# NSERC HI-AM Network

NSERC-HI-AM.CA @NSERC_HI_AM HI-AM LINKEDIN PAGE 2021–2022

HOLISTIC INNOVATION IN ADDITIVE MANUFACTURING

# PROGRESS REPORT 4

NSERC HI-AM | UNIVERSITY OF WATERLOO Department of Mechanical and Mechatronics Engineering | NSERC CRSNG | INNOVATION.CA CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

# PROGRESS REPORT 4

2021–2022

READ OUR PREVIOUS PROGRESS REPORTS

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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 fourth progress report of the NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM). This report summarizes the research outcomes and network activities that took place between July 2021 and December 2022.

The HI-AM Network was established in 2017 as a 5-year project, initially expected to end by June 2022. Disruptions related to the COVID-19 pandemic limited our researchers' access to university campuses and research facilities for over a year, hence the Network duration was extended for a period of two years. We appreciate the approval of the requested extension by the Natural Sciences and Engineering Research Council of Canada (NSERC), allowing the HI-AM teams to complete their projects during the extension.

As the Network is progressing through its first extension year (Year 6), we are very grateful for the support and dedication of all our members including 19 Principal Investigators from University of Waterloo, Dalhousie University, Université Laval, McGill University, University of Toronto, University of Alberta, and The University of British Columbia; 131 highly qualified personnel; four 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.

The HI-AM Network is based on close collaborations between academia, industry, and government agencies. Over the past few years, we have developed strong partnerships with 22 industry, government, and non-profit organizations committed to the success of the Network. We have immensely benefitted from these collaborations and are excited to see the continued interest of the industry partners in the HI-AM research activities, as reflected through the provision of in-kind services beyond their original commitments and into the extension years.

The Network has produced substantial results through its 39 projects across four research themes under the supervision of the Network principal investigators. More than 405 journal and conference papers have been produced through these projects and seven invention disclosures have been filed. Furthermore, two ASTM standard/best practice drafts are under evaluation as a result of our partnership with ASTM International announced in 2021. Across research themes and R&D teams, interesting and impactful results continue to emerge as the Network is nearing completion after years of dedicated research and planning.

After holding the 2020 and 2021 conferences virtually due to the COVID-19 pandemic, we were able to welcome more than 200 Network members and external guests to the HI-AM Conference in person during this reporting period. The conference took place on June 21-22, 2022, in Montreal and featured 105 oral 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 NSERC, University of Waterloo, McGill University, Leichtbau BW GmbH, Multi-Scale Additive Manufacturing Lab, Canada Makes, Metal AM Magazine, EOS, GE Additive, AP&C, Promation, Desktop Metal, Keyence, Phaseshift Technologies, Opti-Tech Scientific, Retinex, C-Therm, Xact Metal, and Tronos.

We appreciate you taking the time to read this report, and we hope you find it useful. To learn more about the Network's 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**.

**Ralph Resnick,**
Chair of the Board of Directors

**Ehsan Toyserkani,**
Network Director

# Shaping the Future of Additive Manufacturing

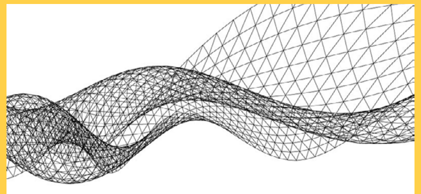
Additive Manufacturing (AM) has the potential to change the entire manufacturing sector by 2030. Despite the recent progress in this field, there are several remaining challenges hindering the widespread industrialization of this technology, from expensive and limited powder feedstock to the need for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

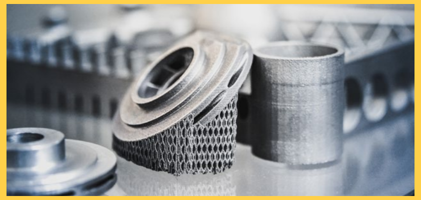
## HI-AM Research Themes

**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

# 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.

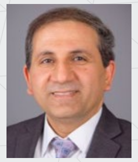
# Governance

## BOARD OF DIRECTORS

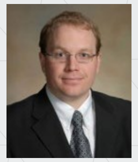
The **Board of Directors** oversees the global direction of the Network, providing bi-annual input on the research program quality and emerging research topics. The Board is also responsible for reviewing the Network's finances to ensure its success within the NSERC's financial guidelines.

### VOTING MEMBERS

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

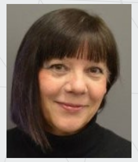


**Ehsan Toyserkani**
**University of Waterloo, Canada**
Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Mechanical and Mechatronics Engineering



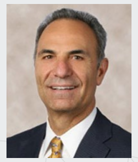
**Mathieu Brochu**
**McGill University, Canada**
Associate Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Materials Engineering

**Stefano Chiovelli**
**Syncrude, Canada**
Senior Technical Advisor



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

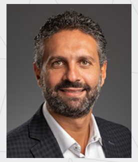
**Ian Donaldson**
**GKN, Canada**
Director, Advanced Engineering Applications



**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



**Mouhab Meshreki**
**National Research Council Canada**
Director R&D
Aerospace Manufacturing

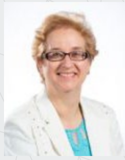
**Mark Zimny**
**Promation, Canada**
President

### NON-VOTING MEMBERS

**Marius Ivan**
**NSERC, Canada**
Manager, Manufacturing, Communications and Technologies Division | Research Partnerships

**Farzad Liravi**
**University of Waterloo, Canada**
Manager, NSERC HI-AM Network & CFI Can-AMN

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

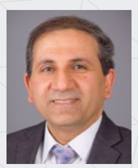


**Nancy Sej**
**University of Waterloo, Canada**
Financial Manager, NSERC HI-AM Network & CFI Can-AMN

# 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**
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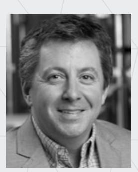
**Paul Bishop**
**Dalhousie University, Canada**
Professor of Mechanical Engineering



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**Siemens Energy, Canada**
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**Milan Brandt**
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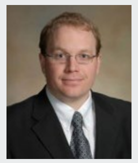

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Professor of Materials Engineering

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

**Ian Gibson**
**UT Twente, The Netherlands**
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**GE additive – AP&C Advanced Powders and Coating Inc., Canada**
Senior External R&D Manager

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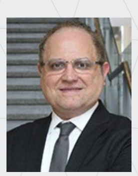
**University of Alberta, Canada**
Professor of Chemical and Materials Engineering



**Hani Naguib**
**University of Toronto, Canada**
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**The University of Toledo, USA**
Research Professor

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

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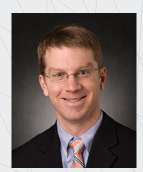
**The University of Texas at Austin, USA**
J. Mike Walker Professor of Mechanical Engineering



**Timothy Simpson**
**Pennsylvania State University, USA**
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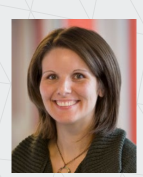
**National Research Council Canada**
Principal Research Officer



