NSERC HI-AM Network

2017–2019 NSERC-HI-AM.CA @NSERC_HI_AM

HOLISTIC INNOVATION IN ADDITIVE MANUFACTURING

PROGRESS REPORT 1

NSERC HI-AM

UNIVERSITY OF WATERLOO | Department of Mechanical and Mechatronics Engineering

NSERC CRSNG

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

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Message from the Chair and Director

Ralph Resnick
Chair of the Board of Directors

Ehsan Toyserkani
Network Director

It is our privilege to present the first progress report of the NSERC Strategic Network for Holistic Innovation in Additive Manufacturing (HI-AM). This report provides an overview of the Network activities and research outcomes from September 2017 to July 2019.

The HI-AM Network that was awarded in 2017 brought together 7 universities from coast to coast, 14 original industrial partners, 4 non-profit organizations and 5 collaborative international institutions to expand academic research and development on additive manufacturing in a holistic fashion across Canada. To this end, our main mission has been pinpointed on fostering collaborative interactions between partners from private and public sectors and academic researchers to develop and commercialize novel materials, processes, control systems and products of metal AM.

In 2017 and early 2018, the Board of Directors (BoD) and the Scientific Advisory Committee (SAC) were formed and met to guide the Network in its mission and vision. We are grateful to the members of BoD and SAC for their invaluable time and contributions. In 2018, tremendous effort was made to execute a master agreement between the many parties involved in this project. In parallel, 19 principal investigators were very busy hiring more than 77 highly qualified personnel to carry out 36 on-going projects. The Network was formally announced by the Honorable Kirsty Duncan, the Minister of Science, on August 10, 2018 at Promation, one of our industrial partners sites in Oakville, ON.

Since the commencement of the Network, we hosted two major events: the first HI-AM conference on May 22-23, 2018 in Waterloo, ON and the second HI-AM conference on June 26-27, 2019 in Vancouver, BC. Both conferences have received tremendous attentions from academia and industry. We welcomed more than 200 national/international researchers, industrial representatives and international keynote speakers to each event. More can be read about these conferences in the corresponding section of this report.

Our international collaborations have been ramping up. We have facilitated student exchanges between pioneer additive manufacturing R&D centers in the world, such as Singapore 3D Printing Center in Nanyang University, Singapore and the National Institute of Standards and Technology (NIST), United States.

Moreover, two new collaborative institutions (University of Windsor and École de Technologie Supérieure (ETS) Montréal), as well as three new companies (GE Additive/AP&C, KSB and Equispheres) joined the Network in 2019.

For many years, AM has been known to address "economies of scope" in which customization, prototyping and low volume manufacturing have been the main foci. However, in recent years, AM has positioned itself to deploy for "economies of scale", i.e., mass production, without compromising the economies of scope. This promotion from prototyping to a serial production platform has opened up many R&D opportunities. Like all conventional techniques, quality assurance procedures/tools (either online or offline) are of the utmost importance to aid manufacturers in quality management and certification when it comes to serial production. In the HI-AM, we are rigorously working on many R&D projects that address the above-mentioned needs for this disruptive technology that is disrupting itself regularly.

There are many activities that we were not able to highlight in this report. We look forward to sharing more about the achievements of our Network in the second progress report.

Sincerely Yours,

Ralph Resnick,
Chair of the Board of Directors

Ehsan Toyserkani,
Network Director

Shaping the Future of Additive Manufacturing

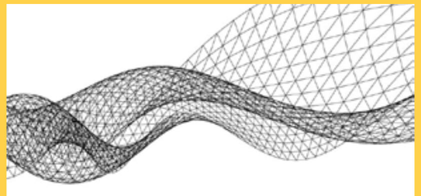
Additive Manufacturing (AM) has the potential to change the entire manufacturing sector by 2030. Despite the recent progress in this field, there are several remaining challenges hindering the widespread industrialization of this technology, from expensive and limited powder feedstock to the need for increased process reliability.

The **NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM)** is working on innovative solutions to address these challenges and to equip Canada for the era of Industry 4.0. With major investments from the **Natural Sciences and Engineering Research Council of Canada (NSERC)** and **Canada Foundation for Innovation (CFI)**, the Network investigates the fundamental scientific issues associated with metal processing. As the first national academic AM initiative in Canada, this Network builds the partnerships, develops the intellectual property, and trains the highly skilled individuals Canada needs to compete in the crucial arena of advanced manufacturing.

The **University of Waterloo** is proud to host this NSERC Strategic Network bringing together 19 leading AM experts from 7 Canadian universities. These researchers and their teams share ideas, innovations, and access to advanced research infrastructure and devices essential for holistic AM experiments. The HI-AM Network is also in partnership with 22 industrial and government organizations demonstrating the broad impact potential of AM technology and the need for a collaborative approach. These partners include natural resource and energy firms, tooling and part repair specialists, and software developers, as well as major aerospace, automotive, and biomedical device manufacturers. These research-driven partnerships ensure the Network results are directly applicable to manufacturing in Canada and abroad, so innovations can be rapidly transferred to, and implemented by industry.

HI-AM Research Themes

THEME 1: Material Development Tailored with Optimum Process Parameters



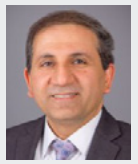
THEME 2: Advanced Process Modeling and Coupled Component/Process Design

THEME 3: In-line Monitoring/ Metrology and Intelligent Process Control Strategies

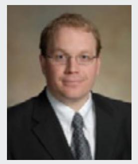
THEME 4: Innovative AM Processes and AM-made Parts

Principal Investigators

THEME/NODE LEADERS

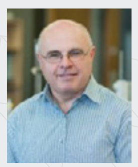


Ehsan Toyserkani
PhD, PEng
NETWORK DIRECTOR AND THEME 3 LEADER
University of Waterloo
Dept. of Mechanical and Mechatronics Engineering



Mathieu Brochu
PhD, ing.
ASSOCIATE DIRECTOR AND THEME 4 LEADER
McGill University
Dept. of Materials Engineering

Paul Bishop
PhD, PEng
THEME 1 LEADER
Dalhousie University
Dept. of Mechanical Engineering



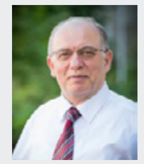
Steven Cockcroft
PhD, PEng
THEME 2 LEADER
University of British Columbia
Dept. of Materials Engineering

Carl Blais
PhD, ing.
NODE LEADER
Université Laval
Département de génie des mines
Département de la métallurgie et des matériaux

Hani Henein
PhD, PEng
NODE LEADER
University of Alberta
Dept. of Chemical and Materials Engineering

Hani Naguib
PhD, PEng
NODE LEADER
University of Toronto
Dept. of Materials Science and Engineering
Dept. of Mechanical and Industrial Engineering

CO-INVESTIGATORS



Yusuf Altintas
PhD, PEng
University of British Columbia
Dept. of Mechanical Engineering

Ahmed Qureshi
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University of Alberta
Dept. of Mechanical Engineering

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Dept. of Materials Engineering

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Dept. of Mechanical and Mechatronics Engineering

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Dept. of Mechanical and Mechatronics Engineering

Kevin Plucknett
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Dept. of Mechanical Engineering

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Gisele Azimi
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University of Toronto
Dept. of Materials Science and Engineering

Mihaela Vlasea
PhD
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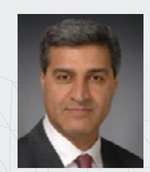
Dept. of Mechanical and Mechatronics Engineering

Damiano Pasini
PhD, ing.
McGill University
Dept. of Mechanical Engineering

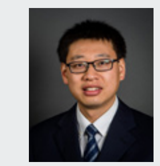


Amir Khajepour
PhD, PEng
University of Waterloo
Dept. of Mechanical and Mechatronics Engineering

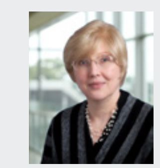
Yaoyao Fiona Zhao
PhD
McGill University
Dept. of Mechanical Engineering

COLLABORATORS

Vladimir Brailovski
PhD, ing.
École de technologie supérieure (ÉTS)
Département de génie mécanique



Yu Zou
PhD
University of Toronto
Dept. of Materials Science and Engineering
Dept. of Mechanical & Industrial Engineering



Jill Urbanic
PhD, PEng
University of Windsor
Dept. of Mechanical, Automotive and Materials Engineering

Announcement of HI-AM Network

The $5.5M grant for establishment of NSERC HI-AM Network was announced on August 10, 2018 by the Honorable Kirsty Duncan, Minister of Science and Sport during a visit to Promation, an Ontario-based company involved in the HI-AM Network.

"I commend today's recipients for the important work they are doing to contribute to Canada's competitiveness. We are investing in you today because we know that when we invest in science and research we are investing in Canadians. The bold ideas your innovative partnerships will generate will have an important impact on our economy, creating good jobs and unique training opportunities for scientists and engineers here in Oakville and across the country", Duncan said. The Network receives another $5M in support of its research activities from industrial and academic partners.

The Director of HI-AM Network, Ehsan Toyserkani, explained about the importance of this grant in ensuring Canada's leading role in transition to Industry 4.0 during the announcement ceremony. "This investment will enable the team led by the University of Waterloo to increase our collaborations and partnerships with industry in Canada and abroad to help insure that our country plays a major role in integrating the transformative impacts of Additive Manufacturing globally, thereby securing Canada's leadership in the realization of Industry 4.0", Toyserkani said.

The research outcomes of this Network is hoped to lead to numerous economic impacts, including reduction in manufacturing costs in terms of raw materials and manufacturing processes, improvements in mechanical properties and consistency of AM-parts, and a more rapid adoption of AM products and processes across Canadian manufacturing sectors which leads to increased market potential nationally and internationally.

$5.5M GRANT

FOR ESTABLISHMENT OF THE NSERC HI-AM NETWORK

Announcement of $78M NSERC Strategic Partnership Grants 2018, Promation, Oakville, ON. From left: Pam Damoff, MP for Oakville North-Burlington; Mark Zimny, President of Promation; Monica Emelko, Director of forWater Network; Kirsty Duncan, Minister of Science and Sport; Charmaine Dean, University of Waterloo VP Research and International; Ehsan Toyserkani, Director of HI-AM Network; Marc Fortin, NSERC VP Research Partnerships.

> *I commend today's recipients for the important work they are doing to contribute to Canada's competitiveness. We are investing in you today because we know that when we invest in science and research we are investing in Canadians. The bold ideas your innovative partnerships will generate will have an important impact on our economy, creating good jobs and unique training opportunities for scientists and engineers here in Oakville and across the country.*
>
> **Honorable Kirsty Duncan, Minister of Science and Sport**

Mission and Vision

The overall mission of the HI-AM Network is to create collaborative interactions between partners from private and public sectors and academic researchers in order to develop and commercialize novel materials, processes, control systems, and products for metal AM.

The research program of HI-AM Network has been designed and planned to achieve the vision of providing realistic and transferable solutions for the foremost challenges preventing the industry from converting their conventional manufacturing methods into metal AM processes.

To this end, the following objectives are pursued:

SECURING CANADIAN LEADERSHIP IN THE AM SECTOR through enabling a more rapid adoption and commercialization of novel AM technologies and decreasing the timeframe for the translation of HI-AM innovations to Canadian industry.

DEVELOPING, OPTIMIZING, AND IMPLEMENTING new feedstock materials, AM process models and simulations, monitoring sensors and closed-loop control systems, and novel AM processes and products in partnership with Canadian industries and government agencies.

FORGE LASTING RELATIONSHIPS AMONG PARTNERS from the private and public sectors by strengthening the collaborative interactions between academic researchers, the Canadian manufacturing industry, industrial organizations, government, and international collaborators working together to address the complex and technical challenges associated with metal AM.

PROVIDING AN EXCEPTIONAL RESEARCH AND INNOVATION ENABLED ACTIVE LEARNING ATMOSPHERE for undergraduate and graduate students and post-doctoral fellows to train the highly qualified personnel (HQP) in the strategic discipline of AM.

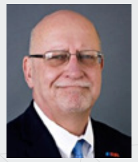
ADVANCING THE AM INFRASTRUCTURE at four universities involved in the Network (University of Waterloo, Dalhousie University, The University of British Columbia, and McGill University) through a CFI AM initiative.

