NSERC HI-AM Network

2019–2020 NSERC-HI-AM.CA @NSERC_HI_AM

HOLISTIC INNOVATION IN ADDITIVE MANUFACTURING

PROGRESS REPORT 2

NSERC HI-AM

UNIVERSITY OF WATERLOO | Department of Mechanical and Mechatronics Engineering

NSERC CRSNG

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CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

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PROGRESS REPORT 2

2019-2020

READ OUR PREVIOUS PROGRESS REPORT: 2017-2019

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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 second progress report of the NSERC Strategic Network for Holistic Innovation in Additive Manufacturing (HI-AM). In addition to an overview of the Network vision, mission and governance, this report summarizes the research outcomes and network activities that took place between July 2019 and July 2020.

First and foremost, we are very grateful to the members of the Network, including 19 Principal Investigators, 22 Industry/Government/Non-profit partners, 95 highly qualified personnel, two academic collaborators, and ten international academic partners. Furthermore, we recognize the contributions of the members of the Board of Directors, the Scientific Advisory Committee, and the Commercialization and Outreach Advisory Committee.

We are very pleased to let you know that we have 37 active projects across four research themes under the supervision of the Network principal investigators. More than 180 journal and conference papers have been produced through these projects. This number is more than 250 papers if we include those papers that are produced by the HI-AM researchers related to metal AM but not directly supported by HI-AM financially. Additionally, three invention disclosures have been filed, and interesting and impactful results are now emerging from the HI-AM R&D teams. Efforts are being made to commercialize these inventions through our industrial partners.

As we entered 2020, many of our plans were affected by the global pandemic. We originally planned to hold the 2020 HI-AM conference at McGill University in Montreal; however, the pandemic gave us no choice but to either cancel the conference or organize it online. As we believe that the scientific progress and sharing research results should not stop, we decided to use a virtual conference platform to organize the HI-AM conference online. The online HI-AM conference, held on June 25th and 26th, 2020, included 99 talks and poster presentations. This conference would not have been possible without the contributions of many individuals and organizations. In particular, we would like to extend our appreciation to the Natural Sciences and Engineering Research Council of Canada (NSERC), University of Waterloo, McGill University, Javelin Technologies, EOS, KEYENCE CORPORATION, KSB Company, Leichtbau BW GmbH, Multi-Scale Additive Manufacturing Laboratory, Promation, Proto3000, TRUMPF, and Xact Metal.

One of the major negative impacts of the pandemic has been the cancellation of our exchange programs in 2020. In addition, several outreach programs have been delayed. The network manager is working very hard to push these activities to 2021 with the hope that the global pandemic will have subsided by Spring 2021. It is also obvious that several experimental projects have been altered, and we will face some progress delays in these projects.

We appreciate you taking the time to read this report, and we hope you find it useful. To learn more about the Network statistics and progress, please explore the HI-AM Network website at **nserc-hi-am.ca**. If you need any further information, please feel free to contact our Network Manager, Farzad Liravi, at **fliravi@uwaterloo.ca**.

Sincerely Yours,

Ralph Resnick,
Chair of the Board of Directors

Ehsan Toyserkani,
Network Director

Shaping the Future of Additive Manufacturing

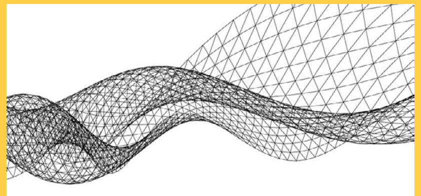
Additive Manufacturing (AM) has the potential to change the entire manufacturing sector by 2030. Despite the recent progress in this field, there are several remaining challenges hindering the widespread industrialization of this technology, from expensive and limited powder feedstock to the need for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



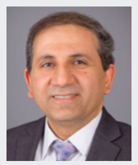
THEME 2: Advanced Process Modeling and Coupled Component/Process Design

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

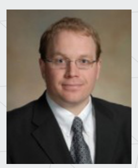
THEME 4: Innovative AM Processes and AM-made Parts

Principal Investigators

THEME/NODE LEADERS



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



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

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PhD, PEng
THEME 1 LEADER,
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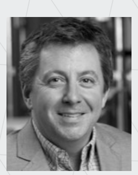

Carl Blais
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NODE LEADER
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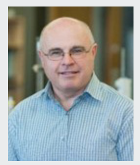
Département de la métallurgie et des matériaux



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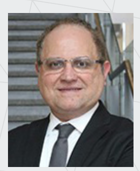
Dept. of Chemical and Materials Engineering



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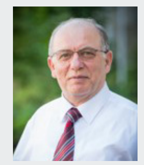
CO-INVESTIGATORS



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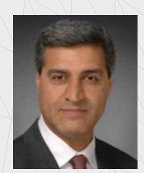

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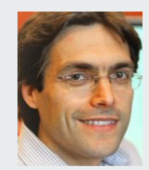

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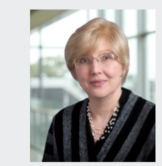
Département de génie mécanique



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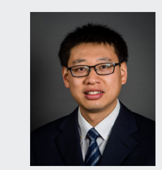
Dept. of Mechanical, Automotive and Materials Engineering



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

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.

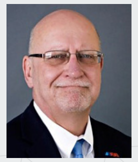
ADVANCING THE AM INFRASTRUCTURE at four universities involved in the Network (University of Waterloo, Dalhousie University, The University of British Columbia, and McGill University) through a CFI AM initiative.

Governance

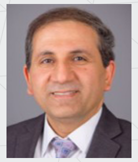
BOARD OF DIRECTORS*

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.

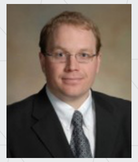
VOTING MEMBERS



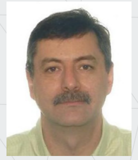
Ralph Resnick
Chair
America Makes, USA
Founding Director, President and Executive Director of NCDMM (Retired)



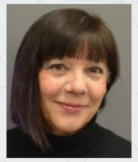
Ehsan Toyserkani
University of Waterloo, Canada
Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Mechanical and Mechatronics Engineering



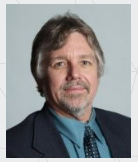
Mathieu Brochu
McGill University, Canada
Associate Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Materials Engineering



Stefano Chiovelli
Syncrude, Canada
Senior Technical Advisor



Vesna Cota
Tyco Electronics, Canada
Additive Manufacturing Specialist (Retired)

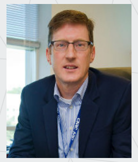


Ian Donaldson
GKN, Canada
Director, Advanced Engineering Applications

Mohammad Ehteshami
GE Additive, USA
CEO (Retired)

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

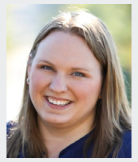
Benoit Leduc
Ministry of Innovation, Science and Economic Development, Canada
Manager of Life Science Industries Directorate



David Muir
National Research Council Canada
Director, Research and Development

Mark Zimny
Promation, Canada
President

NON-VOTING MEMBERS



Catherine Demers
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Financial Manager, NSERC HI-AM Network & CFI Can-AMN

Farzad Liravi
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Manager, NSERC HI-AM Network & CFI Can-AMN

Linda Martin
NSERC, Canada
Manager, Research Partnerships

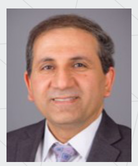
Denise Porter
University of Waterloo, Canada
Financial Advisor, NSERC HI-AM Network & CFI Can-AMN

*As of October 2020

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.



Ehsan Toyserkani
University of Waterloo, Canada
Director, NSERC HI-AM Network
Professor of Mechanical and Mechatronics Engineering

Paul Bishop
Dalhousie University, Canada
Professor of Mechanical Engineering

Carl Blais
Université Laval, Canada
Professor of Mining, Metallurgy and Materials Engineering

Ali Bonakdar
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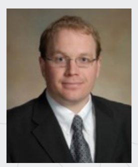
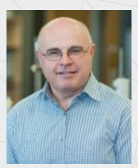
Advanced Manufacturing Leader

Milan Brandt
RMIT, Australia
Professor of Manufacturing, Materials and Mechatronics



Mathieu Brochu
McGill University, Canada
Associate Director, NSERC HI-AM Network
Professor of Materials Engineering

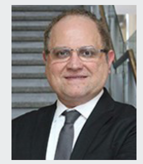


Steve Cockcroft
The University of British Columbia, Canada
Professor of Materials Engineering

Ian Gibson
UT Twente, The Netherlands
Professor of Design Engineering

Mahdi Habibnejad
GE additive – AP&C Advanced Powders and Coating Inc., Canada
Senior External R&D Manager

Hani Henein
University of Alberta, Canada
Professor of Chemical and Materials Engineering



Hani Naguib
University of Toronto, Canada
Professor of Materials Science and Engineering

Behrang Poorganji
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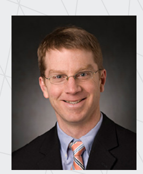
Materials Development Manager

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

Carolyn Seepersad
The University of Texas at Austin, USA
J. Mike Walker Professor of Mechanical Engineering



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

Tonya Wolfe
Elementiam Materials and Manufacturing Inc., Canada
CEO and Co-founder

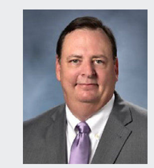
*As of October 2020

COMMERCIALIZATION AND OUTREACH ADVISORY COMMITTEE*

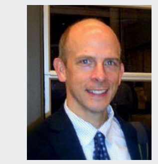
The Commercialization and Outreach Advisory Committee liaises with HI-AM Partners on IP-related matters, and acts as an additional resource to HI-AM Partners in the commercialization of the Network results. This committee also provides recommendations and feedback on technology development necessary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

Gary Brock
Chair
University of Waterloo, Canada
Director of Strategic Initiatives