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

## 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**
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**Dave Dietz**
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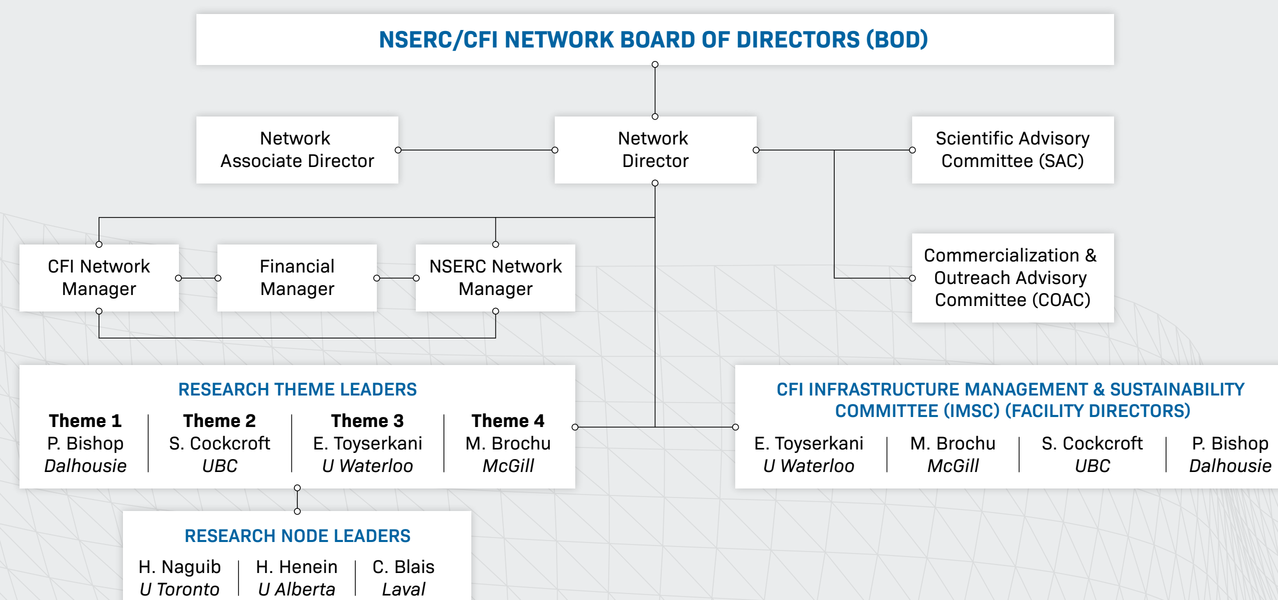
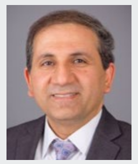
## GOVERNANCE STRUCTURE



# Principal Investigators

## THEME/NODE LEADERS



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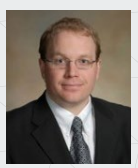

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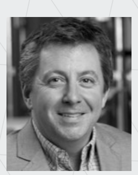

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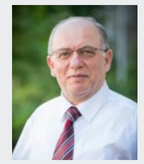

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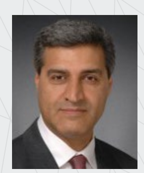

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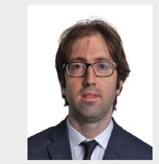
## COLLABORATORS



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Dept. of Mechanical Engineering

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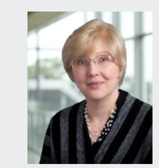
Département de génie mécanique



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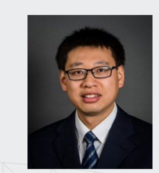
**University of Windsor**
Dept. of Mechanical, Automotive and Materials Engineering



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

# Network Partners

## ACADEMIC AND RESEARCH INSTITUTION PARTNERS

### MEMBERS

University of Waterloo
University of Alberta
The University of British Columbia
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
equispheres
FLEXCAP
GKN
KSB
MDA
Pratt & Whitney Canada, A United Technologies Company
PROMATION
RENISHAW apply innovation™
Rio Tinto
Siemens energy
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
MTDG Manufacturing Technology Deployment Group, Inc.
Mount Sinai Hospital
ReMAP Refined Manufacturing Acceleration Process / AAPF Accélération de l'amélioration des processus de fabrication

# Network Statistics (To Date)

| | | | |
|---|---|---|---|
| 7 UNIVERSITIES | 2 ACADEMIC COLLABORATORS | 22 INDUSTRIAL/ GOVERNMENT PARTNERS | 24 ACTIVE PROJECTS; 15 COMPLETED PROJECTS |
| 23 PRINCIPAL INVESTIGATORS | 131 HIGHLY QUALIFIED PERSONNEL* | 92 JOURNAL PAPERS | 66 CONFERENCE PAPERS/ PRESENTATIONS |
| 204 HI-AM CONFERENCE PAPERS/ PRESENTATIONS | 43 OTHER PUBLICATIONS** | 7 INVENTION DISCLOSURE | 5 EVENTS |

* 39 HQP have been funded from external sources; 107 HQP have been graduated or completed their program
** Thesis, Technical report, Patent

## HIGHLY QUALIFIED PERSONNEL (HQP) BY THEME

| | Undergraduate | MASc | PhD | PDF/RA |
|---|---|---|---|---|
| THEME 1 | 10 | 13 | 17 | 8 |
| THEME 2 | 0 | 9 | 9 | 4 |
| THEME 3 | 3 | 14 | 15 | 5 |
| THEME 4 | 6 | 7 | 6 | 5 |
| **TOTAL** | **19** | **43** | **47** | **22** |

# 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.

### SUB-PROJECT 1.1.1: DEVELOPMENT OF THERMALLY STABLE ALUMINUM ALLOYS FOR LPB-AM

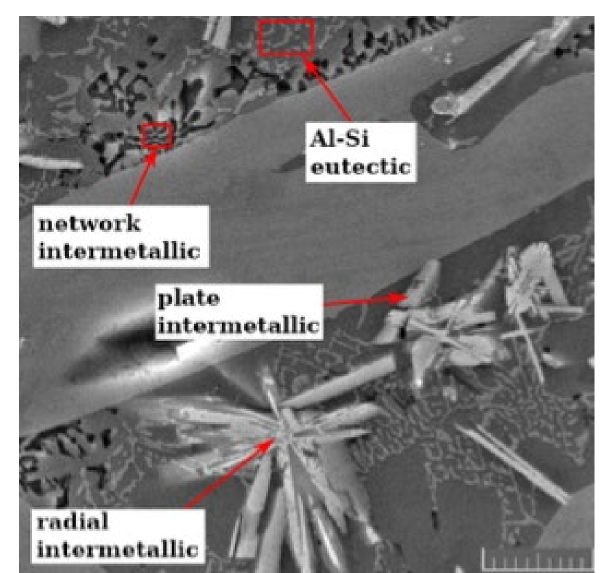
### PROGRESS

- [Dalhousie University] On research dedicated to the Al-Zr-Y system, the build plates were pre-scanned using a laser beam to obtain a more AM-like microstructure within the starting plates, which was followed by additional laser ablation trials and microstructural characterization. In-house production of A-Zr-Y powders via gas atomization and completion of L-PBF builds is planned for May 2023.
- [Dalhousie University] On research on metal matrix composite (MMC) systems, raw materials for the development of AlSi10Mg-AlN were procured and characterized. Different mixtures of AlSi10Mg with varying concentrations of aluminum nitride particulate were produced and characterized in terms of flowability and apparent density. Processing maps were developed for each MMC mixture using experimental analysis. Various imaging and mechanical characterization tests were carried out on the as-built and heat-treated test specimens.
- [McGill University] Mechanical and microstructural characterization of L-PBF Al-40Si in as-built and heat-treated conditions was completed. Solidification parameters were correlated with the processing conditions and mechanical properties of the test specimens.
- [McGill University] Microstructural characterization was performed for the Pandalloy powder and an optimized L-PBF processing window was obtained for this alloy. Thermodynamic modeling and estimation of the solidification parameters for Pandalloy is underway.