Governance

BOARD OF DIRECTORS

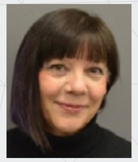
The Board of Directors oversees the global direction of the Network, providing bi-annual input on the research program quality and emerging research topics. The Board is also responsible for reviewing the Network's finances to ensure its success within the NSERC's financial guidelines.

VOTING MEMBERS

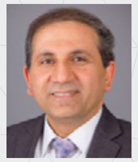


Ralph Resnick
Chair
America Makes
Retired Founding Director, President and Executive Director of NCDMM

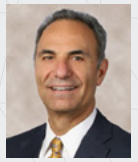
Benoit Leduc
PhD
Ministry of Innovation, Science and Economic Development
Manager of Life Science Industries Directorate



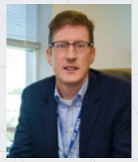
Vesna Cota
Tyco Electronics
Retired Additive Manufacturing Specialist



Ehsan Toyserkani
PhD
University of Waterloo
HI-AM Network Director

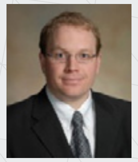


Mohammad Ehteshami
GE Additive
Retired CEO

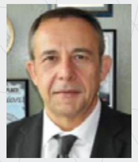


David Muir
PhD
National Research Council Canada
Director, Research and Development

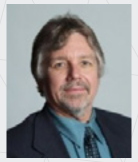
Mathieu Fagnan
Pratt and Whitney Canada
Manager, Acquisition and Deployment of Manufacturing Technologies



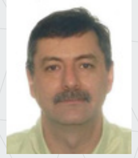
Mathieu Brochu
PhD
McGill University
HI-AM Network Associate Director



Mark Zimny
Promation
President



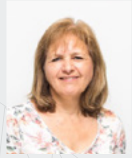
Ian Donaldson
GKN
Director, Advanced Engineering Applications



Stefano Chiovelli
Syncrude
Senior Technical Advisor

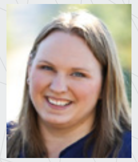
NON-VOTING MEMBERS

Linda Martin
NSERC
Manager



Laurie Wilfong
University of Waterloo
Financial Advisor

Vladimir Paserin
PhD
University of Waterloo
Network Manager-CFI



Catherine Demers
University of Waterloo
Financial Manager

Farzad Liravi
PhD
University of Waterloo
Network Manager NSERC

Network Statistics

- **7** ACADEMIC PARTNERS
- **2** ACADEMIC COLLABORATORS
- **25** INDUSTRIAL/ GOVERNMENT PARTNERS
- **36** ACTIVE PROJECTS
- **22** PRINCIPAL INVESTIGATORS
- **73** HIGHLY QUALIFIED PERSONNEL
- **16** JOURNAL PAPERS DIRECTLY FUNDED BY HI-AM
- **105** JOURNAL PAPERS RELATED TO HI-AM PROJECTS
- **24** CONFERENCE PAPERS/ PRESENTATIONS
- **44** HI-AM CONFERENCE PAPERS/ PRESENTATIONS
- **1** INVENTION DISCLOSURE
- **2** EVENTS

HIGHLY QUALIFIED PERSONNEL (HQP) BY THEME

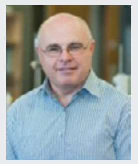
	UNDERGRADUATE	MASC	PHD	PDF/RA
THEME 1	2	8	9	4
THEME 2	0	6	6	2
THEME 3	1	9	10	3
THEME 4	0	4	7	2
TOTAL	**3**	**27**	**32**	**11**

19 HQP ARE FUNDED EXTERNALLY

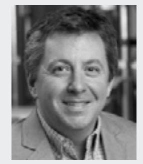
Governance

SCIENTIFIC ADVISORY COMMITTEE

The Scientific Advisory Committee is comprised of the Network Director, Node Leaders, Network Partner representatives, and external academic experts. This committee manages the research programs of the Network, and ensures the objectives, milestones and deliverables are met, and scientific excellence is achieved.

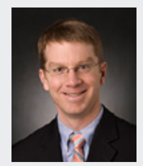


Steve Cockcroft
PhD
The University of British Columbia, Canada
Theme 2 Leader



Carl Blais
PhD
Université Laval, Canada
Node Leader

Hani Henein
PhD
University of Alberta, Canada
Node Leader



Timothy Simpson
PhD
Pennsylvania State University, USA
Paul Morrow Professor of Engineering Design and Manufacturing

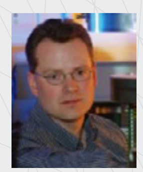
Milan Brandt
PhD
RMIT, Australia
Professor and Technical Director Advanced Manufacturing Precinct

Ian Gibson
PhD
UT Twente, The Netherlands
Chair Professor and Director of Fraunhofer Project Center

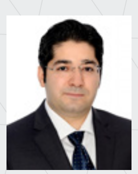
Behrang Poorganji
PhD
GE Additive, USA
Materials Development Manager

Ali Bonakdar
PhD
Siemens, Canada
Advanced Manufacturing Leader

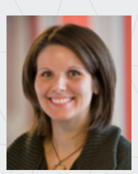
Vladimir Paserin
PhD
University of Waterloo, Canada
CFI Network Manager



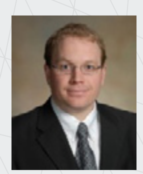
Paul Bishop
PhD
Dalhousie University, Canada
Theme 1 Leader



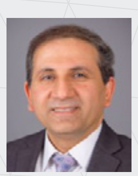
Mohsen Seifi
PhD
ASTM International, USA
Director of Global Additive Manufacturing Programs



Tonya Wolfe
PhD
InnoTech Alberta, Canada
Senior Metallurgical Engineer
Lead, Additive Manufacturing



Mathieu Brochu
PhD
McGill University, Canada
Theme 4 Leader



Ehsan Toyserkani
PhD
University of Waterloo, Canada
Theme 3 Leader

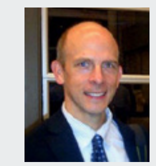
Hani Naguib
PhD
University of Toronto, Canada
Node Leader

COMMERCIALIZATION AND OUTREACH ADVISORY COMMITTEE

The Commercialization and Outreach Advisory Committee liaises with HI-AM Partners on IP-related matters, and acts as an additional resource to HI-AM Partners in the commercialization of the Network results. This committee also provides recommendations and feedback on technology development necessary for advancing the market readiness/ adoption of the Network results.

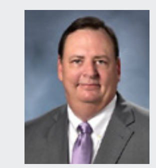
Gary Brock
Chair
University of Waterloo
Director of Strategic Initiatives

Farzad Liravi
PhD
University of Waterloo
Network Manager
NSERC



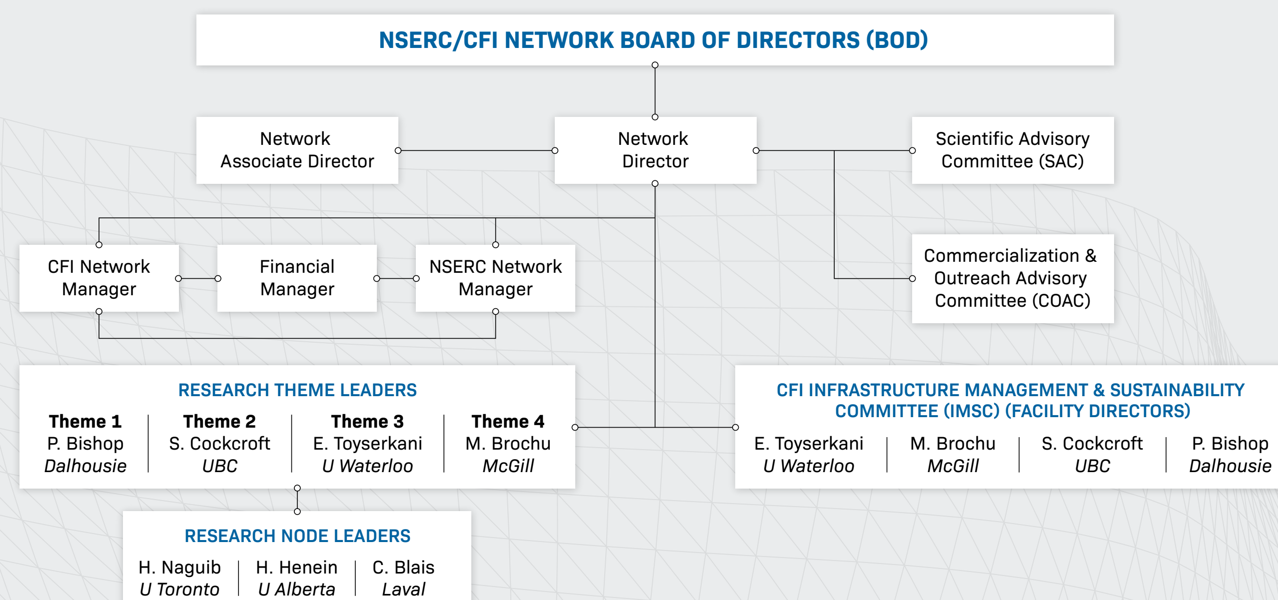
Dave Dietz
University of Waterloo
Director of Engineering Research

Vladimir Paserin
PhD
University of Waterloo
Network Manager
CFI



Gary Biermann
Global Science & Technology Engagement at Lockheed Martin
Regional Technology Manager

GOVERNANCE STRUCTURE



Academic Members

- University of Alberta
- The University of British Columbia
- Dalhousie University
- Université Laval
- McGill University
- University of Toronto
- University of Waterloo

Partners

ACADEMIC AND RESEARCH INSTITUTION PARTNERS

COLLABORATORS

- École de technologie supérieure (ÉTS)
- University of Windsor

INTERNATIONAL

- FAU Friedrich-Alexander Universität Erlangen-Nürnberg
- Fraunhofer IWS
- Lancaster University
- NIST National Institute of Standards and Technology, U.S. Department of Commerce
- Nanyang Technological University Singapore
- RMIT University
- Taipei Tech
- Technische Universität Dresden
- University of Twente, The Netherlands

INDUSTRY AND HEALTHCARE PARTNERS

- Autodesk
- ABOCO Technology Inc.
- Flexcap
- Linamar
- MDA
- Mount Sinai Hospital
- GKN Driveline
- Pratt & Whitney Canada
- Promation
- Renishaw
- Rio Tinto
- Siemens
- Syncrude
- TIMET

GOVERNMENT PARTNERS

- NRC-CNRC
- Natural Resources Canada / Ressources naturelles Canada
- InnoTech Alberta
- DRDC / RDDC

NON-PROFIT PARTNERS

- Canada Makes
- CM&E Canadian Manufacturers & Exporters
- Canada Mining Innovation Council
- ReMAP / AAPF

Research Progress

THEME 1: MATERIAL DEVELOPMENT TAILORED WITH OPTIMUM PROCESS PARAMETERS

Paul Bishop
PhD, PEng
THEME 1 LEADER
Dalhousie University
Dept. of Mechanical Engineering

While tremendous progress has been made in additive manufacturing over the past 30 years, the focus of new materials and technologies has been on polymeric materials. However, the demand for metallic parts made using AM processes exceeds that of polymeric materials within the global manufacturing sector. The global AM sector has consistently focused on using highly engineered powders which are exceptionally expensive and constitute a significant portion of the final part cost; on average, 20%. The significantly higher net cost of metallic parts made by AM is a key factor inhibiting market growth. As the result of the powder grade constraints, only a limited number of metals or metal alloys are presently being used in commercial metal additive manufacturing. For AM metal parts to be a viable option for industry, new, high quality reproducible powders with characteristics that are appropriate for AM processes and applications must be developed. HI-AM's research in Theme 1 will contribute valuable new metal powder options and it will increase process reliability and repeatability rate by creating dynamic process maps to control the final quality and material properties of the finished part.