Michael Barré
IRAP - NRC, Canada
Industrial Technology Advisor



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

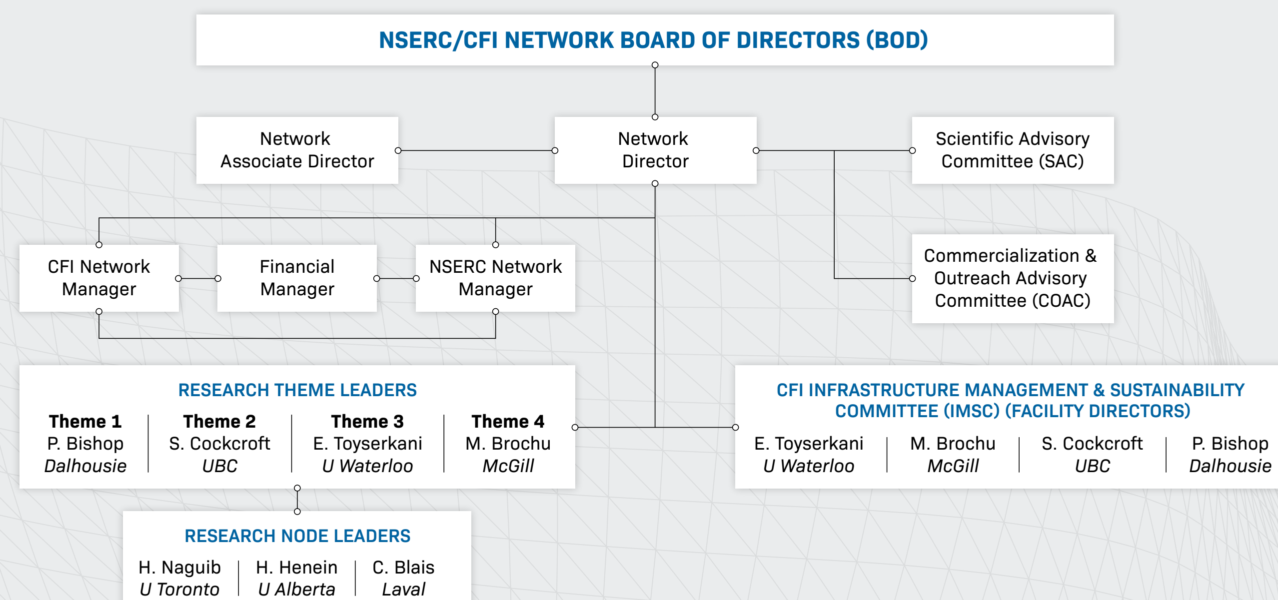


Dave Dietz
University of Waterloo, Canada
Director of Engineering Research

Farzad Liravi
University of Waterloo, Canada
Manager, NSERC HI-AM Network

*As of October 2020

GOVERNANCE STRUCTURE



Network Partners

ACADEMIC AND RESEARCH INSTITUTION PARTNERS*

MEMBERS

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

COLLABORATORS

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

INTERNATIONAL

- Fraunhofer IWS
- FAU Friedrich-Alexander Universität Erlangen-Nürnberg
- 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 PARTNERS*

- AP&C, a GE Additive company
- Autodesk
- BOCO Technology Inc
- equispheres
- FLEXCAP
- GKN
- KSB
- MDA
- Pratt & Whitney Canada, A United Technologies Company
- PROMATION
- Renishaw, apply innovation™
- RioTinto
- Siemens
- Syncrude
- TIMET

GOVERNMENT PARTNERS*

- Canada NRC·CNRC
- DRDC RDDC
- InnoTech Alberta, a subsidiary of Alberta Innovates

NON-PROFIT PARTNERS*

- CM&E Canadian Manufacturers & Exporters
- canadamining innovationcouncil
- ReMAP Refined Manufacturing Acceleration Process
- AAPF Accélération de l'amélioration des processus de fabrication
- Mount Sinai Hospital

*As of October 2020

Network Statistics (To Date)

- **7** UNIVERSITIES
- **2** COLLABORATING UNIVERSITIES
- **22** INDUSTRIAL/GOVERNMENT PARTNERS
- **39** RESEARCH PROJECTS*
- **22** PRINCIPAL INVESTIGATORS
- **95** HIGHLY QUALIFIED PERSONNEL**
- **33** JOURNAL PAPERS DIRECTLY FUNDED BY HI-AM***
- **29** CONFERENCE PAPERS/PRESENTATIONS
- **112** HI-AM CONFERENCE PAPERS/PRESENTATIONS
- **6** OTHER PUBLICATIONS****
- **3** INVENTION DISCLOSURE
- **3** EVENTS

* 37 active projects, 2 completed projects
** 24 HQP have been funded from external sources; 33 HQP have been graduated or completed their program
*** Published or under review
**** Thesis, Technical report

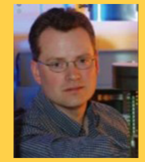
HIGHLY QUALIFIED PERSONNEL (HQP) BY THEME

	Undergraduate	MASc	PhD	PDF/RA
THEME 1	6	9	13	5
THEME 2	0	6	7	2
THEME 3	2	9	13	3
THEME 4	2	8	6	4
TOTAL	**10**	**32**	**39**	**14**

Research Progress

THEME 1: MATERIAL DEVELOPMENT TAILORED WITH OPTIMUM PROCESS PARAMETERS

While tremendous progress has been made in AM 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 in the global manufacturing sector. The global AM sector has consistently focused on using highly engineered powders, which are very 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 a result of the powder grade constraints, only a limited number of metals or metal alloys are presently being used in commercial metal AM. 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 will increase process reliability and repeatability rates by creating dynamic process maps to control the final quality and material properties of the finished part.



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

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

Sub-project 1.1.1: Development of Thermally Stable Aluminum Alloys for LPB-AM

- Design, development, and characterization of over 15 aluminum alloys under three categories: (1) alloys strengthened with coherent L12 precipitates; (2) alloys strengthened with a dispersion of thermally stable phases; (3) alloys of eutectic composition for AM. Development of thermodynamic and solidification models, refinement of alloy chemistry, optimization of LPBF print recipe, and mechanical characterization is ongoing for developed alloys, and are at different stages of progress for each material.
- Investigate manufacturing of Al33Cu3Mg0.5Si 3D lattice structures by hybrid investment casting (HIC), combining stereolithography (SLA) and investment casting as an alternative low-cost technique to LPBF in order to use high-density materials in the production of lightweight components.

Sub-project 1.1.2: Development of Titanium Alloys for LPB-AM and LPF-AM

- Carry out multi-stage experimental design studies to optimize the LPF processing conditions (laser power, scan speed, powder feed rate, hatch spacing, and layer thickness) for select titanium alloys (Ti5553, Ti6242 and Beta 21S) and establish empirical models pertaining to the relationship between density and process parameters. Preliminary microstructural assessment of Beta 21S samples have been completed and mechanical characterization of the samples is ongoing. Expansion of the scope of the LPF research to include a fourth alloy (plasma atomized Ti55511) is expected to begin in Year 4 of the Network.

Sub-project 1.1.3: Development of Tool Steels for LPB-AM and LPF-AM

- Water atomization refinement of the chemistry of A8 and S7 tool steel alloys as a function of the microstructural constituents formed during printing resulted in a reduction of the oxygen content in as-atomized powder from 0.53wt-% to 0.21–0.31wt-%. A lower oxygen content of 0.17 wt-% was achieved through hydrogen-annealing. Future experiments are aimed at reducing the final oxygen content to below 0.1wt-%. Improvement of the morphology of powder particles and production of preliminary LPB and LPF specimens for microstructure and mechanical characterization are ongoing.
- Production of 17-4PH deposits for atomization by plasma transferred arc (PTA) AM. Atomization and characterization of 17-4PH, NiBSi, and NiCrBSi is expected to be completed in Year 4 of the Network.
- Develop a neural network to semantically segment WC from optical images of Ni-based WC composites and machine learning algorithms to determine the effect of different thermal histories on the carbide characteristics, dissolution, and the resulting phases.

Sub-project 1.1.4: Development of Nickel Alloys for LPB-AM

- Optimize and characterize two nickel alloys (Rene 44 and Rene 77) with medium to low levels of weldability for use in LPB processes through understanding their cracking mechanics. Ongoing research includes characterization of powders and of microstructure and mechanical properties of as-fabricated and heat-treated parts, as well as an understanding of the relationships between them. This work is at different stages of progress for each alloy.
- Study the printability and cracking mechanics of three intermetallic superalloys: iron aluminide (Fe3Al (FA-129)), titanium aluminide (TiAl4822), and nickel aluminide (NiAl) for use in LPB processes. Powder characterization, process optimization, microstructure analysis, and cracking development studies have been completed for FA-129 and TiAl4822, and are ongoing for NiAl. The scope of the study has been expanded to include FeAl, Ti3Al, and Ni3Al.

Sub-project 1.1.5: Development of Refractory Metals for LPB-AM

- Develop and optimize pure molybdenum and titanium-zirconium-molybdenum alloy (TZM) for LPB processes. Thermodynamic and solidification modeling, powder characterization, print optimization, microstructure analysis and mechanical characterization studies are ongoing and at different stages of progress for each material. The scope of the study has been expanded to include Mo-Si-B alloy.