- [University of Alberta] On research dedicated to Al-Si-Sc alloy, microstructural and phase characterizations were conducted using Field Emission Scanning Electron Microscopy (FESEM) and Transmission Electron Microscopy (TEM) to determine the influence of the cooling rate and scandium addition. Furthermore, the solidification pathways, formed microstructures, and microhardness responses were quantified for slow and rapid cooling rates. The hardness of Al-10Si-0.4Sc was determined for all aging conditions.
- [University of Alberta] Research on Si modification in the hypereutectic Al-Si system was completed. Microstructures of Al-40Si-1.5Ce, Al-40Si-9.2Mg, and Al-40Si-2.75Fe-2.75Mn-1.5Sc were qualitatively analyzed by comparing the changes in primary Si morphology and distribution across different powder sizes for each alloy and across all alloys for specific powder sizes. The quantitative results include measured phase fractions of primary Si for all alloys and halo and eutectic systems for Al-40Si and Al-40Si-1.5Ce.
- [University of Alberta] Efforts to prepare ingots of Al-33Cu3Mg05Si for mechanical property evaluation continue. Coarsening of the eutectic lamella in rapid solidified Al33Cu powders on a hot stage Scanning Electron Microscopy (SEM) was studied.
- [University of Alberta] The investment casting methodology was extended to Al-4.5Cu-0.4Sc and other Al alloys to increase the solidification rate of the lattice being cast.




Eutectic structure in impulse atomized Al-40Si-2.75Fe-2.75Mn-1.5Sc. (Sub-project 1.1.1)

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Bogno AA, Hearn W, Spinelli JE, Valloton J, Henein H. Quantification of microstructure to reveal the solidification path of an alloy. In IOP Conference Series: Materials Science and Engineering 2019 May 1 (Vol. 529, No. 1, p. 012056). IOP Publishing. **[Link]**
2. Bogno AA, Valloton J, Jimenez DD, Rappaz M, Henein H. Rapid solidification of Al-Cu droplets of near eutectic composition. In IOP Conference Series: Materials Science and Engineering 2019 May 1 (Vol. 529, No. 1, p. 012021). IOP Publishing. **[Link]**
3. Valloton J, Bogno AA, Henein H, Herlach DM, Sediako D. Scandium effect on undercooling and dendrite morphology of Al-4.5 Wt Pct Cu droplets. Metallurgical and Materials Transactions A. 2019 Dec;50:5700-6. **[Link]**
4. Henein H, Bogno AA, Hearn W, Valloton J. Metastable dendrite morphologies in Aluminum alloys. Journal of Phase Equilibria and Diffusion. 2020 Dec;41:784-92. **[Link]**
5. Rayner AJ, Cooke RW, Donaldson IW, Corbin SF, Bishop DP. Binder Jet Printing AISI 5120 Chromium Steel Powder. Metallurgical and Materials Transactions. 2023 Feb 8:1-5. **[Link]**
6. Valloton J, Vogel SC, Henein H. Microstructural study of containerless solidification of Al-5wt% Ce alloy. In IOP Conference Series: Materials Science and Engineering 2023 (Vol. 1274, No. 1, p. 012058). IOP Publishing. **[Link]**
7. Valloton J, Mahdi N, Rabago L, Chung J, Henein H. In situ solidification of eutectic Al-33wt% Cu droplets. InIOP Conference Series: Materials Science and Engineering 2023 (Vol. 1274, No. 1, p. 012034). IOP Publishing. **[Link]**

- At least 3 more manuscripts are in preparation for publication.

#### CONFERENCE PRESENTATION

1. D. Diaz, A. Bogno, J. Valloton, H. Henein, M. Rappaz. Rapid Solidification of Al-Cu Eutectic. Additive Manufacturing Alberta by Innotech Alberta - Edomnton, AB, 2018.
2. A. Sahoo, H. Henein, A. Bogno, W. Hearn. Rapid Solidification of Impulse Atomized Al-Si-Sc. Symposium: Additive Manufacturing and Welding: Physical and Mechanical Metallurgy of Rapidly Solidified Metals, TMS 2019 Annual Meeting & Exhibition - San Antonio, TX, 2019.

*Continued on next page...*

3. M. Dias, A. Bogno, J. Spinelli, A. Garcia, H. Henein. Effects of Bi in Rapid Solidification of a Hypoeutectic Al-Si Alloy. TMS 2020, 149th Annual Meeting and Exhibition - San Diego, CA, 2020.
4. D. Diaz, A. Bogno, H. Henein. Primary Si Modification via Rapid Solidification and Alloying. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
5. A. Bogno, M. Tamboli, A. Sabouraud, A. Qureshi, H. Henein. Manufacturing of 3D Lattice Structures by Hybrid Investment Casting. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
6. J. M Dias, A. Bogno, H. Henein. Effect of Bi on the Rapid Solification Microstructure and Properties of Hypoeutectic Al-Si. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
7. D. Diaz, A. Bogno, H. Henein. Modifying the Morphology of Si in Hypereutectic Al-Si Alloys. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
8. A. Fu, M. Brochu. Composition optimization for Al alloys in additive manufacturing. REGAL Students' Day, 2020.
9. A. Sahoo, A. Bogno, J. Valloton, H. Henein. The Microstructure, Morphology and Mechanical Properties of Rapidly Solidified Al-10wt%Si-0.4wt%Sc Alloy. TMS 2020, 150th Annual Meeting and Exhibition - Virtual, 2021.
10. D. Diaz, A. Bogno, H. Henein. Modification of Primary Si Morphology in hypereutectic Al-Si by Rapid Solidification and Alloying. COM 2021, 60th Conference of Metallurgists - Virtual, 2021.
11. J. Hierlihy, I. Donaldson, M. Brochu, G. Sweet, P. Bishop. Laser Powder Bed Processing of Aluminum Powders Containing Iron and Nickel Additions. COM 2021, 60th Conference of Metallurgists - Virtual, 2021.
12. A. Sahoo, A. Bogno, H. Henein. Study of the Solidification Pathways of Hypo/hyper-eutectic Al-Ce over a Wide Range of Thermal Histories. TMS-DGM Symposium 2021: A Joint US-European Symposium on Linking Basic Science to Advances in Manufacturing of Lightweight Metals, 2021.
13. A. Sahoo, A. Bogno, H. Henein. The Microstructure, Morphology and Mechanical Properties of Rapidly Solidified Al-10wt%Si-0.4wt%Sc Alloy. TMS-DGM Symposium 2021: A Joint US-European Symposium on Linking Basic Science to Advances in Manufacturing of Lightweight Metals, 2021.
14. J. Valloton, A. Bogno, M. Rappaz, H. Henein. Numerical Model of Al-33wt%Cu Eutectic Growth during Impulse Atomization. TMS-DGM Symposium 2021: A Joint US-European Symposium on Linking Basic Science to Advances in Manufacturing of Lightweight Metals, 2021.
15. J. Valloton, A. Bogno, H. Henein. 4D Characterization of Solidification in Al-based Droplets. 3DMS 2021, 5th International Congress on 3D Materials Science - Virtual, 2021.
16. Henein H, Sahoo A, Valloton J. Microstructural Study of Containerless Solidification of Al-20wt% Ce Alloys. In Proceedings of the 61st Conference of Metallurgists, COM 2022 2023 Jan 6 (pp. 471-474). Cham: Springer International Publishing. **[Link]**
17. J. Valloton, A. Sahoo, M. da Silva Dias Filho, H. Henein. Microstructural evaluation of containerless solidification of Al-Ce alloys. Frontiers of Solidification, TMS Annual Meeting, 2023, San Diego, CA, USA, 2023.
18. Henein H, Sahoo A, Valloton J. Microstructural Study of Containerless Solidification of Al-20wt% Ce Alloys. In Proceedings of the 61st Conference of Metallurgists, COM 2022. 2023 Jan 6 (pp. 471-474). Cham: Springer International Publishing. **[Link]**
19. Valloton J, Mahdi N, Rabago L, Chung J, Henein H. In situ solidification of eutectic Al-33wt% Cu droplets. InIOP Conference Series: Materials Science and Engineering 2023 (Vol. 1274, No. 1, p. 012034). IOP Publishing. **[Link]**
20. J. Valloton, A. Sahoo, M. da Silva Dias Filho, H. Henein. Microstructural evaluation of containerless solidification of Al-Ce alloys. Frontiers of Solidification, TMS Annual Meeting, 2023, San Diego, CA, USA, 2023.