Project 1.1: Development of Next Generation Alloys

DESCRIPTION

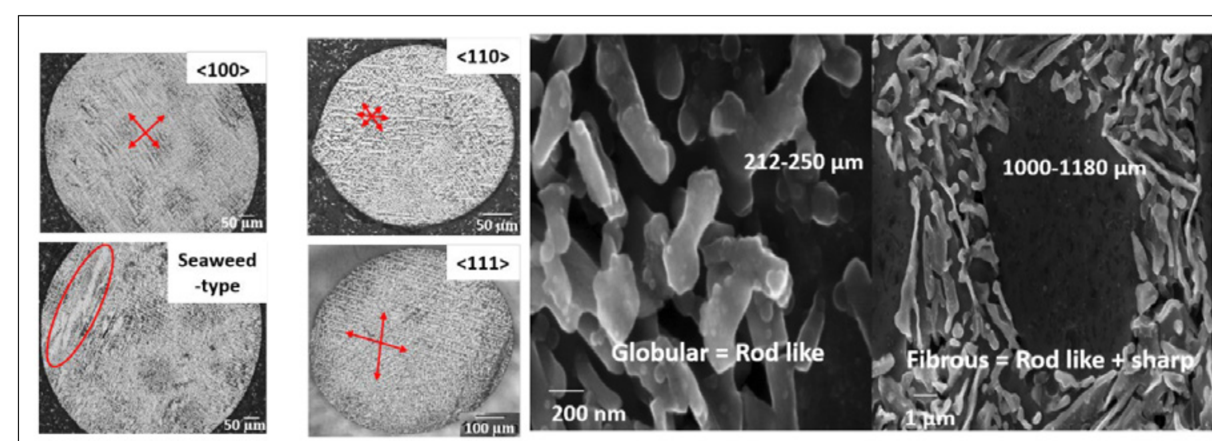
The objective of this project is to generate new powder metal feedstocks, with compositions strategically chosen to have a widespread and immediate impact on the global AM community. These new materials will broaden the mechanical, physical, and corrosion properties attainable within metallic products. This will help position AM as a viable manufacturing approach for a greater number of industrial applications.

PROGRESS

- Designed, developed, and characterized multiple aluminum alloys strengthened with coherent L12 precipitates and thermally stable aluminides. Thermodynamic modeling of the powder systems, print optimization and manufacturing of simple geometries on LPB system, and characterization of printed parts is in progress.
- Characterized Ti-6Al-4V powder and LPF-made parts to develop a comparison baseline dataset.
- Selected and atomized three strategic titanium alloys. Powder characterization and AM process optimization for these alloys is in progress.
- Developed a proprietary water-atomization technique resulting in improved powder morphology and flowability.
- Atomized two tool steel alloys and used them to fabricate coupon samples using LPB and LPF systems. Characterization of the parts and refining the powder chemistry based on the results is in progress.
- Sourced, characterized and used two nickel alloys in preliminary manufacturing tests in LPB-AM. Process optimization, and thermodynamic and kinetic modeling are being carried out.
- Commenced preliminary tests on AM of Ni intermetallics.
- Commenced process parameter optimization, thermodynamic modeling and microstructure analysis of pure molybdenum and a molybdenum alloy for LPB process.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
1.1.1 Development of Thermally Stable Aluminum Alloys for LPB-AM	• Paul Bishop, Dalhousie University • Mathieu Brochu, McGill University • Hani Henein, University of Alberta	• An Fu, McGill University, PhD • Jon Heirly, Dalhousie University, PhD • Quentin Champdoizeau, University of Alberta, MASc • Daniela Diaz, University of Alberta, MASc • Abdoul-Aziz Bogno, University of Alberta, RA • Jose Marcelino Da Silva Dias Filho, University of Alberta, PDF (Collaborator) • Matthew Harding, Dalhousie University, PDF • Ryan Ley, Dalhousie University, Co-op (Collaborator)
1.1.2 Development of Titanium Alloys for LPB-AM and LPF-AM	• Paul Bishop, Dalhousie University • Kevin Plucknett, Dalhousie University	• Matthew Harding, Dalhousie University, PDF • Greg Sweet, Dalhousie University, PDF • Nick Gosse, Dalhousie University, MASc
1.1.3 Development of Tool Steels for LPB-AM and LPF-AM	• Carl Blais, Université Laval • Hani Henein, University of Alberta	• Denis Mutel, Université Laval, PhD • Akankshya Sahoo, University of Alberta, PhD
1.1.4 Development of Nickel Alloys for LPB-AM	• Mathieu Brochu, McGill University • Kevin Plucknett, Dalhousie University	• Sila Atabay, McGill University, PhD • Kevin Lee, McGill University, PhD
1.1.5 Development of Refractory Metals for LPB-AM	• Mathieu Brochu, McGill University	• Tejas Ramakrishnan, McGill University, PhD



(a) Primary α-Al grows with different orientations, and (b) Eutectic Si morphology in smallest and largest particle sizes of rapidly cooled Al-10Si-0.4Sc. (Sub-project 1.1.3)

Project 1.2: AM Processing of Multi-Material Systems

DESCRIPTION

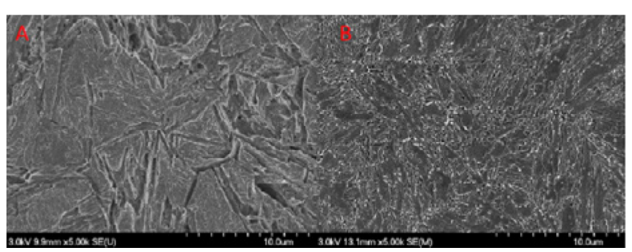
Everyday composite materials are becoming lighter and stronger due to stringent industry standards such as CAFÉ 2025. As a result, lightweight, high strength composite structures are being used in many scenarios, ranging from small-scale biomedical industries to large-scale aerospace and tooling sectors. Customized multi-material objects with a complex internal architecture can easily be created through AM using lightweight, functionally graded polymer materials. Project 1.2 will build on this knowledge to investigate the use of metallic powder feedstocks in the same context, when utilizing BJ- and LPF-AM processes.

PROGRESS

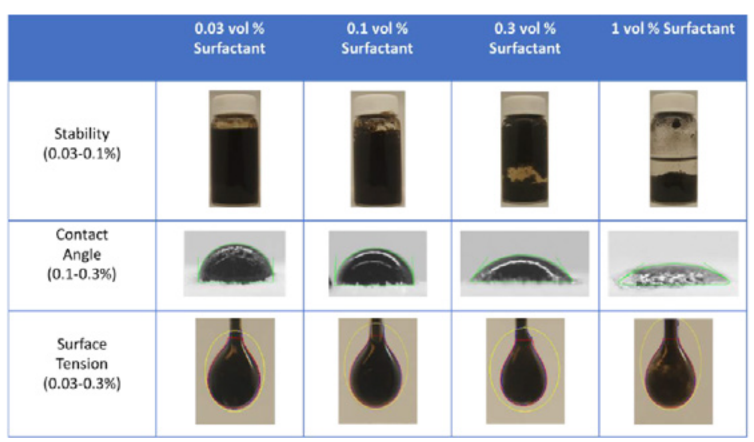
- Developed guidelines for filler-ink (metal-, graphene-, and conjugated polymer-based) and powder systems for binder jetting of functionally graded sensors and actuators.
- Designed and built a flexible powder bed binder jetting system customized for testing of inks containing fillers. Integration of multiple cartridges into the printer is in progress.
- Designed and built a high resolution custom continuous jetting system with inexpensive and exchangeable wet components.
- Commenced LPF-AM process optimization, characterization, and microstructure analysis for fabrication of functionally graded tooling parts.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
1.2.1 Novel Composites for BJ-AM to Develop Foam-based Structures	• Hani Naguib, University of Toronto	• Anastasia Wickeler, University of Toronto, PhD • Xuechen Shen, University of Toronto, MASc • Tylor Morrison, University of Toronto, MASc (Collaborator)
1.2.2 Alloy Alteration for Functionally Graded Materials (FGMs) used in LPF-AM	• Kevin Plucknett, Dalhousie University	• Owen Craig, Dalhousie University, MASc



(A) microstructure of the 600°C single tempered sample and (B) is the 600°C double tempered sample at 5000x. (sub-project 1.2.2)



Surfactant concentration affects stability, contact angle, and surface tension. The 3 factors are important printability parameters. (sub-project 1.2.1)

Project 1.3: Cost Reduction Strategies

DESCRIPTION

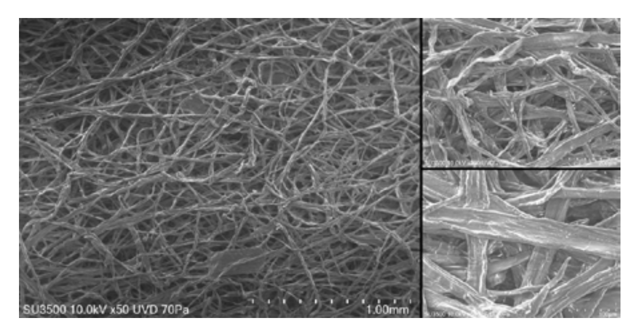
The metal powder costs are the largest continuous expense through the life of an AM machine. Therefore, industry is very interested in concepts that have the potential to reduce raw material costs. Although adoption of AM technologies will most likely lead to a decrease in raw material costs through economies of scale, strategies must be devised to reduce material costs and/or maximize their utilization. Such developments are particularly important in the near term as it is expected that a growing number of new materials designed specifically for AM will soon become commercially available.

PROGRESS

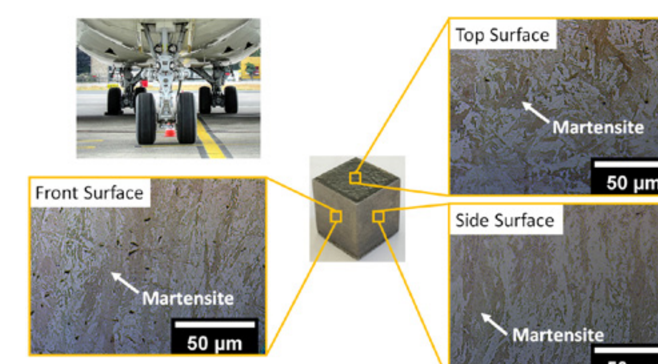
- Studied the effect of moisture on powder processing and part contamination in LPB.
- Commenced studies on the effect of used/recycled powder on microstructure and mechanical properties of LPB-made parts for various alloys to establish a recycling threshold and develop recyclability prediction models.
- Initiated design and development of an electrostatic atomizer (EA) for production of inexpensive feedstock for binder jetting. The initial setup of EA is being tuned, optimized, and augmented with in-situ metrology systems.
- Characterized and tested low-cost water-atomized ferrous alloys for BJ to determine their effectiveness as a manufacturing cost reduction strategy. The characterization of BJ-made parts and their comparison with wrought counterparts is in progress.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
1.3.1 Recyclability of Powder Feedstocks for LPB-AM	• Mathieu Brochu, McGill University • Gisele Azimi, University of Toronto	• Aniruddha Das, McGill University, MASc • Hao Kun Sun, University of Toronto, MASc
1.3.2 Plasma Spheroidization of Low Cost Powders	• Carl Blais, Université Laval	• Starts in Year 3
1.3.3 Cost-effective Steel Feedstock for BJ-AM	• Carl Blais, Université Laval • Paul Bishop, Dalhousie University • Hani Henein, University of Alberta	• Ryan Ley, Dalhousie University, PhD • Bilal Bharadia, University of Alberta, MASc



SEM images of the as-received filter surface at different magnifications (sub-project 1.3.1)



Microstructural analysis of the as-built steel (sub-project 1.3.1)

Research Progress

THEME 2: ADVANCED PROCESS MODELING AND COUPLED COMPONENT/PROCESS DESIGN

A key advantage of AM is the freedom in digital design manipulation providing enhanced part functionality through complex internal topology and material composition, without the need for specialized tooling. Metal AM has been proven to lower costs by reducing the design to fabrication cycle and through consolidating assemblies. Unfortunately, these lower costs are offset by the high cost of the raw materials/feedstock, and the need to use experimental trial-and-error to ensure part quality, reliability and repeatability. Currently, there are no reliable tools to correlate topology optimization and AM process constraints. Modeling and simulation of AM processes have been studied by many groups, however, there are still critical challenges that should be addressed. In particular, there is a need for the integration of reliable models with the topology optimization algorithms. These integrated models must be rapidly executed to be used within controller units for closed-loop control of AM process. The integration is challenging because of the many uncertainties associated with AM processes which all affect the melt pool dynamic significantly. Researchers of Theme 2 are developing innovative platforms/solutions to address these challenges.