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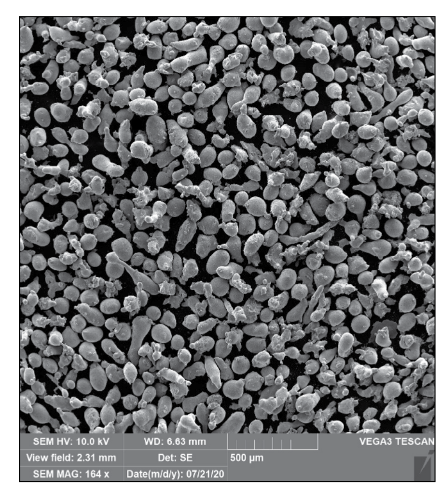
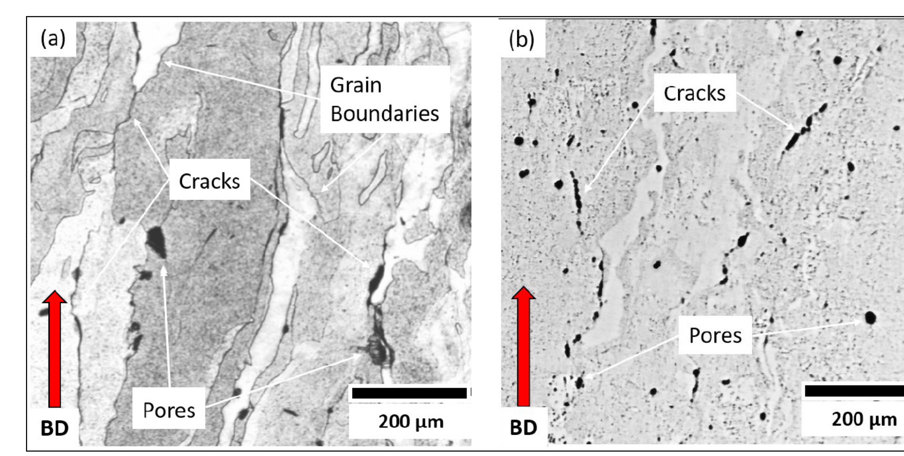


Low magnification SEM micrograph of water-atomized S7-based tool steel (Sub-project 1.1.3)



Optical micrographs of LPBF-AM processed (a) Mo, and (b) TZM samples (Sub-project 1.1.5)

Project 1.1: Development of Next Generation Alloys (Continued)

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) • Akankshya Sahoo, University of Alberta, PhD (Collaborator) • Matthew Harding, Dalhousie University, PDF • Maéva Chrzaszcz, McGill University, Co-op • Ryan Ley, Dalhousie University, Co-op (Collaborator)
1.1.2 Development of Titanium Alloys for LPB-AM and LPF-AM	• Paul Bishop, Dalhousie University	• Matthew Harding, Dalhousie University, PDF • Greg Sweet, Dalhousie University, PDF • Nick Gosse, Dalhousie University, Co-op, PhD • M.D. Hasan Khondoker, Dalhousie University, PDF (Collaborator)
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 • William Chaîné, Université Laval, MASc • Anne McDonald, University of Alberta, URA • Dylan Rose, University of Alberta, PhD (Collaborator)
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 • Anh Tran, McGill University, Co-op
1.1.5 Development of Refractory Metals for LPB-AM	• Mathieu Brochu, McGill University	• Tejas Ramakrishnan, McGill University, PhD

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

Sub-project 1.2.1: Novel Composites for BJ-AM to Develop Foam-based Structures

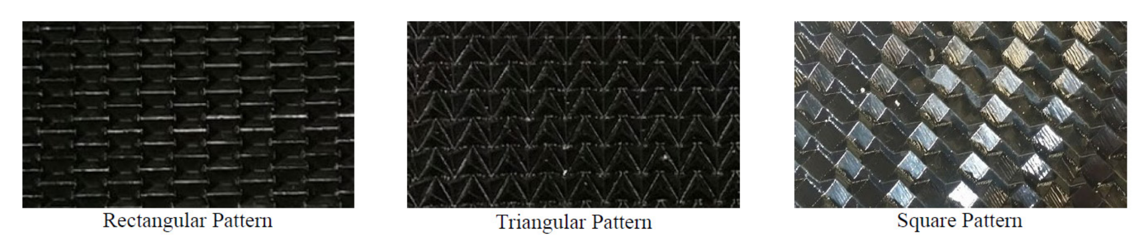
- Develop advanced composite inks and structural materials for material jetting and binder jetting technologies. Ongoing work is being done to improve the electrical conductivity of the parts using various combinations of pure and graphene-coated/infiltrated dimethyl sulfoxide (MDSO) ink and PVA as well as MXene ink. Experiments include identification of suitable surfactant for each ink, determining the maximum material loading and percolation threshold, and printing functional test parts.
- Polyjet printing of multi-material flexible tessellated sheets inspired by origami designs for impact load absorption applications. Ongoing work is being done to achieve optimal designs in terms of dimensions and thickness for maximum impact energy absorption.

Sub-project 1.2.2: Alloy Alteration for Functionally Graded Materials (FGMs) used in LPF-AM

- Optimize LPF process parameters for printing H13 as a function of surface roughness, density, microstructure and mechanical performance. The powder system was characterized and used for fabrication of clads and simple geometries for various tests, such as microstructure analysis, scratch hardness, XRD etc. The system feasibility for incorporation of a second feedstock for production of FGM structures is being investigated.

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) • Kyra Mclellan, University of Toronto, MASc • Terek Li, University of Toronto, MASc (Collaborator) • Andrew Jo, University of Toronto, PhD • Yu-Chen Sun, University of Toronto, PDF
1.2.2 Alloy Alteration for Functionally Graded Materials (FGMs) used in LPF-AM	• Kevin Plucknett, Dalhousie University	• Owen Craig, Dalhousie University, MASc | PhD



3D Printed rubber-like origami patterns (Sub-project 1.2.1)

THEME 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

Sub-project 1.3.1: Recyclability of Powder Feedstocks for LPB-AM

- Study the effect of moisture on powder processing and part contamination in LPB.
- Compare the topography and microstructure of virgin and recycled maraging steel grade 300 powder feedstocks and characterize the microstructure and mechanical properties of parts made with recycled powder after 14 cycles in order to establish a recycling threshold and methodology.

Sub-project 1.3.2: Plasma Spheroidization of Low Cost Powders

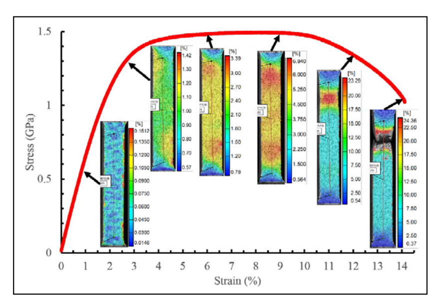
- Initiate plasma spheroidization trials of sponge Ti, HDH Ti, and used Ti powders.

Sub-project 1.3.3: Cost-effective Steel Feedstock for AM

- Study vacuum sintering response by means of thermal dilatometry and differential scanning calorimetry (DSC) for BJAM-made parts from water atomized D2 tool steel at various dimensional scales. Similar tests as well as powder characterization and print optimization are being carried out for a water atomized 5120 alloy.
- Investigate the application of low-cost water atomized steel alloys (DP600 and 4140) in the production of high-density parts using L-DED. Powder atomization and characterization, printing parameter optimization, and mechanical/microstructure characterization of parts have been completed for DP600 and are ongoing for 4140.
- Cast ingots and produce wires of three different custom chemistries for electrostatically assisted atomization (ESA): Industrial grade aluminum (99.99%), aluminum copper scandium (Al 4.5%Cu 0.4%Sc) and aluminum silicon (Al 40%Si). Improving the production throughput of the ESA method through numerical modeling and system design refinement is ongoing.

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 • Yu-Chen Sun, University of Toronto, PDF
1.3.2 Plasma Spheroidization of Low Cost Powders	• Carl Blais, Université Laval	• Zahra Sadeghinia, Universite Laval, PhD
1.3.3 Cost-effective Steel Feedstock for 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



A stress-strain curve with DIC images measured from the as-produced Maraging Steel 300 specimen. (Sub-project 1.3.1)

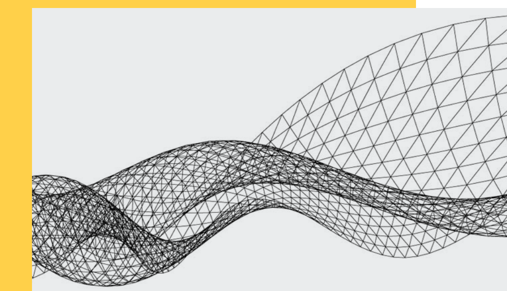
THEME 2

Research Progress

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

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

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 time of 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, all of which significantly affect the melt pool dynamic. Researchers of Theme 2 are developing innovative platforms and solutions to address these challenges.



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 enables the prediction of the macro-thermal field, and subsequently 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

Sub-project 2.1.1 Beam-powder/Melt Pool Interaction and Energy Transport: Experimental Validation

- Develop a macro-scale thermal model of EBAM processes, including the analysis of the entire powder-bed elements including the build part, using a super element approach.
- Develop and experimentally verify a macro-scale thermal model of the LPBF process to investigate the effect of the support structure geometry on the thermal field in cantilevered plates.
- Develop and simulate an improved base plate with two embedded thermocouples to record the temperature data in LPBF. Refinement of the FEA model of the single-thermocouple base plate has been completed, and development of an inverse heat conduction model based on the FEA data is planned.

Sub-project 2.1.2: Meso-scale Thermal Field Evolution in Melt Pool Substrate

- Develop and experimentally verify a 3D meso-scale thermal field evolution model of the EBAM process. The experimental trials with various beam parameters have been completed to measure the evolution of the powder structure and microstructure in consolidation. Metallographic analysis is ongoing.

Continued on next page...