#### THESIS

1. Hierlihy J. Laser Powder Bed Fusion Processing of Aluminum Powders Containing Iron and Nickel. **[Link]**
2. Diaz Jimenez D. Si modification in hypereutectic Al-Si: Combining rapid solidification and alloying. **[Link]**





## SUB-PROJECT 1.1.2: DEVELOPMENT OF TITANIUM ALLOYS FOR LPB-AM AND LPF-AM

### PROGRESS

- In partnership with GE Additive (AP&C), the project resources were directed into an expansion of efforts related to DED by expanding the scope of alloys investigated. Therefore, objectives related to L-PBF processing of titanium alloys were not instigated.
- Additional tensile and O-H-N analysis testing were completed for Ti6242 and Beta 21S products. The heat treatment response of optimally built DED specimens was explored using Differential Scanning Calorimetry (DSC), mechanical testing and microstructural analysis. Furthermore, samples were printed for fatigue testing of optimally built DED products.
- Additional work to assess the tensile and microstructural properties of Ti55511 products and the effects of heat treatment was completed.

### RESEARCH OUTCOME

#### JOURNAL PAPER

- At least 1 manuscript is in preparation for publication.

#### THESIS

1. Gosse N. Directed Energy Deposition of Alpha-Beta, Near-Alpha, and Beta Titanium Alloys. Master's Thesis. Dalhousie University. 2022. **[Link]**

## SUB-PROJECT 1.1.3: DEVELOPMENT OF TOOL STEELS FOR LPB-AM AND LPF-AM

### PROGRESS

- [Université Laval] The oxygen content in water-atomized A8-modified tool steel was further reduced to below 0.05 wt-% by performing Inductively Coupled Plasma (ICP) spheroidization and hydrogen annealing. This alloy was pre-mixed with tungsten carbide (WC) prior to spheroidization to increase its wear resistance. The modified powder shows similar or superior flow and density properties compared with commercial H13 tool steel powder manufactured via gas atomization. The team also completed work on the development and characterization of a novel water-atomized powder based on S7 tool steel with similar or higher mechanical properties compared to wrought S7 tool steel.
- [Université Laval] The L-PBF process parameters for modified A8 and S7 alloys were optimized and test specimens were fabricated to characterize their mechanical properties (hardness, wear, and tensile strength) and microstructure.
- [University of Alberta] Characterization of 17-4PH powder was conducted. An improved thermal modeling of this alloy was completed with specific heat treatment data obtained from a trial DSC run. The Secondary Dendrite Arm Spacing (SDAS) was measured for 17-4PH atomized droplets and the correlation between SDAS and cooling rate was determined. Test samples were printed using Wire Arc Additive Manufacturing (WAAM), and characterization (micro-hardness and microstructure) was initiated. The thermal history and cooling rate of the process was simulated using ABAQUS and compared with WAAM experimental results.
- [University of Alberta] The developed machine learning model was successful at segmentation of Ni-WC, determining the mean free path, and predicting the carbide percentage.
- [University of Alberta] Microstructural analysis of electromagnetically levitated samples of Ni-WC were carried out. Furthermore, a heat transfer model was developed to test whether the WC particles reach their liquidus temperature during Plasma Transferred Arc Additive Manufacturing (PTA-AM) deposition. The goal of this work is to quantify the amount of liquid being formed, and relate this quantity to the amount of W that is dissolved in the Ni matrix during PTA-AM of Ni-WC deposits.
- [University of Alberta] The microstructure and composition of NiBSi and NiCrBSi containing various weight concentrations of monocrystalline WC were characterized. The cooling rate and SDAS were measured for 70 wt-% WC-NiBSi and used to estimate the cooling rate of PTA-AM and correlate it to the composition. Thermo-calc was used to model the equilibrium and Scheil solidification of the mentioned compositions and the results were compared to the PTA-AM microstructure.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Lehmann T, Rose D, Ranjbar E, Ghasri-Khouzani M, Tavakoli M, Henein H, Wolfe T, Jawad Qureshi A. Large-scale metal additive manufacturing: a holistic review of the state of the art and challenges. International Materials Reviews. 2022 May 19; 67(4):410-59. **[Link]**

*Continued on next page...*

2. Rose D, Forth J, Henein H, Wolfe T, Qureshi AJ. Automated semantic segmentation of NiCrBSi-WC optical microscopy images using convolutional neural networks. Computational Materials Science. 2022 Jul 1;210:111391. **[Link]**
3. Mutel D, Gélinas S, Blais C. Rheological characterisation of water atomised tool steel powders developed for laser powder bed fusion by supervised and unsupervised machine learning. Powder Metallurgy. 2023 Mar 21:1-3. **[Link]**

- At least 2 more manuscripts are in preparation for publication. 1 manuscript is under review.

#### CONFERENCE PRESENTATION

1. D. Mutel, C. Blais. Optimization of Water-atomized Tool Steel Powders for Utilization in Laser Powder Bed Fusion (L-PBF). 2020 World Congress on Powder Metallurgy and Particulate Materials (WorldPM) - Montreal, QC, 2020.
2. D. Mutel, C. Blais. Towards the development of water-atomized tool steel powders for utilization in Direct Energy Deposition (DED) and Laser Powder Bed (LPB). Powdermet 2021, International Conference on Powder Metallurgy and Particulate Materials - Orlando, FL, 2021.
3. W. Chaîné, C. Blais. Development of Novel A8 Tool Steel Powders for AM Produced by Water Atomization. Powdermet 2021, International Conference on Powder Metallurgy and Particulate Materials - Orlando, FL, 2021.
4. D. Rose, J. Forth, H. Henein, T. Wolfe, A. Qureshi. Semantic Segmentation of Plasma Transferred Arc Additively Manufactured NiBSi-WC Optical Microscopy Images Using a Convolutional Neural Network. MS&T 2021, 2021.
5. D. Mutel, S. Gelinas, C. Blais. Rheological characterization of water atomized tool steel powders developed for laser powder bed fusion by supervised and unsupervised machine learning. WorldPM2022, Lyon, France, 2022.