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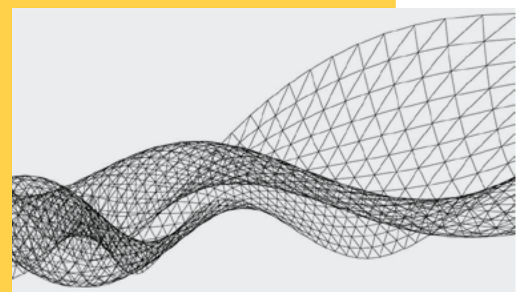


Project 2.1: Multi-scale Modeling of AM

DESCRIPTION

Currently, the energy transport characteristics of the beam/feedstock interaction in powder-bed based AM processes are not well understood. Physics-based process models are critically needed to describe the energy input profile and powder bed/substrate thermal diffusion and advection (when liquid is present) during AM processing. Quantification of these phenomena that are occurring at the meso-scale then leads the way to the prediction of the macro-thermal field, and then to the coupling of the two. Finally, the macro-scale models can be run over a range of conditions to produce the data necessary to develop the fast simulation models.

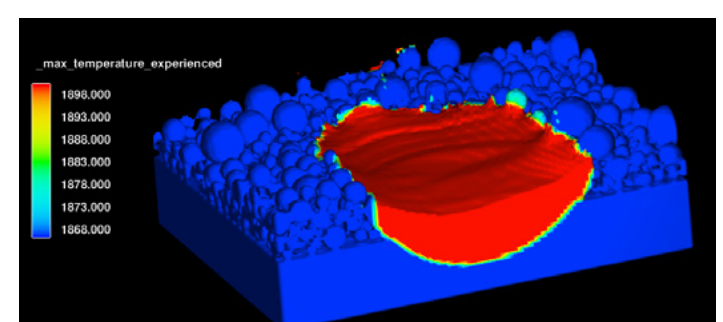
PROGRESS

- Completed literature review of the macro-scale thermal field modeling in powder bed systems with a focus on electron beam (EB) processes.
- Initiated development of methods for extraction of beam trajectory/powder data from the beam control and applied the data as an input in a physics-based model of EB/powder/melt pool interaction.
- Developed and simulated an instrumented base plate with embedded near-surface thermocouples to provide quantitative knowledge on the boundary conditions and interactions that occur during laser-based AM.
- Developed a 3D meso-scale thermal field evolution model with and without powder, and validated the model experimentally without powder. The work on validation of the model with powder with various thicknesses and beam/scan properties is progressing.
- Developed a 3D macro-scale thermal field evolution model for multiple layers. Studies for reduction of the computation cost and model refinement through adaptive mesh schemes are being conducted.

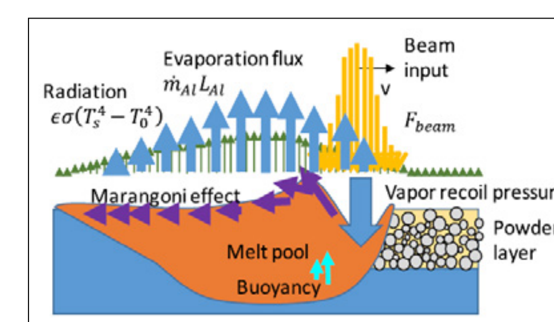
- Developed 2D and 3D coupled thermal-stress models of EBM process using a novel approach to strain accumulation.
- Developed a numerical model for generation of solidification continuous cooling transformation (SCCT) diagram over a wide range of liquid cooling rates for alloys used in AM. An executable file of the model will be generated after the model is coupled to ThermoCalc Software to extract additional information.
- Developed a numerical model of the solidification of eutectic droplets for AM alloys during free fall.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
2.1.1 Beam-powder/ Melt Pool Interaction and Energy Transport: Experimental Validation	• Steve Cockcroft, The University of British Columbia • Mary Wells, University of Waterloo	• Arman Khobzi, The University of British Columbia, MASc • Emre Ogeturk, University of Waterloo, MASc • Farzaneh Farhang-Mehr, The University of British Columbia, RA
2.1.2 Meso-scale Thermal Field Evolution in Melt Pool Substrate	• Steve Cockcroft, The University of British Col umbia	• Eiko Nishimura, The University of British Columbia, PhD • Farzaneh Farhang-Mehr, The University of British Columbia, RA
2.1.3 Macro-scale Thermal Field Evolution	• Yaoyao Fiona Zhao, McGill University	• Zhibo Luo, McGill University, PhD
2.1.4 Multi-Scale Modeling of AM: **(a) Macro-scale Stress Field Evolution Simulation** **(b) Meso-scale Stress Field Evolution Simulation** **(c) Residual Stress Characterization**	• Steve Cockcroft, The University of British Columbia • Daan Maijer, The University of British Columbia	• Pegah Pourabdollah, The University of British Columbia, PhD • Farzaneh Farhang-Mehr, The University of British Columbia, RA • Asmita Chakarborty, The University of British Columbia, MASc • Farhad Rahimi, The University of British Columbia, MASc
2.1.5 Microstructural Modeling and Experimental Validation	• Hani Henein, University of Alberta	• Quentin Champdoizeau, University of Alberta, MASc • Daniela Diaz, University of Alberta, MASc • Jonas Valloton, University of Alberta, RA



Meso-scale thermal field evolution model of the melt pool (sub-project 2.1.2)



Melt pool transport processes and flow drivers. (sub-project 2.1.2)

Project 2.2: Accelerated Real-time Simulation Platforms

DESCRIPTION

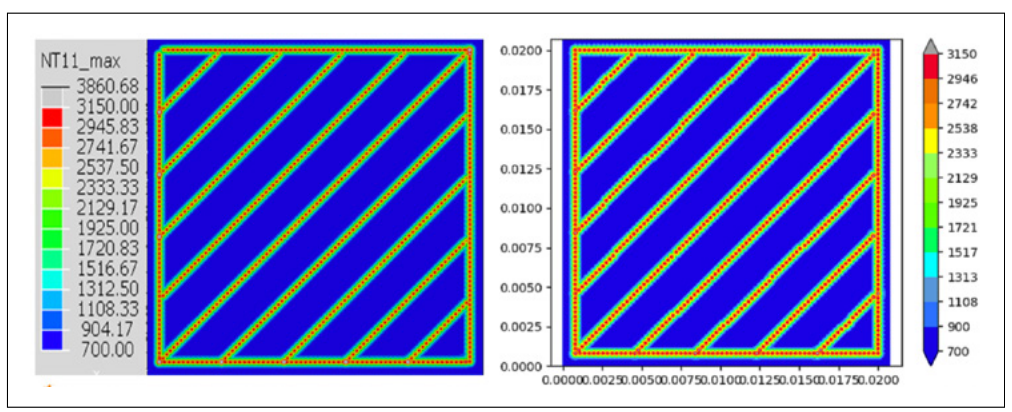
For dynamic process control, melting and solidification occur over short time scales requiring fast sampling frequencies of data. This implies that the process model should have at least the same order of magnitude in terms of computation time to be able to react in order to respond to process perturbations. To achieve an appropriate computational speed, a surrogate reduced-order thermal model should be developed and deployed for process predictive and process feedback control. Fast process predictive thermo-mechanical models for stress field simulation have potential for being used in digital topology design optimization and in predictive control approaches.

PROGRESS

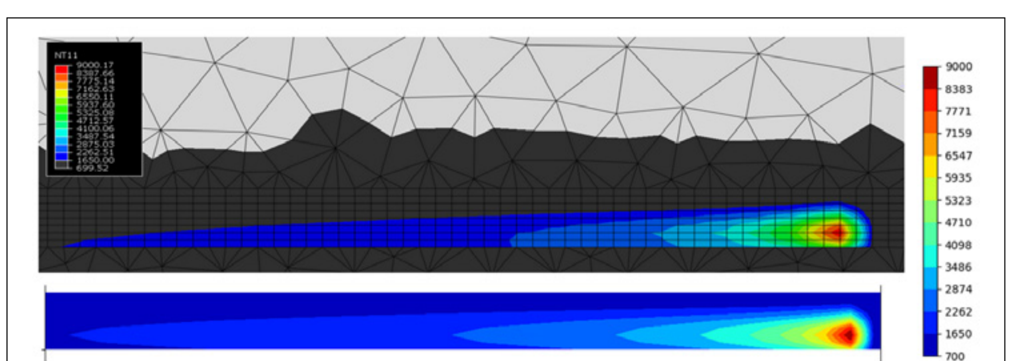
- Developed an approximate fast-to-run (FTR) solution method for modeling the thermal fields during melting by a moving heat source.
- Developed a CFD model to provide data for and train the FTR model. Experimental validation of the model is planned.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
2.2.1 Fast Process Thermal-Field Simulation	• Daan Maijer, The University of British Columbia	• Meet Uphadhyay, The University of British Columbia, MASc
2.2.2 Fast Process Stress-Field Simulation	• Mary Wells, University of Waterloo	• Starts in Year 3



Comparison of simulation times: (left) Abaqus thermal only model – 40 CPU hours, (right) Fast to Run model executed in Python – 20 sec (sub-project 2.2.1)



Comparison of temperature contours (sub-project 2.2.1)

Project 2.3: Pre-processing for Optimization of AM Process Parameters

DESCRIPTION

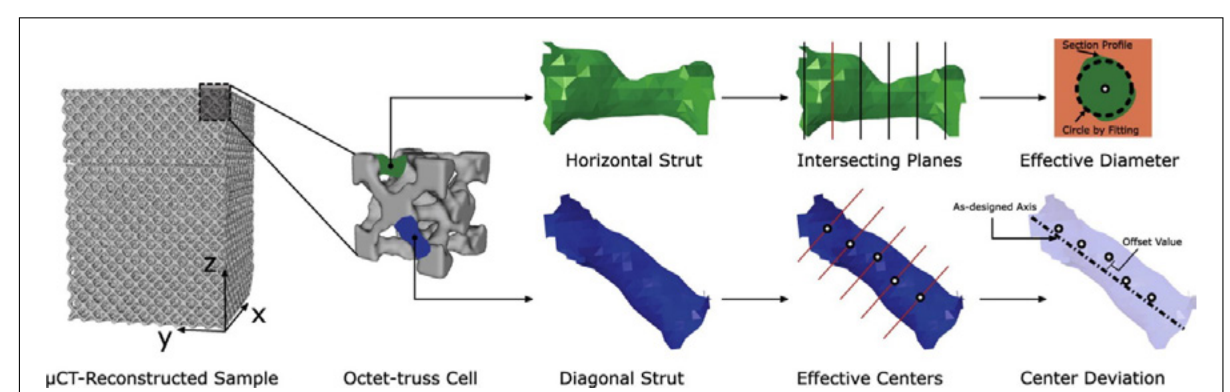
There are three areas of potential improvement that could be realized prior to AM fabrication: 1) part geometry compensation for in-situ deformation; 2) lattice structure design for AM processing; and 3) process parameter optimization for microstructural control. Optimization of the part build geometry at all three areas is pursued by the researchers of project 2.3 in order to eliminate the trial-and-error steps usually needed for obtaining a part corresponding to a given requirement, taking advantage of AM's unique capability in light weighting, and incorporating the predicted part deformation into the design of AM parts.

PROGRESS

- Developed a geometric quality assessment framework and total geometric deviation model for a geometric dimensioning and tolerancing-based process capability study and geometric quality prediction for metal AM.
- Characterized and classified geometrical imperfections in metallic lattices made using LPB systems.
- Started developing a probabilistic predictive model that captures the distributions and magnitude of a number of geometric defects such as mass agglomeration at joints and missing struts that emerge during the additive process of metals.
- Initiated the development of a machine learning algorithm to predict the printability map of 3D objects in LPB process.