Project 2.1: Multi-scale Modeling of AM (Continued)

Sub-project 2.1.3: Macro-scale Thermal Field Evolution – COMPLETED

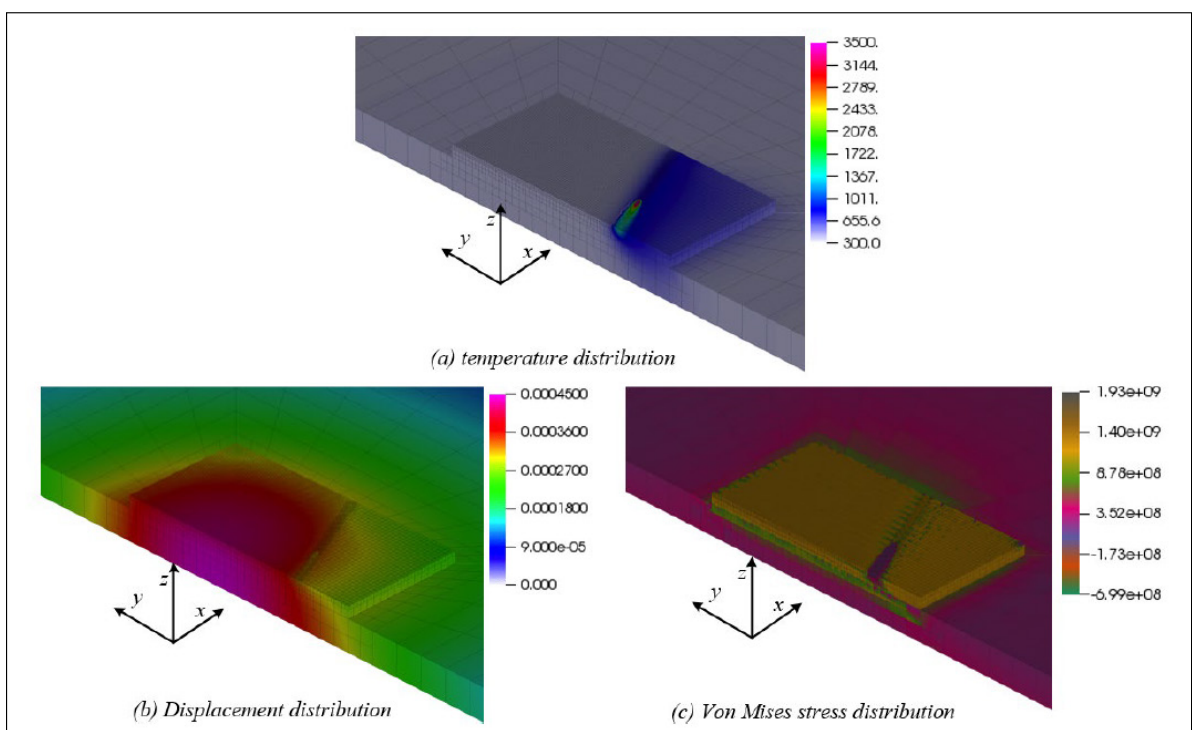
- Developed and experimentally verified a comprehensive 3D macro-scale thermal model to simulate the temperature distribution of multiple layers with multiple scan tracks for LPBF processes. This enables a considerable reduction in computation cost through the use of novel cell activation strategies, heat source models, and simulation schemes.

Sub-project 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

- Develop and experimentally verify meso- and macro-scale thermal-stress models of EBAM processes, as well as a macro-scale thermal-stress model of EB-DED processes. Model refinement and experimental verification are at different stages of progress for each model.
- Develop an in-situ data acquisition system capable of operating in a vacuum environment of an electron beam chamber to collect the thermocouple data needed for validation of the macro-scale thermal and stress models. Design and production of electrical and physical components, and development of a macro-scale model of the build chamber to account for radiative heat transport between the powder bed and heat shielded walls is ongoing.

Sub-project 2.1.5: Microstructural Modeling and Experimental Validation

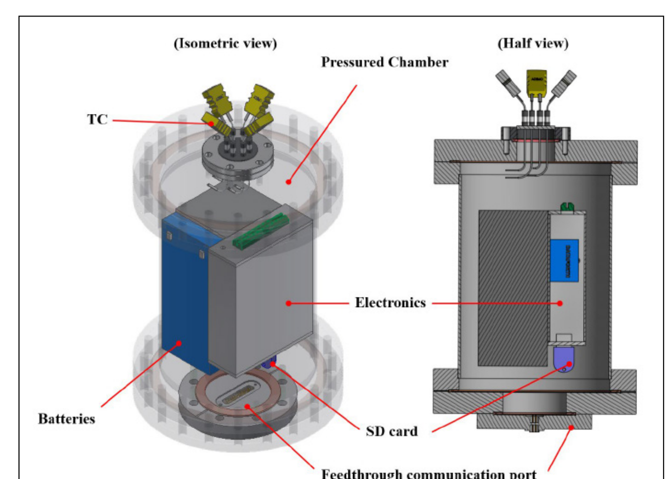
- Generate a solidification continuous cooling transformation (SCCT) diagram for impulse atomized AL-40wt%Si with focus on primary Si undercooling, eutectic undercooling, and morphology transitions through 2D characterization of particle shapes.
- Develop a numerical model of eutectic growth for impulse atomized Al-33wt%Cu and determine the optimal heat treatment conditions to improve the mechanical properties of parts made from such alloys. In-situ study of the dynamic evolution of microstructure for rapidly solidified droplet samples of Al-Cu is ongoing.



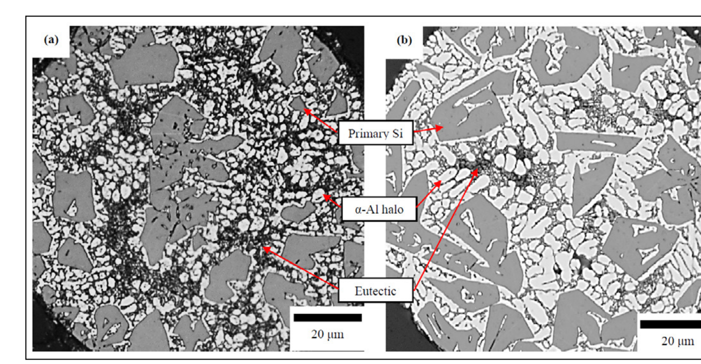
Material's thermo-mechanical responses after depositing initial four layers (Sub-project 2.1.3)

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 (COMPLETED)	• 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



Comparison of (a) predicted and (b) actual distorted build (Sub-project 2.1.4)



OM images of microstructure in 90-106 μm droplets of (a) Al-40Si and (b) Al-40Si-1.5Ce (sub-project 2.1.5)

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

Sub-project 2.2.1: Fast Process Thermal-Field Simulation (COMPLETED)

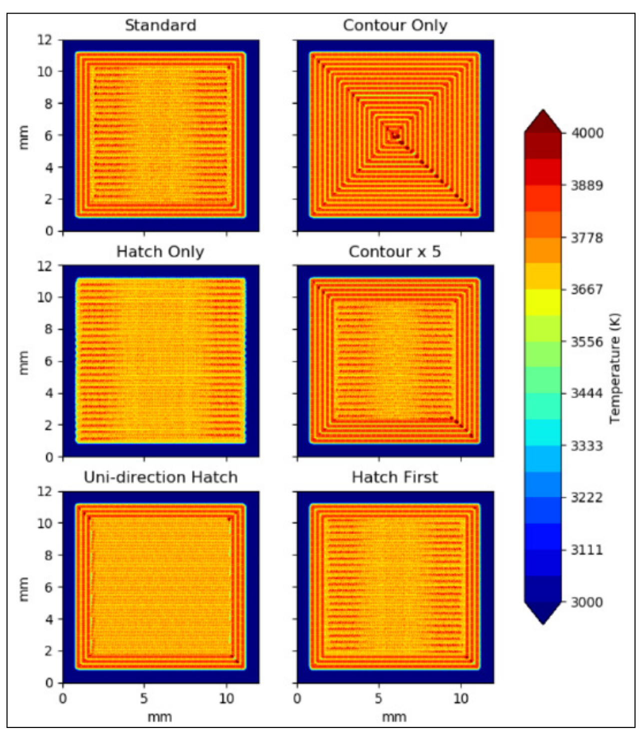
- Developed an approximate fast-to-run (FTR) solution method for modeling the thermal fields during melting by a moving heat source, resulting in the reduction of the simulation time by a factor of 130 compared to an FEM simulation. A CFD-based model incorporating effects like buoyancy, Marangoni flow, melting and solidification was used to train the FTR model.

Sub-project 2.2.2: Fast Process Stress-Field Simulation

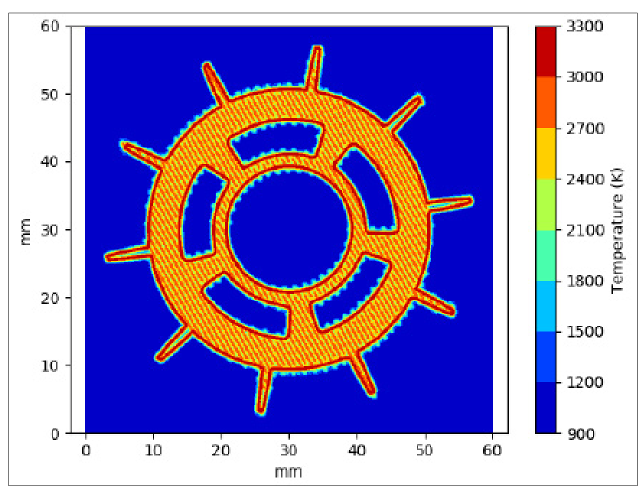
- Project is yet to be started.

RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
2.2.1 Fast Process Thermal-Field Simulation (COMPLETED)	• Daan Maijer, The University of British Columbia	• Meet Uphadhyay, The University of British Columbia, MASc (Collaborator)
2.2.2 Fast Process Stress-Field Simulation	• Ehsan Toyserkani, University of Waterloo	• Starts in Year 4



FTR simulated maximum temperature for different hatching strategies (Sub-project 2.2.1)



Maximum temperatures for a simulated layer (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 being 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

Sub-project 2.3.1: Pre-processing for Dimensional Control

- Develop a normative GBTA to characterize geometric dimensioning and tolerancing (GD&T) for LPBF and a macro-scale FE model to quantify the thermo-mechanical deviation in LPBF, accounting for GD&T characteristics for the first time. A simulation-based study for establishing a relationship between input and interim parameters and final geometric tolerances is ongoing.