## SUB-PROJECT 1.1.4: DEVELOPMENT OF NICKEL ALLOYS FOR LPB-AM

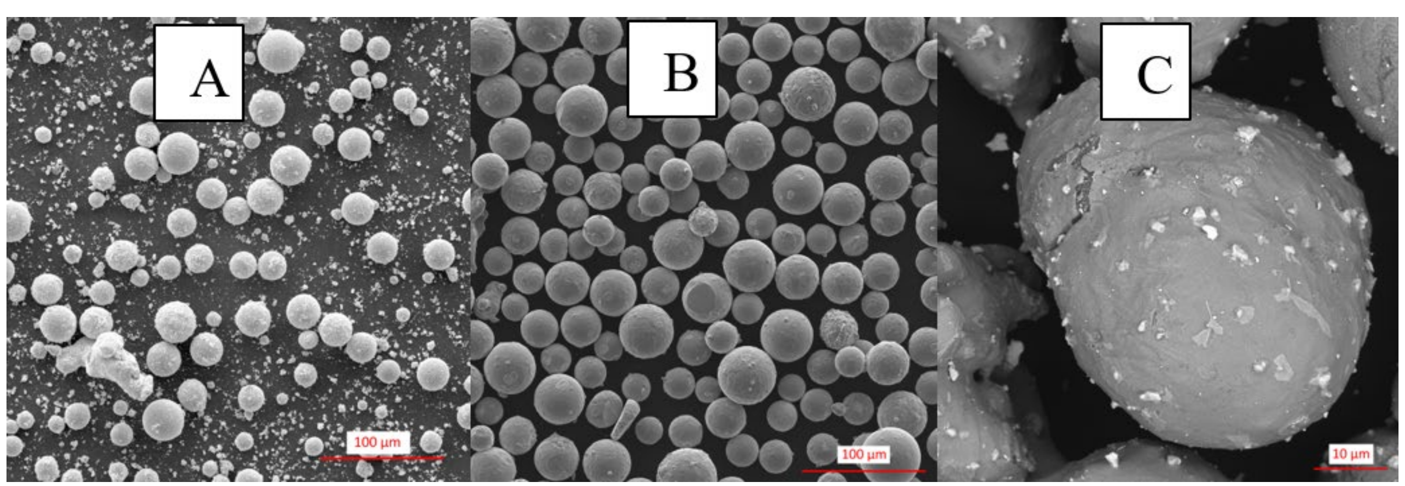
### PROGRESS

- The microstructural development of L-PBF-made Rene 77 samples after heat treatment was characterized and correlated with the hardness measurements.
- The microstructural development of L-PBF-made Rene 41 samples was studied and the crack development in this alloy was associated with the change in the segregation behavior of different cross-sectional areas. The microstructure of the printed parts was correlated with their hardness.
- Process parameters for L-PBF of intermetallic alloys including Fe3Al (Fe-129), TiAl, Ti3Al, and NiAl were developed. Ongoing research is focusing on crack mitigation and scaling up the process.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Atabay SE, Sanchez-Mata O, Muniz-Lerma JA, Gauvin R, Brochu M. Microstructure and mechanical properties of rene 41 alloy manufactured by laser powder bed fusion. Materials Science and Engineering: A. 2020 Jan 31;773:138849. **[Link]**




(a) Plasma spheroidized A8 powder showing nanoparticles, (b) plasma spheroidized A8 powder after heat treatment showing the nanoparticles have been removed, (c) WC sintered onto A8 particles. (Sub-project 1.1.3)





2. Atabay SE, Sanchez-Mata O, Muñiz-Lerma JA, Brochu M. Effect of heat treatment on the microstructure and elevated temperature tensile properties of Rene 41 alloy produced by laser powder bed fusion. Journal of Alloys and Compounds. 2021 Mar 25;858:157645. **[Link]**
3. Atabay SE, Sanchez-Mata O, Muniz-Lerma JA, Brochu M. Microstructure and mechanical properties of difficult to weld Rene 77 superalloy produced by laser powder bed fusion. Materials Science and Engineering: A. 2021 Oct 19;827:142053. **[Link]**

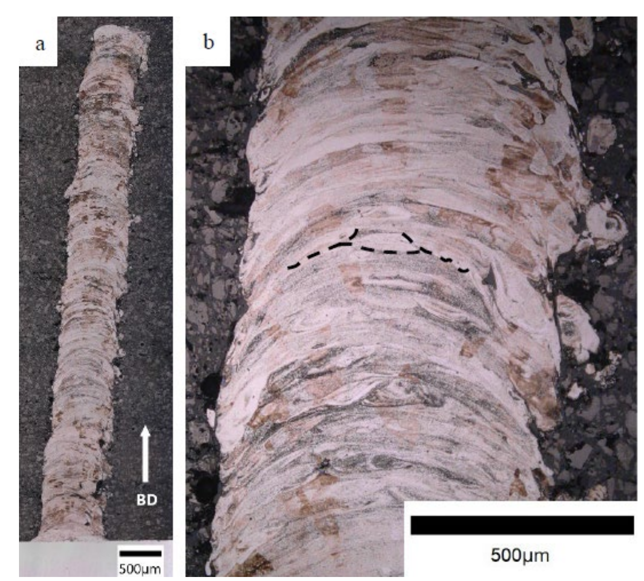
- At least 3 more manuscripts are in preparation for publication.

#### CONFERENCE PRESENTATION

1. S. Atabay, K. Plucknett, M. Brochu. Microstructural Evaluation of AM Fabricated Rene 41 Alloy. Materials Science and Technology 2018 (MS&T) - Columbus, OH, 2018.
2. S. Atabay, O. Sanchez-Mata, J. Muniz-Lerma, M. Brochu. Microstructure and Mechanical Properties of Rene 77 Alloy Manufactured by Laser Powder Bed Fusion. Aeromat 2021 - 32nd Conference and Exposition, 2021.

#### THESIS

1. Atabay SE. Laser powder bed fusion of precipitation-hardened rene 41 and rene 77 nickel base superalloys. McGill University (Canada); 2021. **[Link]**




(a) Overall morphology of the as-built FA-129 strut, (b) optical microscopy image at a higher magnification of a region in the middle of the strut with melt pool boundaries marked. (Sub-project 1.1.4)

## SUB-PROJECT 1.1.5: DEVELOPMENT OF REFRACTORY METALS FOR LPB-AM

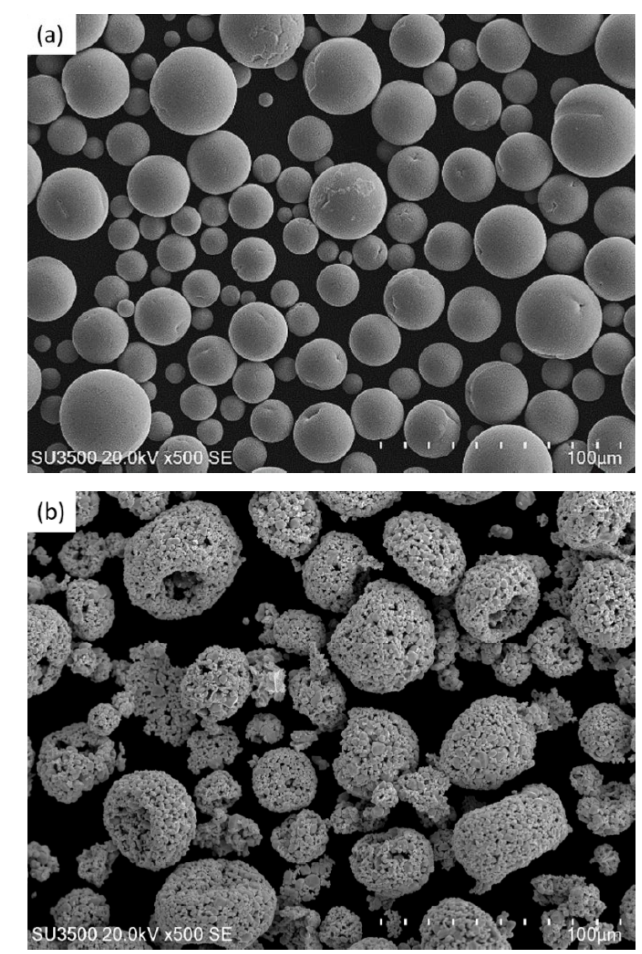
### PROGRESS

- Mo alloy heat sink/heat exchanger parts were fabricated using the L-PBF process for performance assessment followed by microstructural assessment of the constructs using optical and electron microscopy.
- The influence of heat exposure/extraction on cracking resistance, and the impact of heat exposure on material properties (microstructure, Coefficient of Thermal Expansion (CTE), etc.) were evaluated.

### RESEARCH OUTCOME

#### JOURNAL PAPER

- At least 2 manuscripts are in preparation for publication.