SUB-PROJECTS AND RESEARCHERS

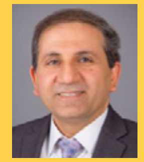
SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
2.3.1 Pre-processing for Dimensional Control	• Ahmed Qureshi, University of Alberta	• Baltej Rupal, University of Alberta, PhD
2.3.2 Lattice Structure Design for AM Processing	• Damiano Pasini, McGill University • Yaoyao Fiona Zhao, McGill University	• Asma El Elmi, McGill University, PhD • Ying Zhang, McGill University, PhD
2.3.3 Component Build Geometry Optimization for AM Processing	• Yaoyao Fiona Zhao, McGill University	• Starts in Year 3



Lattice structure design for additive manufacturing (sub-project 2.3.2)

Research Progress

THEME 3: IN-LINE MONITORING/METROLOGY AND INTELLIGENT PROCESS CONTROL STRATEGIES



Ehsan Toyserkani
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NETWORK DIRECTOR
AND THEME 3 LEADER
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Insufficient process reliability and repeatability, resulting from random and environmental disturbances, are critical impediments for widespread AM adoption. A key solution to compensate for these disturbances is using closed-loop control systems and algorithms to monitor the process, and to tune actuating signals accordingly. However, implementing this approach is challenging as there are many input physical parameters that govern metal AM processes. Furthermore, the output of the process is composed of many factors such as microstructure, hardness, geometry etc. Several non-destructive and in-situ monitoring methods have been investigated for different AM technologies with various degrees of success, however, further work is required to deal with the "big data" that can potentially be collected during AM processes, and to detect the process defects automatically based on the collected data. The researchers of Theme 3 are developing novel on- and off-line quality assurance protocols combining machine learning algorithms and sophisticated monitoring and metrology devices to establish the relationship between in-process feedback data and post-process part characterization. The end result will push AM technology toward "Certify-as-you-build" platforms.

Project 3.1: Innovative In-situ and Ex-situ Monitoring Strategies for AM-made Product Quality Analysis

DESCRIPTION

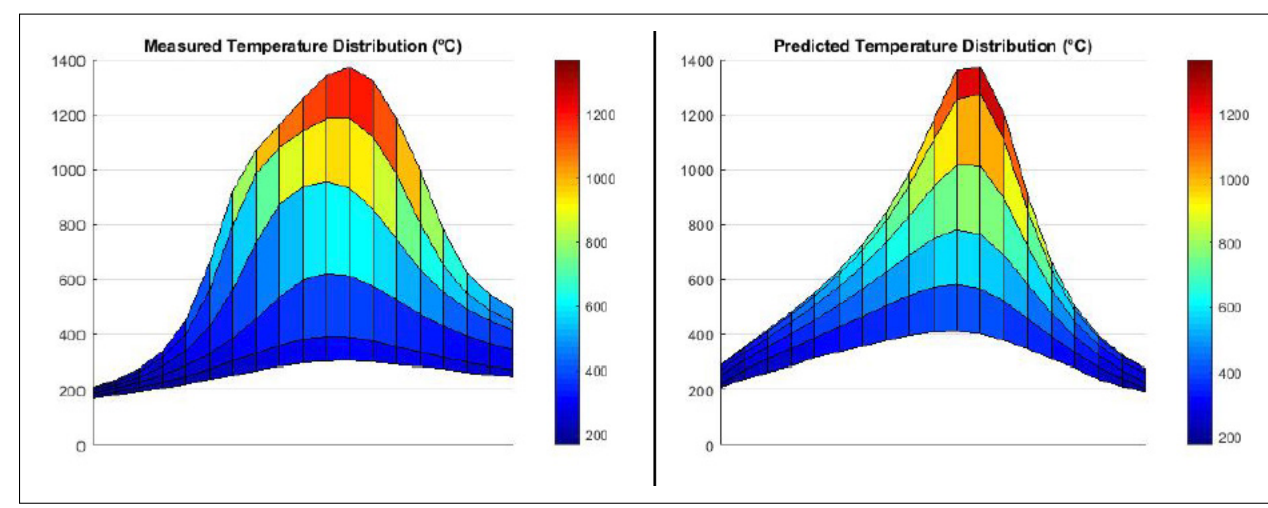
Implementing control algorithms in metal AM systems is challenging due to the high number of parameters involved and narrow temporal opportunity to capture perturbations. This lack of control results in build defects such as porosity. Currently, most quality control measurements are conducted offline, and defects are corrected through costly experimental design techniques. Theme 3 researchers are developing or adopting a new generation of monitoring and control strategies that permit rapid data collection, processing, and analysis for the design controls algorithms and part certification strategies. Real-time quality control will ensure the AM processes can be instantly adjusted to reduce part defects, improve efficiency and reduce costs.

PROGRESS

- Commenced studies for development of a discrete dynamic model for predicting and controlling a melt pool in laser-based AM systems using various radiometric sensing/metrology devices.
- Tested, calibrated, and embedded vision systems into wire arc technology in order to capture process characteristics and layer height quality. Machine learning and experimental approaches are both being investigated for layer height monitoring.
- Started developing both analytical and numerical models of eddy current for finding sub-surface defects in AM-made parts. Procuring an eddy current test setup and the experimental validation of models is ongoing.
- Started investigating the effectiveness of an ultrasonic laser system in monitoring the presence of porosities inside LPB- and LPF-made parts. The system has been setup and modeling the initial results in order to image pores with certain geometrical properties is progressing.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
3.1.1 Development of Non-contact Dynamic Melt Pool Characteristic Measurement via Radiometric Monitoring for LPB- and LPF-AM	• Amir Khajepour, University of Waterloo	• Lucas Botelho, University of Waterloo, MASc • Neel Bhatt, University of Waterloo, MASc (Collaborator) • Shuchen Huang, University of Waterloo, MASc (Collaborator) • Hamid Tahir, University of Waterloo, MASc (Collaborator) • Hasan Askari, University of Waterloo, PhD (Collaborator)
3.1.2 Development of Continuous and Layer-intermittent Imaging Capabilities for LPF-, LPB-, and BJ-AM	• Ahmad Qureshi, University of Alberta	• Colle Milburn, University of Alberta, Co-op • Thomas Lehmann, University of Alberta, PDF (Collaborator)
3.1.3 Development of Non-contact Capability to Detect Sub-surface Properties Using Eddy Current Inductive Measurements	• Behrad Khamesee, University of Waterloo • Ehsan Toyserkani, University of Waterloo	• Heba Elsayed Farag, University of Waterloo, PhD
3.1.4 Laser Ultrasonic Sensing for LPB- and LPF-AM	• Ehsan Toyserkani, University of Waterloo	• Alex Martinez, University of Waterloo, PhD



Measured and Predicted Temperature Distributions (Laser Movement: Left to Right) (sub-project 3.1.1)

Project 3.2: Real-time Control and Machine Learning Algorithms for LPB- and LPF-AM Processes

DESCRIPTION

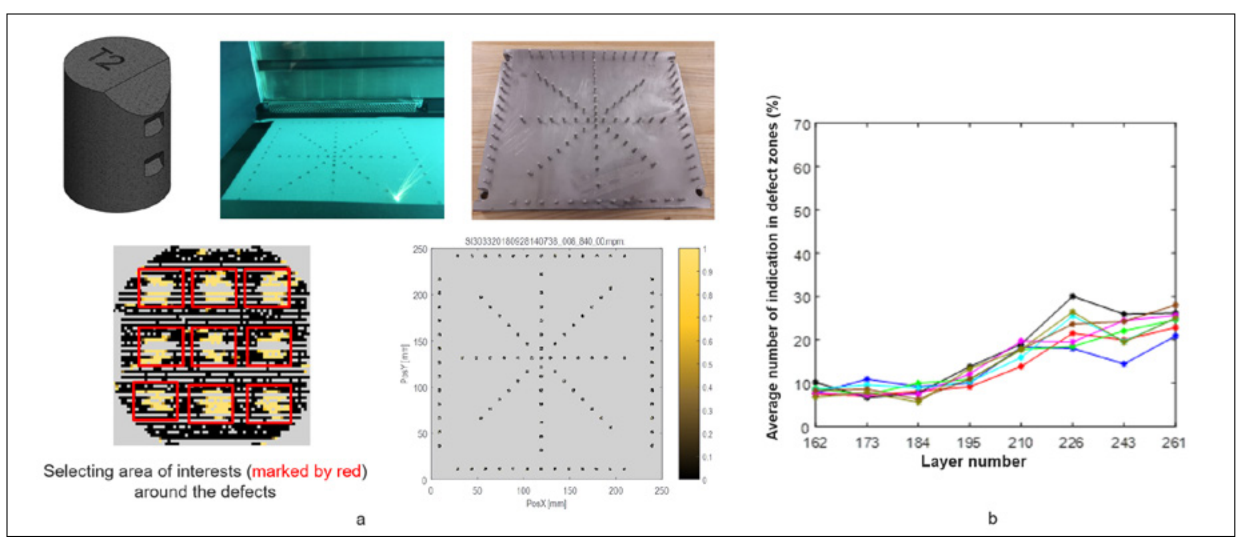
Due to process variability and complexity, metal AM processes suffer from low productivity and excessive variability in part performance. This limits their adoption in critical applications. In addition to the melt pool geometry, it is important to monitor thermal history to detect solidification and cooling rates. Monitoring these rates is challenging due to the fluctuating material emissivity during part build. The use of multiple real-time control sensors will create a stream of "big data" that will require special machine learning algorithms. In this project, researchers are integrating novel machine and deep learning algorithms to LPB- and LPF-AM processes to control part variability.

PROGRESS

- Conducted experimental design studies to investigate the effect of spatial parameters on surface roughness and powder inter-/intra-layer organization as part of the efforts to model the melting mode transition in EBM.
- Installed and tested light recording sensors in a LPB system for melt pool monitoring in order to develop quality assurance algorithms. Correlating the properties of artificial defects embedded in AM builds to the sensors' signal perturbation is in progress.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
3.2.1 Knowledge-based Lumped Models	• Mihaela Vlasea, University of Waterloo • Kaan Erkorkmaz, University of Waterloo	• Gitanjali Shanbhag, University of Waterloo, PhD • Sagar Patel, University of Waterloo, PhD (Collaborator) • Ahmet Okyay, University of Waterloo, RA
3.2.2 Development of Intelligent Controllers	• Ehsan Toyserkani, University of Waterloo	• Katayoon Taherkhani, University of Waterloo, PhD • Esmat Sheydaeian, University of Waterloo, PDF (Collaborator) • Winston Ma, University of Waterloo, PhD (Collaborator)



Design and analysis of a test sample embedded with artificial defects (sub-project 3.2.2)

Project 3.3: Intelligent Closed-loop Control of Compaction Density for Powder-bed Based AM Processes

DESCRIPTION

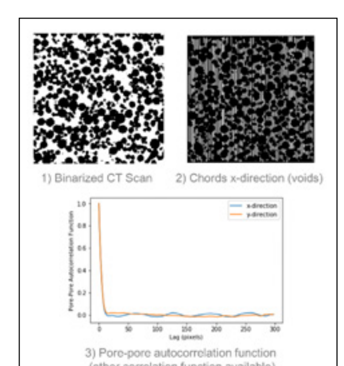
The properties of parts manufactured using powder bed metal AM processes are directly affected by the specifications of the powder layer such as powder morphology, layer thickness, and applied powder compaction force. The compaction force is particularly important as it affects powder packing density. The lack of control over compaction densities in turn results in many issues such as instability in the melt pool and inconsistency in part density, porosity, and mechanical strength. This project investigates methods to control the compaction force, particularly the distribution of mechanical stress applied by the roller on the powder build bed.