Sub-project 2.3.2: Lattice Structure Design for AM Processing

- Gather data on the manufacturing constraints, such as the maximum cell size, minimum strut thickness, support requirements etc., during LPBF fabrication and develop a numerical model that accounts for the manufacturing defects and the geometrical parameters of the metal lattice structures. Experimental validation of the model and development of a computational design framework that accounts for the impact of defects is ongoing. The scope of the project will be expanded to include design of polymeric lattice structures.
- Development of an efficient machine learning model for high-dimensional design matrix to link the design, process, and quality of the final products has resulted in a considerable reduction of the computation cost and improvement of the prediction accuracy. The objectives of the model are to predict the manufacturability of a given design through the LPBF system and to identify the potential failure areas for each voxel.
- Develop an entity relationship diagram for the management of process parameters and design files as part of the efforts to establish a data management system for LPBF.

Sub-project 2.3.3: Component Build Geometry Optimization for AM Processing

- Achieved accurate analysis of surface features and the associated dimensional variabilities in as-built thin struts via micro-tomography and successfully integrated the CT results into measurement of tensile properties of struts.
- Develop a CAD model of thin struts representing the as-built surface to be used for FEA of stress concentration and triaxiality associated with surface defects. The FEA model results were compared with experimental measurements of strength and ductility of struts.
- Demonstrated adverse effect of surface defects in as-built thin struts on their tensile properties and the need for surface treatment for obtaining superior tensile properties.

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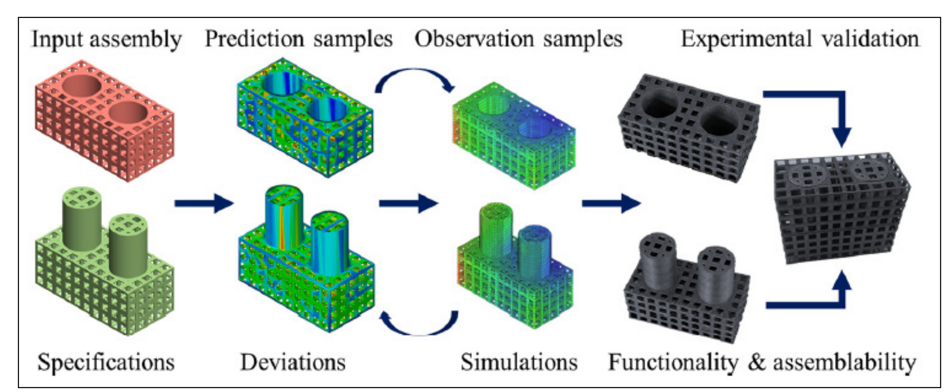


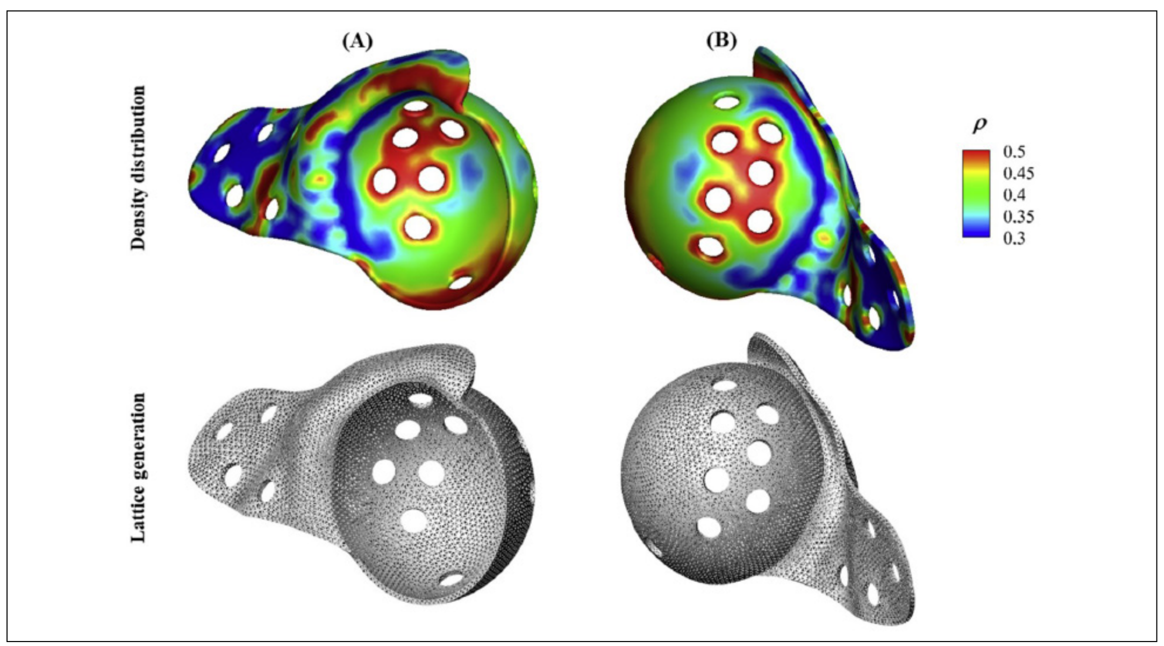
Geometric tolerance and manufacturing assemblability estimation of metal additive manufacturing (AM) processes (Sub-project 2.3.1)

THEME 2

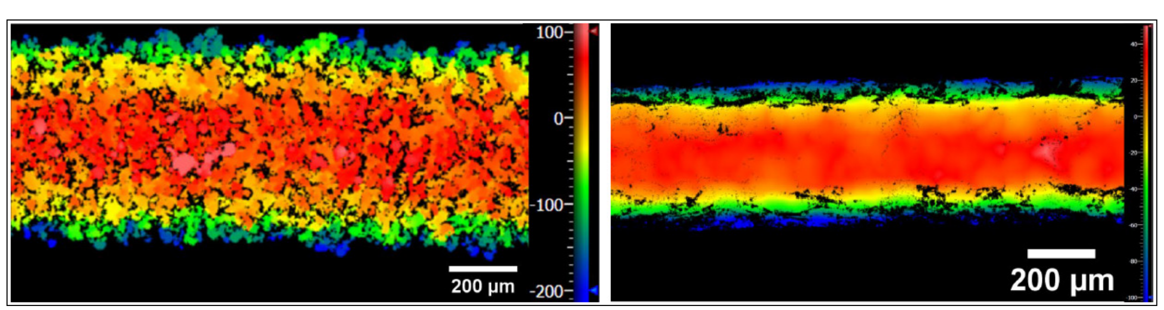
Project 2.3: Pre-processing for Optimization of AM Process Parameters (Continued)

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	• Mathieu Brochu, McGill University • Yaoyao Fiona Zhao, McGill University	• Abhi Ghosh, McGill University, PhD (Collaborator)



Optimized relative density distribution of the implant and the corresponding lattice architecture with, (a) front side adjacent to the solid layer and (b) backside adjacent to the bone (Sub-project 2.3.2)



Surface profiles of as-built (left) and electropolished (right) micro-struts (Sub-project 2.3.3)

THEME 3

Research Progress

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

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

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 determined by 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 control algorithms and part certification strategies. Real-time quality control will ensure that the AM processes can be instantly adjusted to reduce part defects, improve efficiency and reduce costs.

PROGRESS

Sub-project 3.1.1: Development of Non-contact Dynamic Melt Pool Characteristic Measurement via Radiometric Monitoring for LPB- and LPF-AM

- Develop a melt-pool monitoring system composed of thermal camera and CCD for collecting the maximum amount of useful data during LPBF/LPF processes to be integrated into a control system. A functional prototype of the metrology system has been developed and experimental trials are ongoing to improve the robustness of the system in laser heat treatment and laser AM frameworks.
- Deploy IR and vision monitoring into the control system to characterize and predict the clad dimensions and laser-material interaction.
- Develop a discrete dynamic model with a mean absolute percentage accuracy of 1% for the peak temperature and 4% for the cooling rate for laser heat treatment. Work to integrate the model into a controller for development of a model-predictive controller (MPC) is ongoing.

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

Sub-project 3.1.2: Development of Continuous and Layer-intermittent Imaging Capabilities for LPF-, LPB-, and BJ-AM

- Develop an in-situ sensing and monitoring hardware system composed of a displacement measurement sensor and infrared camera for observation of the melt-pool, solidification area, and substrate plate temperature, and bead geometry in wire arc AM. Development of a point streaming interface and a thermal camera interface with the robotic operating system (ROS) is ongoing.

Sub-project 3.1.3: Development of Non-contact Capability to Detect Sub-surface Properties Using Eddy Current Inductive Measurements

- Develop numerical and analytical models of eddy current with a focus on defect detection capability of the system in a substrate through variation of coil impedance. Development of tuning probe parameters for detection of defects smaller than 0.2 mm using ANSYS Maxwell is ongoing.
- Development of an eddy current test setup for validation of the models and real-time defect detection is ongoing. Several commercial eddy current equipment are being tested to identify the most reliable system for metal AM applications.

Sub-project 3.1.4: Laser Ultrasonic Sensing for LPB- and LPF-AM

- Design and develop an ultrasonic monitoring technique and initial testing of the system through brightness scanning (B-scanning) of a sample with known sub-surface defect parameters in order to compare with CT scan data.
- Numerical modelling of elastic wave propagation to obtain artificial B-scan data and using phase shift migration method (PSM) to reconstruct defects in simulated data is ongoing.
- Developing a process map required for imaging a given defect with certain dimension and location characteristics has been initiated.

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, PhD • 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) • Yeon Kyu Kwak, University of Alberta, PhD
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

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 into LPB- and LPF-AM processes to control part variability.