SEM micrographs of (a) Mo and (b) TZM powders. (Sub-project 1.1.5)

## 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<br>• Mathieu Brochu, McGill University<br>• Hani Henein, University of Alberta | • An Fu, McGill University, PhD<br>• Jon Heirly, Dalhousie University, PhD<br>• Quentin Champdoizeau, University of Alberta, MASc<br>• Daniela Diaz, University of Alberta, RA, MASc<br>• Abdoul-Aziz Bogno, University of Alberta, RA<br>• Jose Marcelino Da Silva Dias Filho, University of Alberta, PDF (Collaborator)<br>• Akankshya Sahoo, University of Alberta, PhD (Collaborator)<br>• Matthew Harding, Dalhousie University, PDF<br>• Greg Sweet, Dalhousie University, PDF<br>• Maéva Chrzaszcz, McGill University, Co-op<br>• Ryan Ley, Dalhousie University, Co-op (Collaborator)<br>• Jon Comhaire, Dalhousie University, MASc<br>• Loraine Rabago, University of Alberta, Co-op/URA (Collaborator)<br>• Batool Aleeza, University of Alberta, Co-op/URA (Collaborator) |
| **1.1.2 Development of Titanium Alloys for LPB-AM and LPF-AM** | • Paul Bishop, Dalhousie University | • Matthew Harding, Dalhousie University, PDF<br>• Greg Sweet, Dalhousie University, PDF<br>• Nick Gosse, Dalhousie University, Co-op, PhD<br>• M.D. Hasan Khondoker, Dalhousie University, PDF (Collaborator)<br>• Addison Rayner, Dalhousie University, PDF |
| **1.1.3 Development of Tool Steels for LPB-AM and LPF-AM** | • Carl Blais, Université Laval<br>• Hani Henein, University of Alberta | • Denis Mutel, Université Laval, PhD<br>• William Chaîné, Université Laval, MASc<br>• Anne McDonald, University of Alberta, URA<br>• Dylan Rose, University of Alberta, PhD (Collaborator)<br>• Nasim Navid Moghadam, University of Alberta, PhD<br>• Swalihah Noorani, University of Alberta, URA<br>• Yume Bhutia, University of Alberta, URA (Collaborator)<br>• Jolene Borrelli, University of Alberta, URA (Collaborator) |
| **1.1.4 Development of Nickel Alloys for LPB-AM** | • Mathieu Brochu, McGill University | • Sila Atabay, McGill University, PhD<br>• Kevin Lee, McGill University, PhD<br>• 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.

### SUB-PROJECT 1.2.1: NOVEL COMPOSITES FOR BJ-AM TO DEVELOP FOAM-BASED STRUCTURES

## PROGRESS

- The research on MXene shape memory composites was expanded to include the FDM process by formation of printable filament from this material. Demonstrator self-deployable structures were successfully printed and characterized, and the material was optimized to improve the mechanical and shape memory performance.
- Shape memory polymer inks for precipitation DIW printing were developed and initial print trials were conducted. Ongoing work is focusing on the development of a mathematical model to optimize the DIW printing parameters for viscous conductive inks, such as MXene-PEDOT:PSS.
- Research on AM of origami structures using multi-material FDM was completed.

## RESEARCH OUTCOME

### JOURNAL PAPER

1. Shen X, Naguib HE. A robust ink deposition system for binder jetting and material jetting. Additive Manufacturing. 2019 Oct 1;29:100820. **[Link]**
2. Wickeler AL, Naguib HE. Novel origami-inspired metamaterials: Design, mechanical testing and finite element modelling. Materials & Design. 2020 Jan 15; 186:108242. **[Link]**
3. Shen X, Chu M, Hariri F, Vedula G, Naguib HE. Binder jetting fabrication of highly flexible and electrically conductive graphene/PVOH composites. Additive Manufacturing. 2020 Dec 1;36:101565. **[Link]**
4. Wickeler AL, Naguib HE. 3D printed geometrically tessellated sheets with origami-inspired patterns. Journal of Cellular Plastics. 2022 Mar;58(2):377-95. **[Link]**
5. Li T, Chen T, Shen X, Shi HH, Jabari E, Naguib HE. A binder jet 3D printed MXene composite for strain sensing and energy storage application. Nanoscale Advances. 2022;4(3):916-25. **[Link]**
6. McLellan K, Sun YC, Naguib H. A review of 4D printing: Materials, structures, and designs towards the printing of biomedical wearable devices. Bioprinting. 2022 May 28:e00217. **[Link]**
7. McLellan K, Li T, Sun YC, Jakubinek MB, Naguib HE. 4D Printing of MXene Composites for Deployable Actuating Structures. ACS Applied Polymer Materials. 2022 Nov 7;4(12):8774-85. **[Link]**

- At least 1 more manuscript is in preparation for publication. 1 manuscript has been accepted by Progress in Additive Manufacturing.

### CONFERENCE PRESENTATION

1. A. Wickeler, H. Naguib. Correlation between Varying Shapes and Dimension, and Mechanical Properties of Metamaterials. ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS) - San Antonio, TX, 2018.
2. T. Morrison, H. Naguib. Graphene-based Nanocellulose Composites for 3D Printed Electrodes. Materials Research Society (MRS) Fall 2018 - Boston, MA, 2018.
3. X. Shen, T. Morrison, H. Naguib. Binder Jetting Fabrication of Graphene Composites Structures for Printed 3D Electronics Devices. Materials Research Society (MRS) Fall 2018 - Boston, MA, 2018.
4. X. Shen, H. Naguib. A Novel Binder Jetting Approach to Print 4D Functionally Grade Materials. TWENTY-SECOND International Conference on composite materials (ICCM22) - Melbourne, Australia, 2019.
5. X. Shen, M. Chu, Y. Kazemi, H Naguib. 3D Printing Multi-Material and Functionally Graded Composites. UT2-MAC Joint Workshop, 2019.
6. X. Shen, H. Naguib. A Facile Ink Jetting System for Additive Manufacturing with Caustic and Abrasive Ink Compositions. TWENTY-SECOND International Conference on composite materials (ICCM22) - Melbourne, Australia, 2019.

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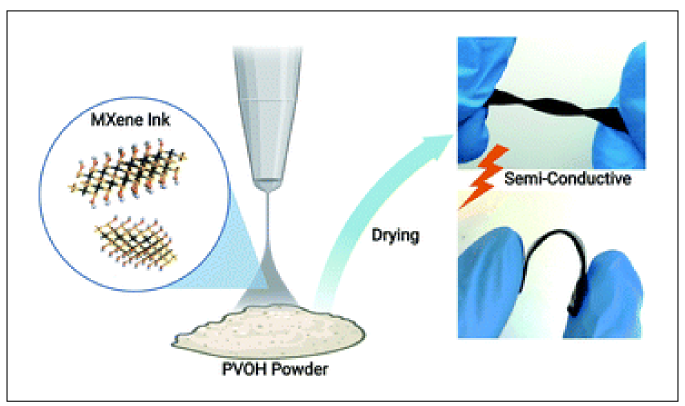
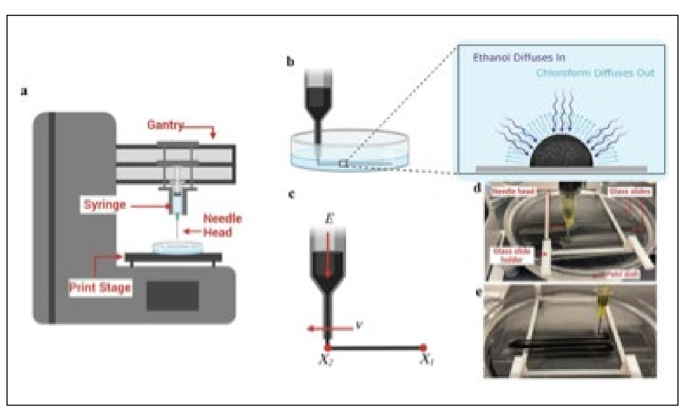
7. A. Wickeler, H. Naguib. Experimental Approach to the Design of Additively Manufactured Tessellated Metamaterial Sheets for Protective Applications Requiring Impact Energy Absorption. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
8. K. McLellan, T. Li, H. Naguib. 4D Precipitation Printing of Shape Memory Polymer Artificial Muscles. 2022 Materials Research Society (MRS) Spring Meeting, 2022.