PROGRESS

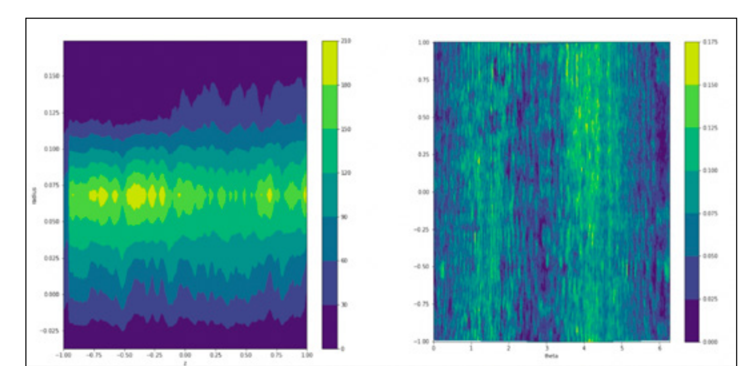
- Implemented a discrete element method to develop a dynamic powder compaction/spread model.
- Developed multiple pore network reconstruction techniques to model liquid-powder imbibition. The experimental validation of the models using CT scanning and high speed imaging is ongoing.
- Developed two experimental platforms to detect the powder compaction experimentally. The work on adding sensors utilizing active thermography or acoustics to the platforms is ongoing.
- Currently developing new algorithms to allow for changing the greyscale binder levels through dithering in a custom binder jetting machine.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
3.3.1 Measurement System Development and Validation of Combined Powder Spread, Compaction and Binder Fluid Dynamics Linked with Sintering Model	• Kaan Erkorkmaz, University of Waterloo • Mihaela Vlasea, University of Waterloo	• Alex Groen, University of Waterloo, MASc • Mark Wang, University of Waterloo, MASc (Collaborator)
3.3.2 Closed-loop Control of Compaction Density and Binder Imbibition and Experimental Validation	• Mihaela Vlasea, University of Waterloo • Kaan Erkorkmaz, University of Waterloo	• Alex Groen, University of Waterloo, MASc • Mark Wang, University of Waterloo, MASc (Collaborator)



Preliminary analysis of FeSi green PBBJ part pore network (sub-project 3.3.1)



Particle organization and distribution as a function of layer stacking along the product height (sub-project 3.3.2)

Project 3.4: Process-based Adaptive Path Planning Protocols for LPF-AM

DESCRIPTION

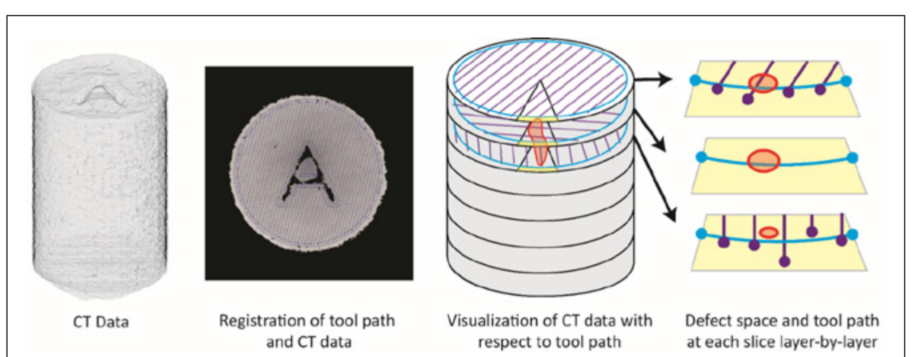
Industry currently uses a limited number of path planning algorithms/protocols (e.g. raster path determination) based on proprietary algorithms that accommodates desired part characteristics. However, for parts with multi-materials and special internal architectures, such as molds and turbojet nozzles, novel adaptive path planning protocols are needed to fulfill AM promises. This project investigates adaptive path planning protocols for continuous and pulsed laser AM processes and integrates the knowledge of process modeling and optimized geometrical designs.

PROGRESS

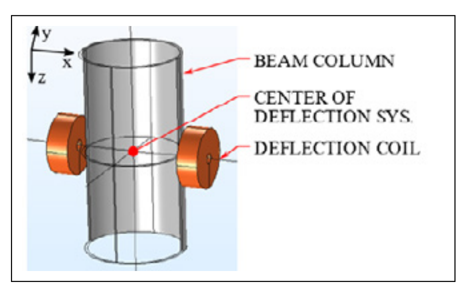
- Retrofit an electron beam welding machine for AM, including the development of z-axis linear drive and material deposition systems.
- Developed an analytical model of a two-axis EB deflection system and a FEM of a single-axis EB deflection system to predict the beam position and the states of deflection, respectively, in order to obtain adequate precision for trajectory optimization.
- Designed and built a single-axis deflection system experimental setup to measure the magnetic flux density distribution of the system for a given input signal in order to validate the beam position/state predictive models.
- Deployed an analytical approach to model the thermal melt pool morphology along deposition path. The models are being calibrated based on experimental data and validated.
- An experimentally-driven model based on system identification is under development.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
3.4.1 Combined Trajectory Optimization and Thermal Analytical Models	• Yusuf Altintas, The University of British Columbia	• Scott Parks, The University o British Columbia, MASc • Varun Jacob-John, The University of British Columbia, MASc (Collaborator) • Graham Williamson, The University of British Columbia, MEng (Collaborator)
3.4.2 Adaptive Path Planning Protocols/ Controllers and Experimental Validation	• Mihaela Vlasea, University of Waterloo	• Gijs Johannes Jozef van Houtum, University of Waterloo, PhD • Deniz Sera Ertay, University of Waterloo, PhD (Collaborator)



Adaptive path planning for LPB (sub-project 3.4.2)



Section view of single axis deflection system modelled in COMSOL Multiphysics (sub-project 3.4.1)

Research Progress

THEME 4: INNOVATIVE AM PROCESSES AND AM-MADE PRODUCTS

Mathieu Brochu
PhD, ing.
ASSOCIATE DIRECTOR AND THEME 4 LEADER
McGill University
Dept. of Materials Engineering

An important advantage of using AM processes is the ability to create complex shapes that are impossible to make by conventional manufacturing methods. Examples include, but are not limited to, multi-material molds with conformal channels, functionally graded materials, cellular structures, and optimized orthopedic implants. Another advantage of AM is that its processes can be used to repair high-value parts. Being able to repair parts rather than replacing them is forecasted to revolutionize the supply of spare parts. Large numbers of parts would no longer need to be readily available (saving costs) and delays related to part availability would be eliminated (saving time and cost). To accelerate the industrialization of AM and to update its design and application, strategic process roadmaps should be developed. One process challenge that impedes this up-take is the low speed of the AM platforms, e.g. the low powder catchment efficiency in DED processes resulting in powder loss and lower production speed. The research outcomes of Theme 4 will provide innovative new methods to address these issues and to facilitate wider adoption of metal AM processes.

Project 4.1: Innovative AM Processes with Integrated Magnetic Systems

DESCRIPTION

Currently, LPF-AM suffers from low powder catchment efficiency mainly due to a large powder stream divergence angle. This challenge might be addressed through the implementation of a magnetic focusing module integrated in the processing head of LPF-AM. In addition, there is an opportunity to develop a novel LPF-AM-based process, in which the initial material substrate will be levitated using magnetic fields. The main advantage of this technique is that the scope of manufactured parts will not be limited by the supporting platform, an appealing option for many applications in aerospace and automotive.

PROGRESS

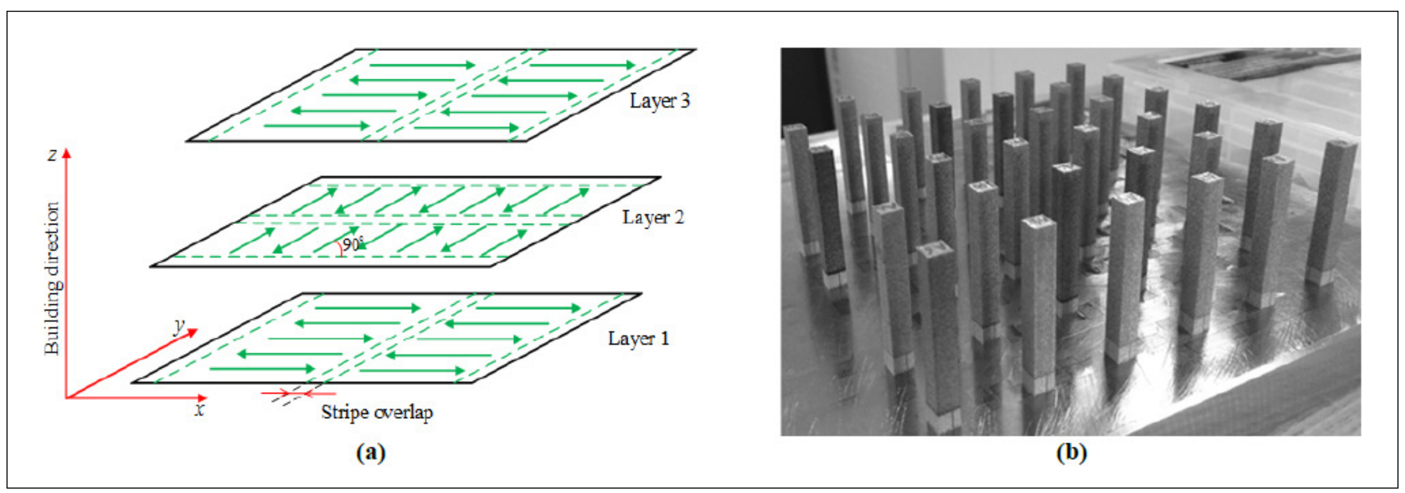
- Investigated the role of eddy current and also static magnetic ring on the powder stream through numerical modeling and experimental validation.
- Established a particle size threshold for the effective control of the powder stream using eddy current.
- Modelled and validated the effect of a vacuum port in the nozzle to improve powder catchment efficiency in LPF.
- Commenced development of methodologies for embedding optical sensors in LPB-made parts and look-up tables guiding the feature optimization of cellular structures through topology optimization.
- Initiated the analytical and numerical modeling of magnetic levitation forces.

Continued on next page...

Project 4.1: Innovative AM Processes with Integrated Magnetic Systems (Continued)

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
4.1.1(i) Magnetically Driven Vacuum-based Powder Delivery Processing Head for LPF-AM (Completed)	• Ehsan Toyserkani, University of Waterloo • Behrad Khamesee, University of Waterloo	• Kelvin Jisoo Son, University of Waterloo, MASc • Yuze Huang, University of Waterloo, PhD / PDF • Ken Nsiempba, University of Waterloo, MASc
4.1.1(ii) Embedding Optical Sensors Inside Optimized Lightweight Structure Made by Laser Powder-bed Fusion	• Ehsan Toyserkani, University of Waterloo	• Kelvin Jisoo Son, University of Waterloo, MASc • Yuze Huang, University of Waterloo, PhD / PDF • Ken Nsiempba, University of Waterloo, MASc
4.1.2 Levitated Additive Manufacturing	• Ehsan Toyserkani, University of Waterloo • Behrad Khamesee, University of Waterloo	• Parichit Kumar, University of Waterloo, PhD • Yuze Huang, University of Waterloo, PDF



Scanning pattern (a) and sample image (b) for LPBF fabrication with SS 17-4 powder (sub-project 4.1.1)

Project 4.2: Development of Innovative Architectural/Cellular/Lightweight/Smart Products

DESCRIPTION

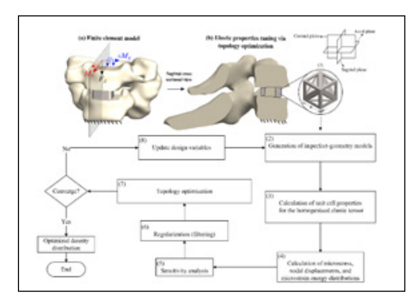
AM is creating new possibilities for developing architectural materials specifically for medical applications. The Project 4.2.1 team is integrating the knowledge of traditional materials used in implants and the optimization abilities gained from Themes 1 to 3, to circumvent some of the key challenges in production of such structures such as: homogeneous microstructure development, distortion, and defect control. Manufacturing processes such as injection molding, die casting, and extrusion require the careful control of surface temperature and heat transfer rates to increase production and improve product quality. Developing efficient AM design optimization methods to improve the manufacturing of conformal cooling channels, and embedding sensors in molds is pursued under project 4.2.2.