PROGRESS

Sub-project 3.2.1: Knowledge-based Lumped Models

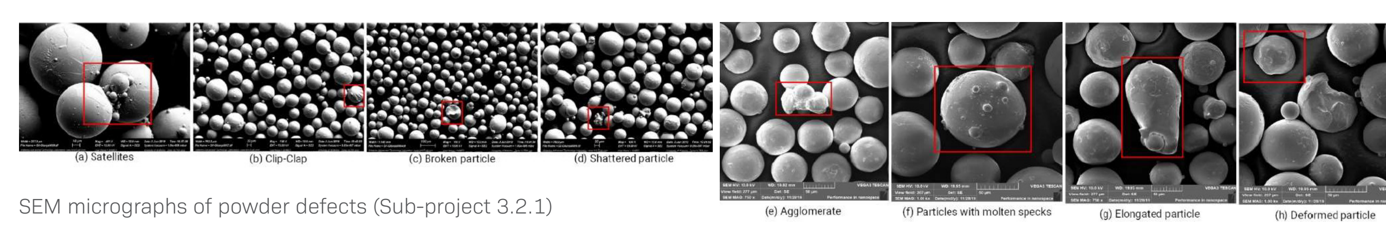
- Develop thermal models to predict porosity formation in EBAM. Literature review and adoption of the results of previous work on combined sinter theory for simulation of pre-heating phase in EBAM is ongoing.
- Develop multiple empirical/statistical/physics-based models for EBAM. Modeling the relationships between the roughness, tensile, porosity, and microstructure properties and spatial/temporal location of the part in the build chamber as well as the effect of powder re-use on powder characteristics is ongoing.

Sub-project 3.2.2: Development of Intelligent Controllers

- Develop an artificial neural network (ANN) algorithm based on unsupervised learning for auto-detection of the location of defects in LPBF systems. Collection, correction, and comparison of data from various sensors and CT scanning results containing information such as light intensity recorded by photodiodes from the melt-pool, x/y position of the scanner, laser power, and modulation of each layer is ongoing. Detection of defects as small as 120 μm has been achieved.

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) • Mojtaba Valipoor, University of Waterloo, PhD (Collaborator)



SEM micrographs of powder defects (Sub-project 3.2.1)

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.

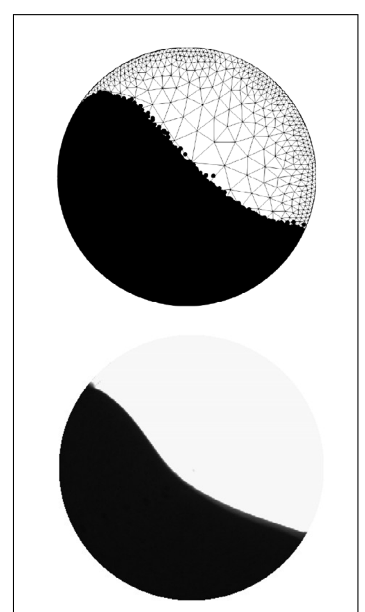
PROGRESS

Sub-project 3.3.1: Measurement System Development and Validation of Combined Powder Spread, Compaction and Binder Fluid Dynamics Linked with Sintering Model

- Development of a dynamic powder compaction/ spread model is in progress. Calibration of the model is ongoing. A master sinter curve model, developed outside the scope of the HI-AM project, will be used to link the compaction/spread model to densification/ sintering theory.
- Develop a sensor-embedded reduced build volume powder bed for detection of powder compaction model and measurement of the density of the compacted model. This apparatus will be used for experimental validation of the compaction/spread model.
- Investigate various approaches for modeling binder-powder interactions in pore networks and detecting such interactions. Based on the initial results, powder particle extraction algorithms and high-speed imaging will be pursued for modeling and experimental validation, respectively.

Sub-project 3.3.2: Closed-loop Control of Compaction Density and Binder Imbibition and Experimental Validation

- Development of a closed-loop control system using classic and advanced soft computing techniques with the desired density as output. Basic interface development has been completed. Integration of a new printhead as well as a force sensing setup into a custom in-house-built binder jetting system is planned to be completed in Year 4 of the Network.



Granudrum comparison of (left) simulated and (right) experiment (Sub-project 3.3.1/3.3.2)

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) • Justin Memar-Makhsous, University of Waterloo, Co-op
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)

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

DESCRIPTION

IIndustry currently uses a limited number of path planning algorithms/protocols (e.g. raster path determination) based on proprietary algorithms that accommodate 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 fulfil 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.

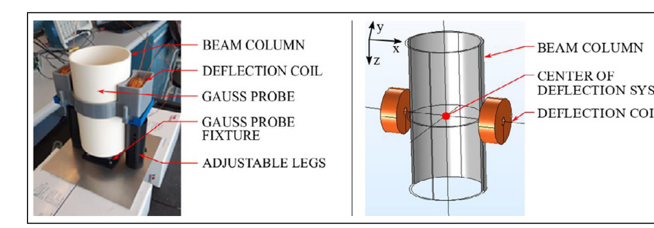
PROGRESS

Sub-project 3.4.1: Combined Trajectory Optimization and Thermal Analytical Models

- Design and construction of 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.
- Develop a mathematical model of EBAM system dynamics to analyze the design parameters of EBAM gun deflection and improve the positioning accuracy of the EB reflected on the build plate using a model based open-loop compensation controller. Experimental validation of the model was successfully carried out, and demonstrated an improvement in dimensional accuracy of the printed parts on an industrial EBAM machine.

Sub-project 3.4.2: Adaptive Path Planning Protocols/ Controllers and Experimental Validation

- Develop an experimentally data classifier to assist in data annotation in large datasets, an experimentally-driven model to train a predictor for surface roughness in LPBF, and a registration algorithm to transform a scan-path data-set and a corresponding CT data-set to the same coordinate system. Development and off-line validation are at different progress stages for each model.
- Investigate VIS high-speed detection and VIS/NIR HDR based sensors for off-axis process monitoring as a preliminary step to embed in-line strategies for process signature detection.
- Initiate investigating surface roughness artefacts for use in training machine learning models.



Single-axis deflection system (a) experimental setup and (b) FEM simulation model (Sub-project 3.4.1)

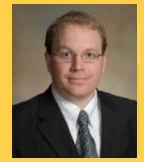
RESEARCHERS

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) • Randy Yuwono, The University of British Columbia, MEng (Collaborator) • Kirubakarann Srenevasan, 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)

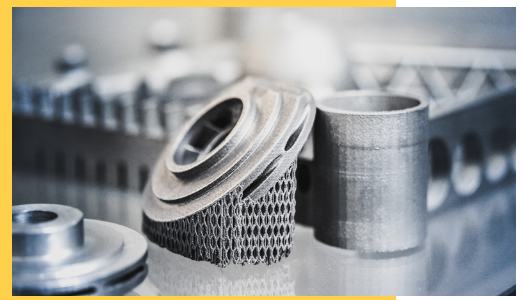
Research Progress

THEME 4: INNOVATIVE AM PROCESSES AND AM-MADE PRODUCTS

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 drastically change 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 must be developed. One process challenge that impedes this uptake 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.



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



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, which is an appealing option for many aerospace and automotive applications.

PROGRESS

Sub-project 4.1.1(ii): Embedding Optical Sensors Inside Optimized Lightweight Structure Made by Laser Powder-bed Fusion

- Optimize coupon manufacturing parameters with linear channels for embedding fiber bragg grating (FBG) sensor inside LPBF parts, such as print parameters, channel dimensions, bonding material etc. The initial cyclic stress and temperature tests demonstrated the feasibility and reliability of FBG sensors in determining the temperature of the host material with high accuracy. Similar studies for fabrication of coupons with varying curvature to test the limits of curvature geometry is ongoing.

THEME 4

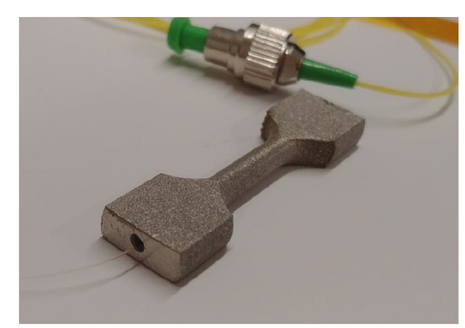
- Develop a look-up table linking the surface roughness of struts to feature parameters such as thickness and printing angle. The table will be used as a guide for feature optimization of cellular structures through topology optimization algorithms to enable effective embedding of optical sensors. To this end, a framework for design of the cellular structures based on the level of stress within a design space under load is being developed.

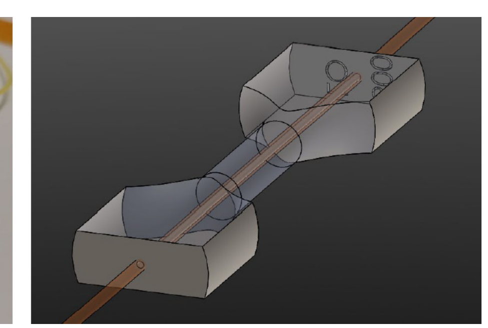
Sub-project 4.1.2: Levitated Additive Manufacturing

- Develop a numerical model of the magnetic levitation setup considering the geometrical constraints of the AM system for estimating the levitation force on the nucleus with different materials and geometry. Initial experimental validation using aluminum alloys have been carried out.
- Develop analytical models for: (a) effect of magnetic levitation force on the nucleus, (b) relationship between input (sinusoidal current) and output (position of the levitated object) for control strategies.
- Design and develop a prototype apparatus for magnetic levitation. Modeling of the final setup and procurement of the required materials and components is ongoing.

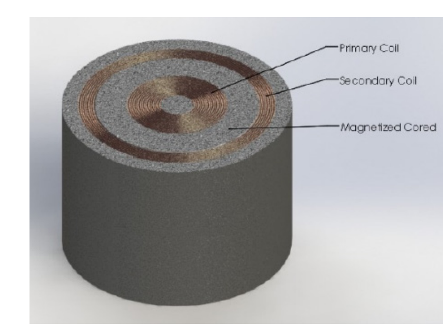
RESEARCHERS

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 • Farid Ahmed, University of Waterloo, PDF (Collaborator)
4.1.2 Levitated Additive Manufacturing	• Behrad Khamesee, University of Waterloo • Ehsan Toyserkani, University of Waterloo	• Parichit Kumar, University of Waterloo, PhD • Yuze Huang, University of Waterloo, PDF • Saksham Malik, University of Waterloo, MASc





Coupon with Embedded FBG Sensor, (right) FBG-Coupon Assembly Schematic (Sub-project 4.1.1)



Optimized levitator setup (Sub-project 4.1.2)

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 the 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 being pursued under project 4.2.2.