**THESIS**

1. Morrison TJ. Material Development and Design for 3D Printable Electronic Devices. University of Toronto (Canada); 2019. **[Link]**
2. Shen X. Towards Integrated 3D Printing as an Industrial Manufacturing Process. University of Toronto (Canada); 2020. **[Link]**
3. Wickeler A. Origami-Inspired Mechanical Metamaterials (Doctoral dissertation, University of Toronto (Canada). **[Link]**




A strain sensor printed using MXene. (Sub-project 1.2.1)




Precipitation DIW setup used for printing shape memory structures. (Sub-project 1.2.1)

## SUB-PROJECT 1.2.2: ALLOY ALTERATION FOR FUNCTIONALLY GRADED MATERIALS (FGMS) USED IN LPF-AM

### PROGRESS

- Hardness mapping of as-printed and heat-treated H13 was completed.
- Various properties of pack-borided DED H13 and wrought counterparts (e.g., surface hardness, scratch testing, microscopy, EDS, WDS, and XRD) were compared.
- DSC analyses on H13/Cu blends of varying compositions under different conditions was completed.
- In partnership with Navajo Technical University (NTU), single tracks, 3-layer tracks, and rectangular FGMs have been printed using H13 and OFHC copper, starting from 100% H13 and grading through to 100% Cu. Parts have been fully characterized (SEM, optical microscopy, Energy-dispersive X-ray spectroscopy (EDS), hardness, X-ray Diffraction (XRD)).
- Attempts at printing on a pure copper substrate, including process parameter optimization and substrate preheating, have been unsuccessful, with deposited tracks resulting in a "balled" appearance.

### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Craig O, Bois-Brochu A, Plucknett K. Geometry and surface characteristics of H13 hot-work tool steel manufactured using laser-directed energy deposition. The International Journal of Advanced Manufacturing Technology. 2021 Sep;116(1-2):699-718. **[Link]**

- At least 4 more manuscripts are in preparation for publication

**CONFERENCE PRESENTATION**

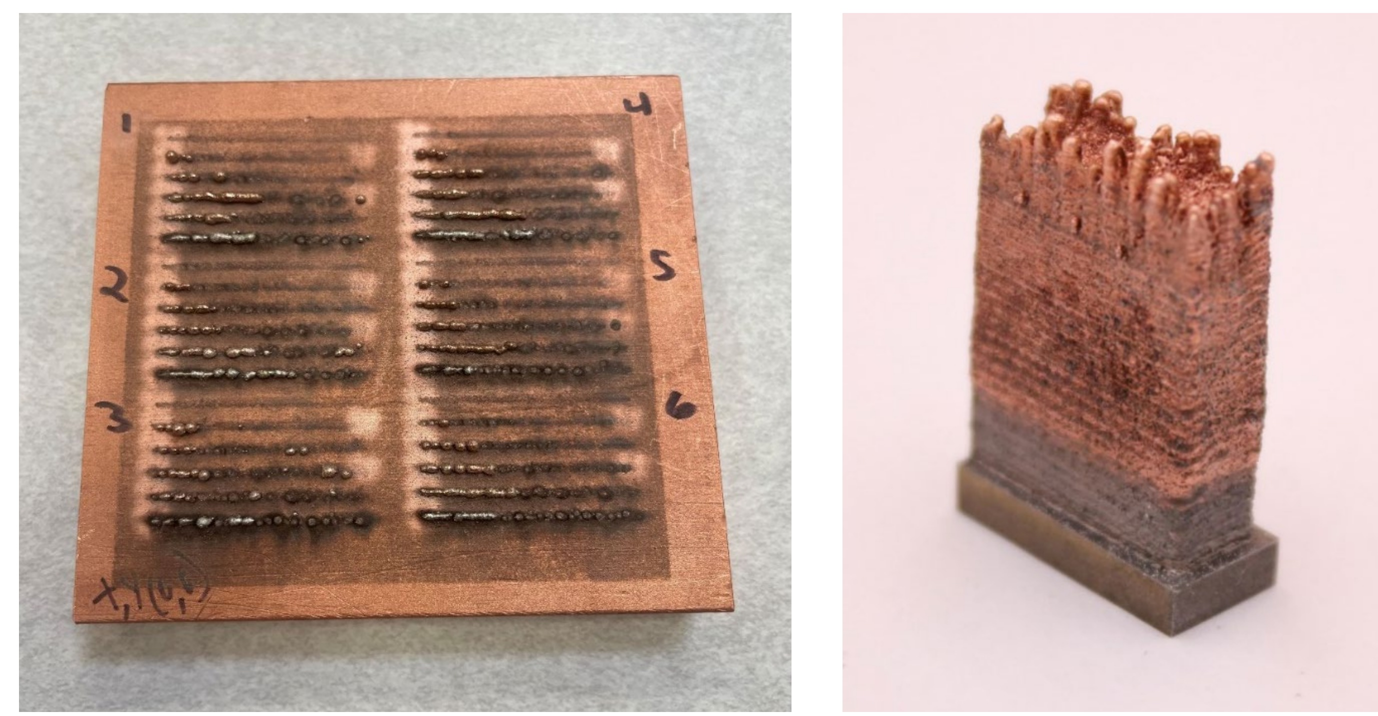
1. O. Craig, K. Plucknett. Scratch Hardness and Wear Response of Additively Manufactured H13 Tool Using Directed Energy Deposition with Post Heat Treatments. Wear of Materials 2021, 23rd International Conference on Wear of Materials - Virtual, 2021.
2. O. Craig, S. Omar, K. Plucknett. Material Characterization Comparison of D2 and H13 Tool Steels Manufactured using Directed Energy Deposition. COM 2021, 60th Conference of Metallurgists - Virtual, 2021.
3. O. Craig, R. Roache, K. Plucknett. Microstructural Characterization of Pack Borided H13 using DED. 2022 Conference of Metallurgists (COM), 2022.





### 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<br>• Xuechen Shen, University of Toronto, MASc<br>• Tylor Morrison, University of Toronto, MASc (Collaborator)<br>• Kyra Mclellan, University of Toronto, MASc<br>• Terek Li, University of Toronto, MASc (Collaborator)<br>• Andrew Jo, University of Toronto, PhD<br>• 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 |



(Left) Deposition of single clad tracks onto a pure Cu-substrate after preheating showing the "balled" appearance.
(Right) Macro image of rectangle FGM printed using DED from H13 and OHFC Copper. (Sub-project 1.2.2)