PROGRESS

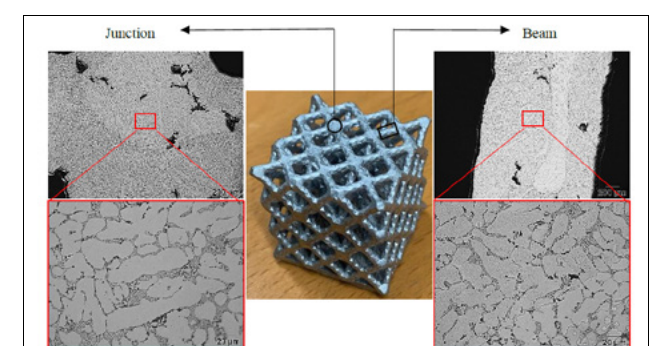
- Reconstructed bone geometry from CT data and assembled with the designed implant.
- Characterized unit cell topology and generated imperfect-geometry models using statistical representation of geometric defects. Manufacturing of the samples made from select unit cell topology and investigation of morphological parameters governing the manufacturing imperfections is ongoing.
- Proposed and evaluated a new method for conformal cooling with a porous structure in order to improve the injection molding performance.
- Developed an algorithm for allocation of sensor space in injection molds.
- Developed optimization algorithms to reduce part temperature variations and a temperature surrogate model trained with artificial neural network. The experimental evaluation of the results of the optimized conformal cooling channel is being carried out.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
4.2.1 Metal AM for Orthopaedic and Implants Technologies	• Damiano Pasini, McGill University	• Ahmed Moussa, McGill University, PhD
4.2.2 Development of Smart Molds with Embedded Optical Sensors and Conformal Channels	• Yaoyao Fiona Zhao, McGill University	• Tang Yunlong, McGill University, PDF • Zhenyang Gao, McGill University, PhD



Process for design and manufacturing of metal implants (sub-project 4.2.1)



A356 lattice structure produced by HIC and the optical micrographs of a longitudinal section of a beam (right) and cross-section of a junction (left). The darkest areas are shrinkage porosities, the light areas are the α-Al matrix surrounded by the eutectic structures. (University of Alberta)

Project 4.3: Development of Innovative FGM Products

DESCRIPTION

Using functionally graded materials (FGM) in AM will enable the tailoring of physical, chemical, and mechanical properties to obtain the desired part functions. The novel materials are typically fabricated by DED methods where multi-deposition nozzles for powder or feeders for wire are simultaneously used to selectively deposit a different metal or alloy at the specific location during manufacturing. Project 4.3 researchers use the research outcomes of sub-project 1.2.2 in the manufacturing of FGM parts, including metal matrix composites (MMCs), with applications in the direct manufacturing of wear-resistant parts, or the repair/cladding of worn and/or corroded parts.

PROGRESS

- The evaluation of the behavior of Ni alloy WC under high loadings using an electromagnetic levitator is in progress. Using PTA-AM for fabrication of FGM structures will be carried out upon completion of the material analyses.
- Developing the appropriate baseline data for subsequent comparison of the properties of materials that will be used in production of FGM molds.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
4.3.1 Direct Manufacturing of FGM Advanced Part Using PTA-AM	• Hani Henein, University of Alberta	• Zahra Abedy, University of Alberta, MASc
4.3.2 Direct Manufacturing of FGM Molds Using LPF-AM	• Kevin Plucknett, Dalhousie University	• Samer Tawfik, Dalhousie University, PhD

Project 4.4: Advanced LPF-, EWF-, and PTA-AM for Repair and Remanufacturing

DESCRIPTION

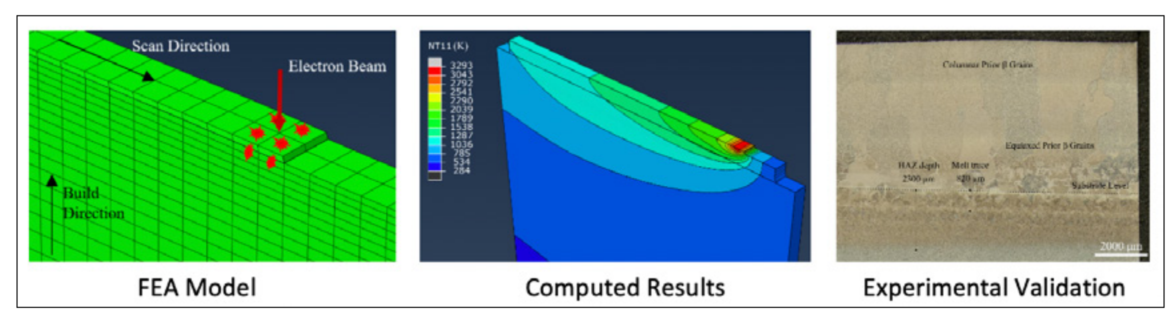
The use of AM for repairing parts is a new concept providing an opportunity to develop novel cost-effective approaches for a variety of metallic alloy substrates. DED processes are specifically well suited for repairing as they allow site-specific repair or surface modification, such that minimal finish machining is required after cladding. The team is investigating the new alloys developed in Project 1.1 as potential new options as a filler material for the repair of parts with matching compositions. Various DED processes including LPF-, PTA-, and EWF-AM are being investigated to compare their results in terms of quality, cost effectiveness, and physical properties.

PROGRESS

- Procured and characterized substrate materials and commercial feedstock powders for LPF repair strategies.
- Adapted a micro-composite powder production method previously developed for HVOF thermal spraying for LPF process. Micro-composite feedstock has been prepared for deposition onto tool steel.
- Designed and constructed a custom-made coating system for dip coating of the substrate materials as an alternate "pre-placement" coating method. Development and rheological characterization of suspensions for dip coating is ongoing.
- Developed a repair-centered thermo-mechanical FEM of the EWF process. The experimental validation of the model is ongoing.
- Investigated the effects of oxygen contamination on mechanical and microstructural properties of titanium alloys
- Fabricated multiple metal-polymer and ceramic-polymer filaments for 3D printing of test specimens using fused filament fabrication (FFF) technology. The particle content optimization is ongoing.
- Commenced studies on vacuum sintering process conditions to optimize densification and microstructure of final products of FFF process.

SUB-PROJECTS AND RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
4.4.1 Repair Strategies with LPF-AM	• Kevin Plucknett, Dalhousie University	• Zhila Russel, Dalhousie University
4.4.2 Repair Strategies Using EWF-AM	• Mathieu Brochu, McGill University	• Fatih Sikan, McGill University, PhD
4.4.3 Repair Strategies Using PTA- and FFF-AM	• Hani Henein, University of Alberta	• Nancy Bhardwaj, University of Alberta, MASc



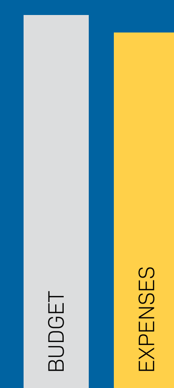
Modeling of repair process using electron wire fed AM (sub-project 4.4.2)

Finances

The HI-AM Network receives funding mainly from NSERC. The Network received $1 million in its first year, and will receive $1.125 million each year after that. This funding is matched by both industry funds, and institutional support from the Universities participating in the Network. As the Network was slow to start, funding at the institutions was delayed, influencing the spending to date. This is expected to accelerate in the next year, catching up with the NSERC spending.

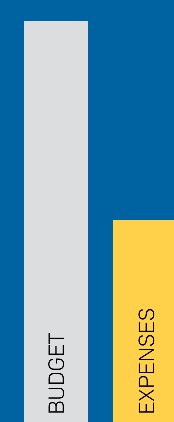
YEAR ONE AND TWO NSERC FUNDING (2017-2019)

	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$ 761,179	$ 532,396
THEME 2	$ 374,810	$ 278,540
THEME 3	$ 266,010	$ 381,519
THEME 4	$ 298,335	$ 369,414
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$ 424,666	$ 462,428
TOTAL	**$ 2,125,000**	**$ 2,024,297**



YEAR ONE AND TWO INDUSTRY/GOVERNMENT PARTNER AND INSTITUTIONS CONTRIBUTIONS (2017-2019)

	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$ 240,541	$ 64,776
THEME 2	$ 203,500	$ 59,324
THEME 3	$ 105,080	$ 42,903
THEME 4	$ 170,955	$ 92,380
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$ 25,750	$ 127,678
TOTAL	**$ 745,826**	**$ 387,061**



*Some data has been prorated, as reporting was not yet received at time of publication.

Outreach and Knowledge Transfer

The HI-AM Network fosters communication and information exchange both inside and outside the Network in numerous ways including Network events, online presence and social media, interaction with additive manufacturing magazines, participation in international engineering conferences, training undergraduate students, and domestic and international exchanges.

HI-AM Conference

The HI-AM Conference is the Network's most important event taking place annually in Spring/Summer to facilitate the dissemination of HI-AM research results to the scientific community and among HI-AM Network members. The first and second HI-AM Conferences were hosted by the University of Waterloo at 2018 and the University of British Columbia at 2019, respectively. As the only academic conference dedicated to additive manufacturing in Canada, these events have attracted many additive manufacturing professionals from outside the Network. The HI-AM Conference includes presentation of cutting-edge research on metal AM by HI-AM and external researchers, a poster session, networking dinner, and Board of Directors and Scientific Committee meetings.

HI-AM 2018

The first HI-AM Conference was a two-day event held on May 22-23, 2018 at Federation Hall, Waterloo, ON. The conference started with remarks from Feridun Hamdullahpur, President and Vice Chancellor of the University of Waterloo and Ehsan Toyserkani, Network Director. The morning session continued by introduction of AM R&D facilities at the 7 universities of HI-AM Network by associated Node Leaders. 18 research papers and 15 posters were presented by HI-AM HQP. The conference also included 4 keynote presentations by Mohammad Ehteshami, General Manager, GE Additive, United States; Mohsen Seifi, Director of Global Additive Manufacturing Programs, ASTM International, United States; Ian Gibson, Professor, Deakin University, Australia; and Timothy Simpson, Professor, Penn State University, United States.

HI-AM Conference 2018 opening by Feridun Hamdullahpur, President and Vice-Chancellor of University of Waterloo

HI-AM Conference 2018, University of Waterloo

HI-AM 2018 CONTINUED

During the first day, Canada Makes' first 3D Design Challenge Award was presented to Master of Applied Science students Lisa Brock and Yanli Zhu from University of Waterloo for their design of biodegradable packaging made from mushroom roots using binder jetting technology.

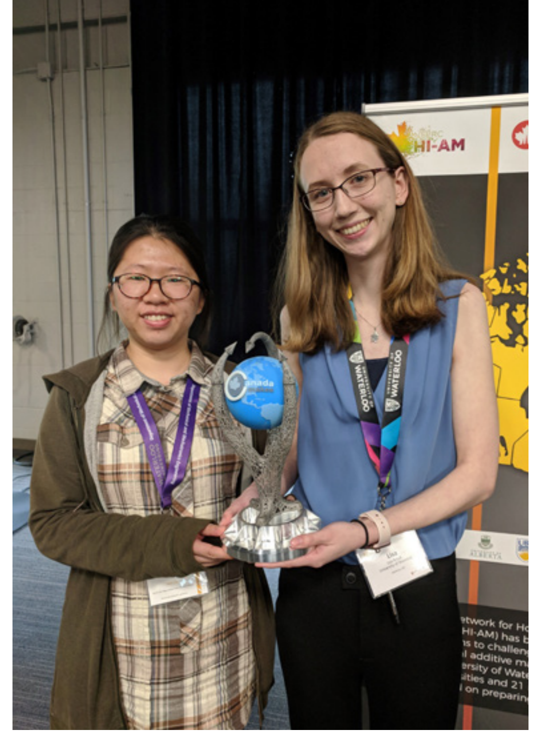
The conference ended by remarks from Ralph Resnick, Chair of HI-AM Board of Directors and Mathieu Brochu of McGill University, Network Associate Director. The three best paper and poster presentation awards were presented to the following HQP during the conference closing:

PRESENTATION COMPETITION:

- **First place:** Issa Rishmawi, University of Waterloo
- **Second place:** Usman Ali, University of Waterloo
- **Third place:** Louis Simoneau, Université Laval

POSTER COMPETITION:

- **First place:** Karolina Stepniak, University of Toronto
- **Second place:** Mehrnaz Salarian, University of Waterloo
- **Third place:** Lisa Brock, University of Waterloo



Recipients of Canada Makes 3D Design Challenge Award: (from left) Yanli Zhu, MASc Candidate, University of Waterloo; Lisa Brock, MASc Candidate, University of Waterloo

HI-AM 2019

The second HI-AM conference took place on June 26-27, 2019 at The AMC, Vancouver, BC, and was co-chaired by Steve Cockcroft of UBC and Ehsan Toyserkani of University of Waterloo. This conference brought together approximately 200 AM professionals from academia, government, industry, and research centers from five continents. The conference opened with a video message from Santa Ono, the President and Vice-Chancellor of the University of British Columbia, followed by welcoming remarks from James Olson, Dean of the UBC Faculty of Applied Science and Ehsan Toyserkani, the Network Director.