PROGRESS

Sub-project 4.2.1: Metal AM for Orthopaedic and Implants Technologies

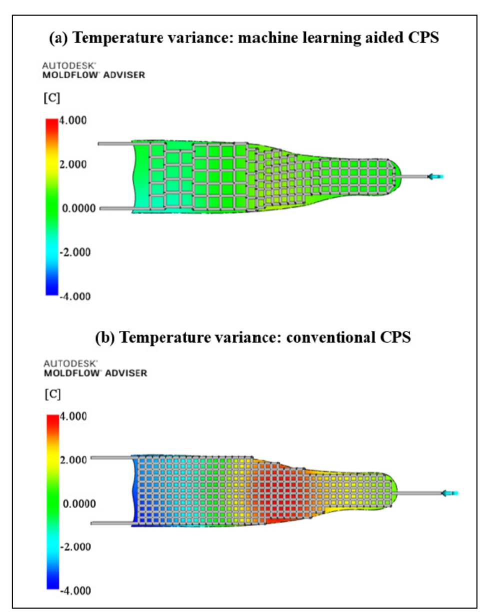
- Develop a high-fidelity homogenization method that can model the mechanical properties of a porous bone replacement implant under physiological loading conditions considering manufacturing imperfections.
- Formulate and solve a topology optimization problem, without resorting to any commercial software, that can optimally resolve the trade-off between identified clinical bottlenecks, and account for the manufacturing defects as well as AM limits.
- Generate patient-specific implant geometry and porous microstructures that respects AM limits and bone ingrowth properties. Design and production of the test implants consisting of a defect-free porous layer with graded attributes, and validation of the general methodology developed under this project through the solution of benchmark problems is ongoing.

Sub-project 4.2.2: Development of Smart Molds with Embedded Optical Sensors and Conformal Channels

- Improve the temperature surrogate model by inputting more training data with consideration of coolant temperature rise.
- Investigate the effectiveness of the proposed design method in other cooling topologies.
- Final validation of the effectiveness of the conformal cooling channel design through temperature measurement using embedded sensors through PBF manufacturing of three sets of injection mold cooling channel designs: 1) drilling channel design; 2) conventional conformal cooling design; 3) the proposed machine learning assisted conformal cooling design is ongoing.

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 • Wendy Li, McGill University, Co-op
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, MASc • Danièle Sossou, McGill University, Co-op



Resulting part temperature variance for machine learning aided CPS and conventional CPS

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

Sub-project 4.3.1: Direct Manufacturing of FGM Advanced Part Using PTA-AM

- Develop methods for deposition of base metal powder and WC-reinforced NiCrBSi coating in a tailored compositional transition from the base part using a two-hopper PTA-AM system in order to increase the in-service lifespan of wear resistance parts. Calibration and optimization of the PTA system with a focus on printing FGM structures, as well as the production and characterization of test samples for measurement of interlayer bonding, microstructure, and mechanical properties, are ongoing.
- Development and experimental validation of thermal and residual stress models of the PTA-AM process.
- Development of fracture mechanics approach for compositional path evaluation.

Sub-project 4.3.2: Direct Manufacturing of FGM Molds Using LPF-AM

- Fully characterize D2 tool steel powder as the base material for development of FGM molds composed of Cu embedded in a tool steel matrix.
- Characterize wrought D2 tool steel under different heat treatment scenarios in order to establish a property/microstructure baseline for this alloy.
- Develop empirical relationships between LPF-AM process parameters and properties of printed parts such as geometrical fidelity, surface properties, and density for D2 tool steel. Further mechanical tests and investigation of the effect of heat treatment on properties of the printed parts are ongoing.
- Developing the appropriate baseline data for subsequent comparison of the properties of materials that will be used in production of FGM molds.

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 • Geoffrey Bonias, University of Alberta, MASC
4.3.2 Direct Manufacturing of FGM Molds Using LPF-AM	• Kevin Plucknett, Dalhousie University	• Samer Tawfik, Dalhousie University, PhD

Direct energy deposited samples (Sub-project 4.3.2)

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, and provides 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 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

Sub-project 4.4.1: Repair Strategies with LPF-AM

- Investigate a pre-placement dip-coating approach in parallel to the original objective of producing micro-composite powders for cladding TiC-Ni3Al cermet onto D2 tool steel substrate as an inexpensive and flexible alternative approach. The effect of dip-coating conditions (e.g. cermet solid content, carrier medium, etc.) and LPF printing parameters on geometry/quality of single and multi-track clads has been investigated through various metallographic characterization tests. The initial results demonstrated generation of a satisfactory level of adhesion with a homogenous distribution of the carbide phase.
- Characterization of the multi-track clads and the corrosion behavior of the coated surfaces is ongoing.

Sub-project 4.4.2: Repair Strategies Using EWF-AM

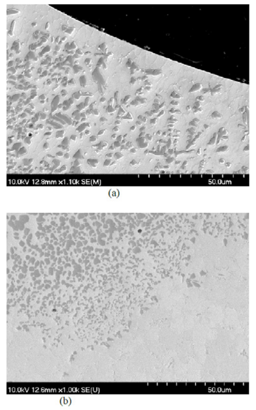
- Develop and experimentally validate a thermos-mechanical FEA model of the EWF-AM process considering phenomena such as phase transformations, temperature and strain rate dependant materials etc. to predict and minimize a possible degradation of parent material during the print. Further model refinement to reduce the error between the simulation and experimental results is ongoing.
- Predict microstructural and macrostructural features of deposits and the heat affected zone during EWF-AM repair methodology using the developed FEA model.

Sub-project 4.4.3: Repair Strategies Using PTA- and FFF-AM

- Design and develop pre-repair process strategies including: (1) in-situ scan setup for PTA-AM system, (2) machine learning approach for treating point cloud mapping for the damaged area, (3) damage volume decomposition, (4) in-situ metrology and comparison with ideal volume, (5) convex hull of repair, and (6) repair path plans; work is at different stages of progress for each item.
- Characterize and optimize the composite filaments considering the following criteria: (1) maximizing particle packing, (2) maximizing carbide content, (3) reliable and successful extrusion.
- Print and characterize simple geometry sample in terms of fill content, composite density, and geometric resolution.

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, PhD
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 (Collaborator) • Remy Samson, University of Alberta, MASc



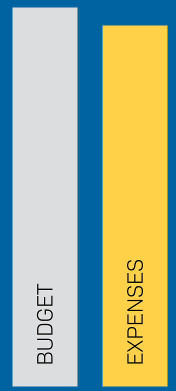
SEM micrographs taken from cross-section of TiC-Ni3Al (40 vol.%) laser deposition on D2 steel, with P = 300 W and τ = 0.5 s (Sub-project 4.4.1)

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. The travel restrictions recently put in place because of the pandemic has caused some delay in spending in any travel related expenses, including the 2020 HI-AM Conference, which moved online; and travel related to exchanges and other conferences.

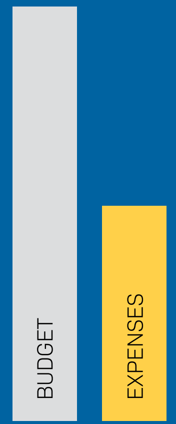
YEAR ONE TO THREE NSERC FUNDING (2017-2020)

	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$ 1,031,595	$ 957,903
THEME 2	$ 543,433	$ 454,163
THEME 3	$ 361,070	$ 468,631
THEME 4	$ 432,723	$ 379,042
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$ 881,179	$ 672,524
TOTAL	**$ 3,250,000**	**$ 2,932,263**



YEAR ONE TO THREE INDUSTRY/GOVERNMENT PARTNER AND INSTITUTIONS CONTRIBUTIONS (2017-2020)

	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$ 411,765	$ 188,229
THEME 2	$ 286,667	$ 121,502
THEME 3	$ 237,080	$ 281,100
THEME 4	$ 336,497	$ 214,499
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$ 52,272	$ 97,675
TOTAL	**$ 1,324,281**	**$ 903,005**



*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 means, including through Network events, our online presence and social media, interaction with AM magazines, participation in international engineering conferences, training undergraduate students, and domestic and international exchanges.

HI-AM Conference

3rd | 2020

JUNE 25-26, 2020

The HI-AM Conference is the Network's most important event, and takes 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 in 2018 and the University of British Columbia in 2019.

The third HI-AM Conference was originally planned to be held at McGill University, Montréal from June 25-26, 2020; however, it was transitioned to an online format due to COVID-19 pandemic. The online HI-AM 2020, co-chaired by Mathieu Brochu of McGill University and Ehsan Toyserkani of University of Waterloo, was received very well by the AM community, with 400+ participants and 120,000+ website views. The conference opened with video messages from the co-Chairs, and was followed by pre-recorded presentations and posters that were available on-demand, Q&A sessions, and various networking opportunities.

A total of 99 research works including 4 keynote presentations were presented during the conference. The keynote talks were delivered by Javier Arreguin, Senior Materials Project Manager, AP&C, Canada; Todd Palmer, Professor of Engineering Science and Mechanics and Materials Science and Engineering, Penn State, United States; Carolyn Seepersad, Professor of Mechanical Engineering, University of Texas-Austin, United States; and Stuart Jackson, Business Development and Key Account Manager, Renishaw, United Kingdom.

The conference was also supported by sponsors and exhibitors from industry and academia: EOS, Javelin Technologies, Keyence, KSB, Leichtbau BW GmbH, Multi-Scale Additive Manufacturing Lab, Proto3000, Trumpf, and Xact Metal each had their own virtual exhibition booth.

