSO phase have been developed via rapidly solidified (RS) ribbon-consolidation processing. These Mg alloys are expected to be used in aerospace industries because of their excellent mechanical properties and high corrosion resistance. However, it has been pointed out that the data on the fracture toughness of the alloys is insufficient. Therefore, in this study, we investigated fracture toughness of the alloys. The RS ribbon-consolidated Mg-Zn-Y alloys subjected to pre-extrusion heat-treatment showed higher fracture toughness than the alloys without heat-treatment. Pre-extrusion heat-treatment conditions affected the morphology of LPSO phase in the RS alloys. In the alloys without heat-treatment, plate-shaped LPSO phase precipitated in grain interior. On the other hand, in the alloys with heat-treatment, LPSO phase precipitates grew into block-shaped ones. Formation of block-shaped LPSO phase and fine a-Mg grains may improve the fracture toughness of the alloys.

On the Precipitation Evolution in a Mg-0.3Ca-0.6Zn Alloy: *Z. Li*[1]; T. Sasaki[1]; D. Chen[2]; K. Wang[2]; B. Zhou[2]; K. Hono[1]; [1]NIMS; [2]University of Virginia

Age-hardenable Mg-Ca-Zn alloys are promising candidates as heat-treatable wrought alloys because of their excellent room temperature formability and high strength. This work aims at establishing a detailed precipitation sequence in the Mg-0.3Ca-0.6Zn (at.%) alloy by (S)TEM and 3DAP analysis. The monoatomic layer Guinier Preston (G.P.) zone is found to be the main strengthening phase in the peak-aged condition. The G.P. zones are thickened to the tri-atomic layer '' and ' phases. The '' and ' basal plates then form in pairs and get clustered upon aging followed by the transformation into 1 and 2 phases. 1000 h aging leads to the precipitation of two equilibrium phases, , and . These observations have established the following precipitation sequence; S.S.S.S solute clusters G.P. zones '''1, 2 , . The structural stability of the G.P. zones and precipitates are verified by DFT calculations.

Oxide Films Formed on $MoSi_2$ Anode in Molten $MgCl_2$-NaCl-$CaCl_2$ and Molten LiCl-KCl: *T. Miyoshi*[1]; T. Morishige[1]; T. Takenaka[1]; [1]Kansai University

The anodic behavior of $MoSi_2$ in molten $MgCl_2$–NaCl–$CaCl_2$ containing oxide ions has been investigated in this study to aim at developing an inert anode in this melt. A sharp anodic current peak appeared around 1.8V (vs. Mg / Mg^{2+}) in a cyclic voltammogram, which suggested that $MoSi_2$ was passivated in the melt with oxide ions. Potentio–static electrolysis was performed at various potentials nobler than the passivation potential. Oxide film was formed on $MoSi_2$ by potentio–static electrolysis regardless of electrolysis potential. The current contributions assuming the dissolution of Mo and the formation of oxide film are estimated from the weight change and the film thickness after the potentio–static electrolysis. The formation of oxide film and its influence in molten $MgCl_2$–NaCl–$CaCl_2$ are compared with those in molten LiCl–KCl, and the suitable condition to form better protection film is discussed.

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