HI-AM Conference 2019, The University of British Columbia

Poster session – HI-AM Conference 2019

HI-AM Conference 2019, The University of British Columbia

Sponsors exhibition - HI-AM Conference 2019

HI-AM 2019 CONTINUED

The conference included 5 keynote presentations from David Bourell, Temple Foundation Professor, University of Texas at Austin, United States; Christoph Leyens, Managing Director, Fraunhofer Institute of Materials and Beam Technology, Germany; Hannes Gostner, Director Research and Development, EOS, Germany; Milan Brandt, Director Centre for Additive Manufacturing, RMIT, Australia, and Ali Bonakdar, Advanced Manufacturing Technology Lead, Siemens, Canada

The conference included 50 oral presentations and 44 posters on different aspects of metal additive manufacturing research including multi-scale modeling of AM systems, novel monitoring/metrology systems for AM, metal feedstock development, recycling strategies, etc.

A highlight of the 2019 conference was the industry exhibition that provided an opportunity for Network members to interact with representatives of leading AM machine and characterization system manufacturers at the conference. This event was supported by KSB, MSAM Laboratory, EOS, Trumpf, Pulstec, Cimetrix, Rapidia, Optomec, Keyence, Stresstech, Canada Makes, America Makes, and Ontario Advanced Manufacturing Consortium.

The conference closing remarks were given by Andrew Szeri, UBC VP Academic and Provost and Mathieu Brochu, Network Associate Director. The conference concluded by announcement of the winners of the student presentation competitions. The 2019 winners were:

PRESENTATION COMPETITION:

- **First place:** Meet Upadhyay, University of British Columbia
- **Second place:** Dylan Rose, University of Alberta
- **Third place:** Lucas Botelho, University of Waterloo

POSTER COMPETITION:

- **First place:** Anatolie Timercan, ETS Montreal
- **Second place:** Henrique Ramos, Federal University of ABC, Brazil
- **Third place:** Nick Gosse, Dalhousie University

Santa Ono, President and Vice-Chancellor of the University of British Columbia, addressed the HI-AM 2019 opening through a video message

Steve Cockcroft, Conference Chair, speaking at the Conference Gala

Ralph Resnick, Chairman of the Board, speaking at the Conference Gala

Events with HI-AM Representation:

University of Toronto, University of Tokyo, and McMaster (UT2-MAC) Joint Workshop

June 27, 2019

CIRP Conference on Manufacturing Systems, Ljubljiana, Slovenia

June 12, 2019

Aero 2019, Canadian Aeronautics and Space Institute, Laval, QB

Canada, May 15, 2019

Invited Lecture, Taipei Tech University, Taiwan

April 23, 2019

Additive Manufacturing and Welding Symposium, TMS 2019 Annual Meeting and Exhibition, San Antonio, TX, USA

March 11-14, 2019

2018 MRS Fall Meeting and Exhibit, Boston, MA, USA

November 25-30, 2018

QANSAS, Agra, India

November 23, 2018

Opportunities of Additive Manufacturing for Energy Industry Panel, Edmonton, AB

October 11, 2018

CME-Canada Makes Symposium, Waterloo, ON, Canada

October 24, 2018

Materials Science and Technology 2018 (MS&T), Columbus, OH

October 14, 2018

Additive Manufacturing Alberta by Innotech Alberta, Edmonton, AB, Canada

October 10-11, 2018

World Congress on Micro and Nano Fabrication, Portorož, Slovenia

September 18, 2018

ASME SMASIS 2018, San Antonio, TX, USA

September 10-12, 2018

ASPE and euspen Summer Topical Meeting on Advancing Precision in Additive Manufacturing, Berkeley, USA

July 2018

28th CIRP Design Conference, Nantes, France

May 2018

Laser Additive Manufacturing Conference, Chicago, IL, USA

March 28, 2018

APICAM 2017, Melbourne, Australia

December 5, 2017

CME-Canada Makes Symposium, Waterloo, ON, Canada

October 11, 2017

TraCLite/Fraunhofer/EOS/Waterloo Workshop, Waterloo, ON, Canada

September 28, 2017

University of Waterloo Engineering Faculty Council, Waterloo, ON, Canada

September 19, 2017

2nd Seminar of the European Group of Research in Tolerancing, Metz, France,

June, 2017

HI-AM Network in the News:

Putting EBM at the heart of additive materials research in Canada, GE Additive (ge.com)

June 26, 2019

HI-AM Network at the Forefront of Tangible Breakthroughs in AM Capabilities and Processes: Exclusive Q&A with HI-AM Director Ehsan Toyserkani, AMazing (additivemanufacturing.com)

May 28, 2019

Canadian Researchers Help Pave the Way for Industrial Adoption of Additive Manufacturing, AMazing (additivemanufacturing.com)

January 22, 2019

Canada's Brightest Minds Collaborate on Bold Ideas for a Better Future, NSERC

August 10, 2018

Holistic Innovation in Additive Manufacturing Conference to Run at Canada's University of Waterloo, Metal AM Magazine

May 7, 2018

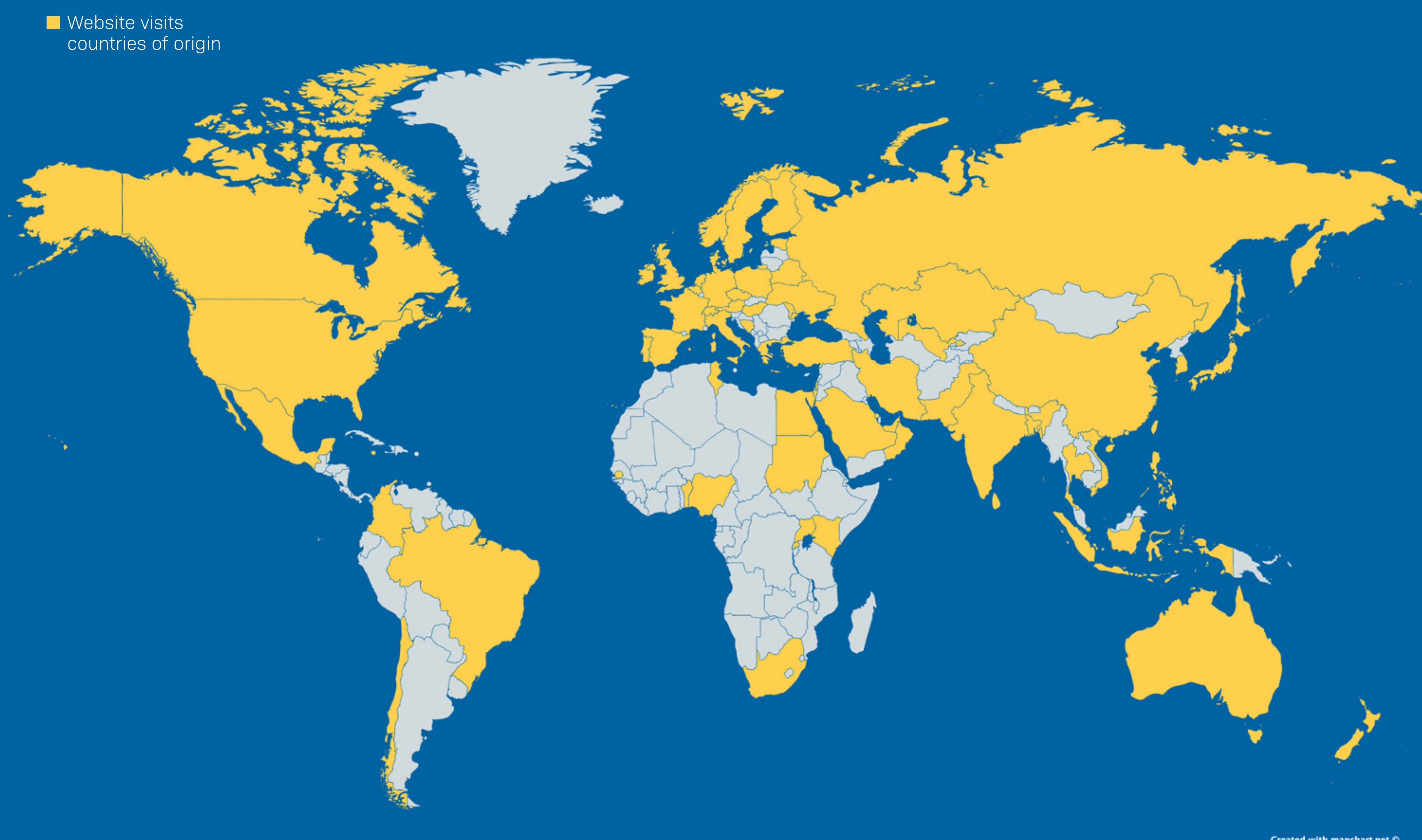
Additive Manufacturing: A Key Enabler of Advanced Manufacturing, The Canadian Society for Mechanical Engineering Bulletin

Spring 2018

HI-AM has been successful in attracting world-class international collaborators from USA, Singapore, Germany, England, Taiwan, Australia, and the Netherlands. The number of our international collaborators has doubled since the announcement of the Network.

7000+
WEBSITE VISITS

68
COUNTRIES



Interaction with Domestic and International Partners

Academic, government, and international researchers with complementary expertise are needed to successfully accomplish the diverse scientific objectives of the Network's Research Program. HI-AM has been successful in attracting world-class international collaborators from USA, Singapore, Germany, England, Taiwan, Australia, and the Netherlands. The number of our international collaborators has doubled since the announcement of the Network. These collaborators contribute to HI-AM by participating in complimentary research projects, through reciprocal exchanges with Network researchers in their laboratories and research facilities, and through participation in Network meetings and conferences.

The exchange program kicked off in the second year of the Network with participation of National Institute of Standards and Technology (NIST) and Singapore 3D Printing Centre. The following HQP have been selected for 4-month exchange terms scheduled to start between Fall 2019 and Spring 2020:

PROJECT: POWDER CHARACTERIZATION

- National Institute of Standards and Technology (NIST), Gaithersburg, MD, United States
- Exchange award recipient 1: Aniruddha Das, MASc Candidate, McGill University
- Exchange award recipient 2: Gitanjali Shanbhag, PhD Candidate, University of Waterloo

PROJECT: METAL 3D PRINTING IN DENTAL APPLICATIONS

- Singapore Center for 3D Printing, Singapore
- Exchange award recipient: Arman Khobzi, MASc Candidate, The University of British Columbia

PROJECT: MODELING OF THE POWDER BED FUSION PROCESS

- Singapore Center for 3D Printing, Singapore
- Exchange award recipient: Ken Nsiempba, MASc Candidate, University of Waterloo

PROJECT: DEVELOPMENT AND INTEGRATION OF FEATURE DETECTION ALGORITHMS FOR METAL-BASED DIRECT DEPOSITION PROCESSES

- Xiris Automation Inc., Burlington, ON, Canada
- Exchange award recipient: Gijs Johannes Jozef van Houtum, University of Waterloo

More exchange positions have been secured at RMIT, Fraunhofer IFAM, and Twente University for Year 3. It is envisioned that student participation in research exchanges with domestic and international partners will strengthen Network linkages, facilitate technology transfer, broaden their expertise, and lead to increased HQP marketability through interactions with HI-AM co-investigators, collaborators, industry technical experts, and government and international research partners.

HI-AM Conference

3rd | 2020

JUNE 25 & 26, 2020

McGill UNIVERSITY

McGILL UNIVERSITY
MONTRÉAL, QC, CANADA

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UNIVERSITY OF WATERLOO | Department of Mechanical and Mechatronics Engineering

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