2020 HI-AM Conference at a Glance

AT A GLANCE

- 400+ participants
- 250+ organizations
- 120,000+ website views
- 10 exhibitors

EDUCATION

- 4 Keynote Talks
- 55 oral presentations
- 40 poster presentations
- Live Q&A

NETWORKING

- 2000 conversations
- 40+ private meetings

KEYNOTE SPEAKERS

Javier Arreguin
Senior Material Project Manager
AP&C - A GE Additive Company, Montreal, Canada

Todd Palmer
Professor of Engineering Science and Mechanics and Materials Science and Engineering
The Pennsylvania State University, University Park, PA, United States

Carolyn Seepersad
J. Mike Walker Professor of Mechanical Engineering
The University of Texas at Austin, Austin, TX, United States

Stuart Jackson
Business Development and Key Account Manager
Renishaw, Staffordshire, United Kingdom

The conference closing remarks were given by HI-AM Network's Theme 1 Leader, Paul Bishop, who is the Chair of 2021 HI-AM Conference hosted by Dalhousie University. The conference concluded with the announcement of the recipients of student presentation competition awards.

THE 2020 WINNERS:

PRESENTATION COMPETITION:

First Place:
- Salah Eddine Brika, École de technologie supérieure Montréal
- Alexander Martinez-Marchese, University of Waterloo

Second place:
- Anastasia Wickeler, University of Toronto
- Osezua Ibhadode, University of Waterloo
- Deniz Sera Ertay, University of Waterloo

Third place:
- Nancy Bhardwaj, University of Alberta
- Ryan Ley, Dalhousie University

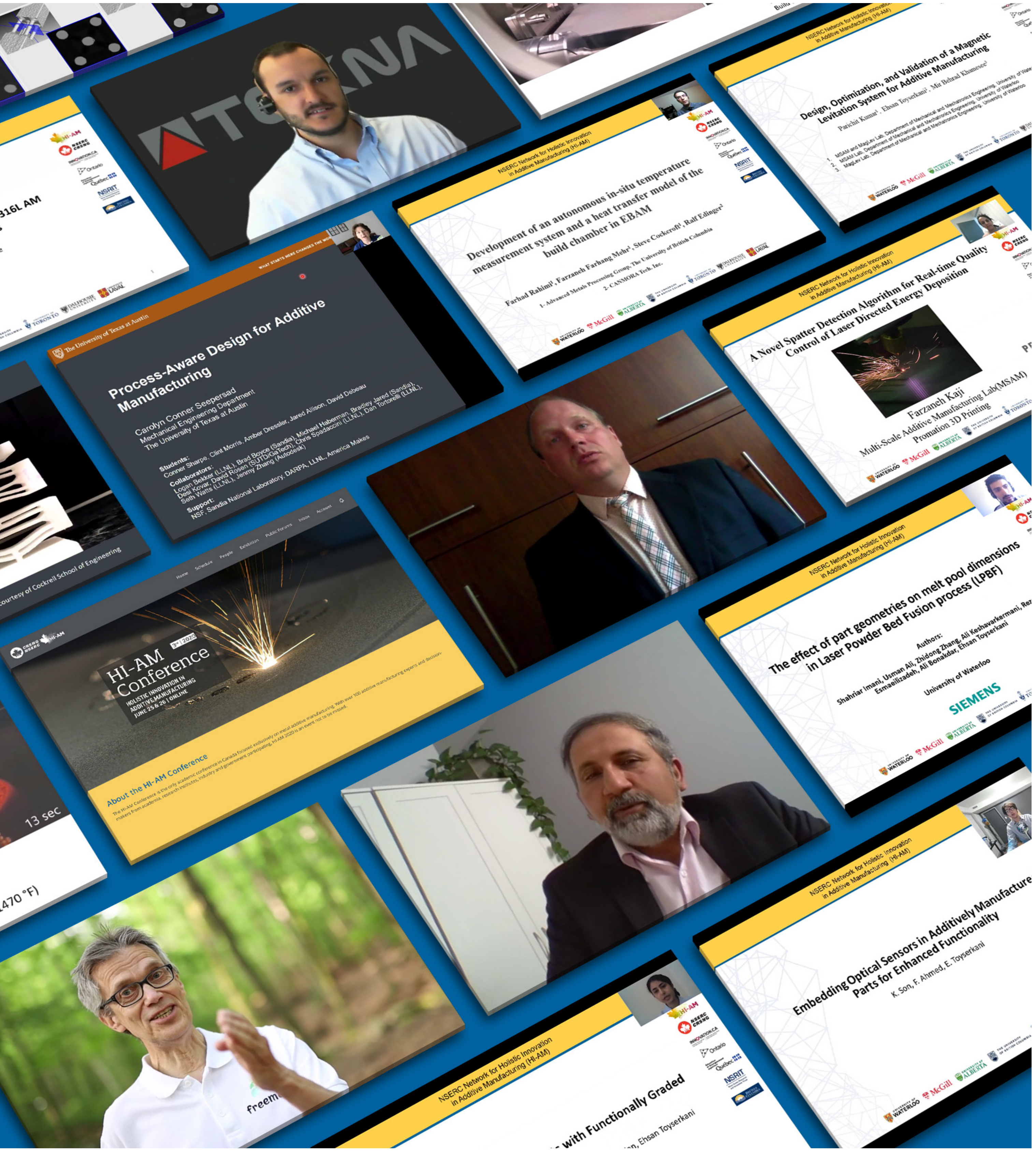
POSTER COMPETITION:

First place:
- Sila Atabay, McGill University
- Mazyar Ansari, University of Waterloo

Second place:
- Remy Samson, University of Alberta
- Pegah Pourabdollah, The University of British Columbia

Third place:
- Moustapha Jadayel, Polytechnique Montréal
- Owen Craig, Dalhousie University
- Rabia Aftab, Tallinn University of Technology

2020 HI-AM Conference Presentation Samples



Events with HI-AM Representation*

CIRP CAT 2020, Charlotte, NC, USA
June 15–17, 2020

TMS 2020, 149th Annual Meeting and Exhibition, San Diego, CA, USA
February 23–27, 2020

32nd SAOT International Workshop on Additive Manufacturing, Erlangen, Germany
December 2, 2019

34th Annual Meeting of American Society for Precision Engineering (ASPE), Pittsburgh, PA, USA
October 28-November 1, 2019

Canadian Manufacturing Technology Show (CMTS), Toronto, ON, Canada
September 30–October 3, 2019

The International Congress on Applications of Lasers & Electro-Optics (ICALEO), Orlando, FL, USA,
October 7–10, 2019

ASME, 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC-CIE), Anaheim, CA, USA
August 18–21, 2019

Solid Freeform Fabrication Symposium, Austin, TX, USA
August 12–14, 2019

22nd International Conference on Composite Materials (ICCM22), Melbourne, Australia
August 11, 2019

International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC-CIE), St. Louis, MO, USA
August 16–19, 2019

UNCCM15, Austin, TX, USA
July 28–August 1, 2019

HI-AM Network in the News*

NSERC's 3rd HI-AM Conference to take place online, Metal AM Magazine
April 13, 2020

NSERC HI-AM Network Announces New Partnerships, AMazing (additivemanufacturing.com)
December 13, 2019

NSERC's HI-AM Network Expands International Collaborations, Metal AM Magazine
August 17, 2019

Canada's Holistic Innovation in Additive Manufacturing Network gains ARCAM EBM Machine, 3D Print Industry
July 1, 2019

*July 1, 2019 to June 30, 2020

Interaction with Internal 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 in August 2018. These collaborators contribute to HI-AM by participating in complementary research projects, through reciprocal exchanges with Network researchers in their laboratories and research facilities, and through participation in Network meetings and conferences.

Although 6 student exchanges were planned to take place in spring/summer 2020, they were mostly postponed to Year 4 or canceled due to travel restrictions as a result of COVID-19. The following HQP were selected for 3 to 4-month exchange terms in Year 3:

PROJECT: DEVELOPMENT OF TITANIUM ALLOYS FOR LPB- AND LPF-AM

- Royal Melbourne Institute of Technology (RMIT), Melbourne, Australia
- Exchange award recipient: Nick Gosse, PhD student, Dalhousie University – Postponed to January 2021 (tentative)

PROJECT: REAL-TIME PROCESS CONTROL FOR ADDITIVE MANUFACTURING

- Royal Melbourne Institute of Technology (RMIT), Melbourne, Australia
- Exchange award recipient: Lucas Botelho, PhD student, University of Waterloo - Postponed to January 2021 (tentative)

PROJECT: THE USE OF DATA SCIENCE IN ELECTRON BEAM MELTING

- Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Dresden, Germany
- Exchange award recipient 1: Asmita Chakraborty, MASc student The University of British Columbia – Canceled due to COVID-19
- Exchange award recipient 2 (replacement): Pegah Pourabdollah, PhD student, The University of British Columbia – Start date TBD

PROJECT: TUNING LPBF PROCESS PARAMETERS USING CAD MODEL ANALYSIS

- University of Twente, Enschede, Netherlands
- Exchange award recipient: Marc Wang, MASc student, University of Waterloo – canceled due to COIVD-19

PROJECT: USING STATISTICAL/MACHINE LEARNING TECHNIQUES IN LPBF PROCESS OPTIMIZATION

- University of Twente, Enschede, Netherlands
- Exchange award recipient 1: Ying Zhang, PhD student, McGill University – Postponed to January 2021 (tentative)
- Exchange award recipient 2: Gijs Johannes Jozef van Houtum, PhD student, University of Waterloo – Started in September 2020

NOTE: All University of Waterloo-sanctioned international travel is suspended until further notice. With this international travel ban in effect and various restrictions set up by host institutions, we are not able to arrange new international exchange terms for Year 4 (2021–2022) at this time. Our priority is to make sure the postponed exchanges listed above will be completed. We are also closely monitoring the situation and will start to secure new positions abroad as soon as it is possible and safe to do so.

USEFUL LINKS:

University of Waterloo COVID-19 Information:
uwaterloo.ca/coronavirus/travel#travel-suspended

Government of Canada Travel Health Notices:
travel.gc.ca/travelling/health-safety/travel-health-notices

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UNIVERSITY OF WATERLOO | Department of Mechanical and Mechatronics Engineering

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