# 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.

## SUB-PROJECT 1.3.1: RECYCLABILITY OF POWDER FEEDSTOCKS FOR LPB-AM

### PROGRESS

- After completing the activities related to studying the effect of moisture on powder processing at McGill University and recyclability of maraging steel 300 at University of Toronto, the project scope was expanded to include the development, characterization, and optimization of recycling strategies for conductive fillers made of MXene powder systems and inks, linking this new phase to sub-project 1.2.1.
- MXene nano-particles were fabricated and characterized. Investigating the long-term oxidation and degradation of MXene is ongoing and has been recorded for a period of 90 days so far. As oxidation leads to a decrease in surface conductivity, the research team is working on a chemical recycling process to stabilize, slow, and possibly reverse the oxidation.
- A performance benchmarking experiment for recycled MXene is being planned using the precipitation DIW process developed in sub-project 1.2.1.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Das A, Muñiz-Lerma JA, Espiritu ER, Nommeots-Nomm A, Waters K, Brochu M. Contribution of cellulosic fibre filter on atmosphere moisture content in laser powder bed fusion additive manufacturing. Scientific Reports. 2019 Sep 24;9(1):1-8. **[Link]**
2. Sun H, Chu X, Liu Z, Gisele A, Zou Y. Selective laser melting of maraging steels using recycled powders: A comprehensive microstructural and mechanical investigation. Metallurgical and Materials Transactions A. 2021 May;52:1714-22. **[Link]**
3. McLellan K, Sun YC, Li T, Chen T, Naguib H. 4D precipitation printing technologies toward sensing devices using microporous structures. Progress in Additive Manufacturing. 2022 Dec 9:1-2. **[Link]**

- At least 1 more manuscript is in preparation for publication

#### CONFERENCE PRESENTATION

1. A. Das, M. Brochu. Relationship of Cellulosic Fiber and Oxygen Content in Laser Powder Based Fusion (L-PBF) Additive Manufacturing. Materials Science and Technology 2018 (MS&T) - Columbus, OH, 2018.

#### THESIS

1. Das A. Moisture Sources in Laser Powder Bed Fusion Additive Manufacturing. McGill University (Canada); 2020. **[Link]**
2. Sun HK. Selective Laser Melting of a High-Strength Steel and Joining of Aluminum and Copper. University of Toronto (Canada). **[Link]**

## SUB-PROJECT 1.3.2: PLASMA SPHEROIDIZATION OF LOW COST POWDERS

### PROGRESS

- Used and oversized Ti64 (Grade 23), Inconel 718 and SS316L powders were spheroidized using ICP spheroidization system followed by flowability, apparent density and chemical characterization of the produced powder batches. The ICP technique was successfully employed to improve the morphology of the used particles by spheroidizing them and smoothing their surfaces, leading to improved flowability.
- The spreadability of the recycled ICP spheroidized powders in the L-PBF system was studied.
- Printing parameters were optimized for L-PBF processing of the recycled powders. Experiments are planned to compare the microstructural properties and mechanical performance of the parts printed using virgin and ICP spheroidized powders.





## SUB-PROJECT 1.3.3: COST-EFFECTIVE STEEL FEEDSTOCK FOR AM

### PROGRESS

- [Université Laval] Specimens combining varying weight fractions of a master alloy were premixed with D2 tool steel and 4340 low-alloyed steel powders to obtain an adequate volume of the liquid phase, and sintered in Ar and under vacuum to characterize the densification, phase transformation, and mechanical properties. Following sintering, densification through permanent liquid phase sintering in Ar reached densities higher than 90% of the theoretical density. Furthermore, test specimens have been fabricated to compare the mechanical properties of BJ-AM parts with conventional sintering.
- [Dalhousie University]: On research dedicated to binder jet printing of water atomized steel powders, heat treatment studies on sintered D2 specimens were completed followed by characterizing the sintered and sintered + heat treated samples (compression tests and microscopy). The process optimization and finite element modeling work related to AISI 5120 chromium steel was completed.
- [Dalhousie University]: Completed work on L-DED of the gas atomized DP600 powder, emphasizing microstructure assessment, heat treatment response, and tensile properties. The team has commenced L-DED work on a new grade of DP steel developed by GKN.
- [University of Alberta]: An electrostatically assisted atomization technique to overcome the limitations of the conventional atomization technologies has been developed. The developed method is built on uniform liquid jet breakup using mechanical disturbances, and an electrostatic field to stress the jet into a smaller diameter before breakup. This method does not require a constant supply of inert gas, pumps, or large atomization units, leading to lower operation and capital costs.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Sweet GA, Donaldson IW, Schade CT, Amegadzie MY, Bishop DP. Laser free-form fabrication of dual phase DP600 steel using water atomized feedstock powder. Additive Manufacturing. 2021 Nov 1; 47:102357. **[Link]**
2. Sweet GA, Donaldson IW, Schade CT, Bishop DP. Laser-Based Directed Energy Deposition (L-DED) Processing of Water Atomized 42CrMo4 Powder. Lasers in Manufacturing and Materials Processing. 2023 Mar;10(1):32-63. **[Link]**

- At least 3 more manuscripts are in preparation for publication. 2 manuscripts have been accepted by Journal of Manufacturing Processes and Metallurgical and Materials Transactions A.

#### CONFERENCE PRESENTATION

1. B. Bharadia , A. Bogno , H. Henein. Electrostatic Atomization: A Containerless Technique. Additive Manufacturing Alberta by Innotech Alberta - Edomnton, AB, 2018.

#### THESIS

1. Bharadia B. Electrostatically Assisted Atomization of a Liquid Jet in the Rayleigh Regime. University of Alberta.

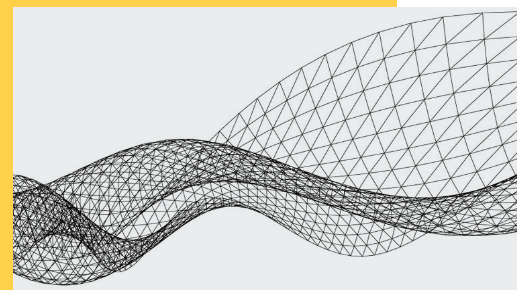
| SUB-PROJECT | PRINCIPAL INVESTIGATOR(S) | HIGHLY QUALIFIED PERSONNEL |
|---|---|---|
| **1.3.1 Recyclability of Powder Feedstocks for LPB-AM** | • Mathieu Brochu, McGill University<br>• Gisele Azimi, University of Toronto | • Aniruddha Das, McGill University, MASc<br>• Hao Kun Sun, University of Toronto, MASc<br>• Yu-Chen Sun, University of Toronto, PDF |
| **1.3.2 Plasma Spheroidization of Low Cost Powders** | • Carl Blais, Université Laval | • Tina Mohamadhassan, Université Laval, PhD |
| **1.3.3 Cost-effective Steel Feedstock for AM** | • Carl Blais, Université Laval<br>• Paul Bishop, Dalhousie University<br>• Hani Henein, University of Alberta | • Ryan Ley, Dalhousie University, PhD<br>• Bilal Bharadia, University of Alberta, MASc<br>• William Bouchard, Université Laval, MASc<br>• Addison Rayner, Dalhousie University, PDF |

# Research Progress

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

A key advantage of AM is the freedom in digital design manipulation providing enhanced part functionality through complex internal topology and material composition, without the need for specialized tooling. Metal AM has been proven to lower costs by reducing 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.

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



# 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.

### SUB-PROJECT 2.1.1 BEAM-POWDER/MELT POOL INTERACTION AND ENERGY TRANSPORT: EXPERIMENTAL VALIDATION

### PROGRESS

- [The University of British Columbia] The EB-PBF modeling project was completed.
- [University of Waterloo] Experiments were carried out to collect thermal data from the revised baseplate both with and without powder, while investigating the effect of scan speed and laser power on the temperature evolution. The powder experiments were conducted using up to 5 layers of Hastelloy X.
- [University of Waterloo] The thermal data collected experimentally, as well as the simulated data from COMSOL Multiphysics, were used as inputs for the Inverse Heat Conduction (IHC) model to accurately estimate the heat flux through the laser heat source during the L-PBF process. The developed model and baseplate have potential applications in real-time process control.

### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Khobzi A, Mehr FF, Cockcroft S, Maijer D, Sing SL, Yeong WY. The role of block-type support structure design on the thermal field and deformation in components fabricated by Laser Powder Bed Fusion. Additive Manufacturing. 2022 Mar 1;51:102644. **[Link]**

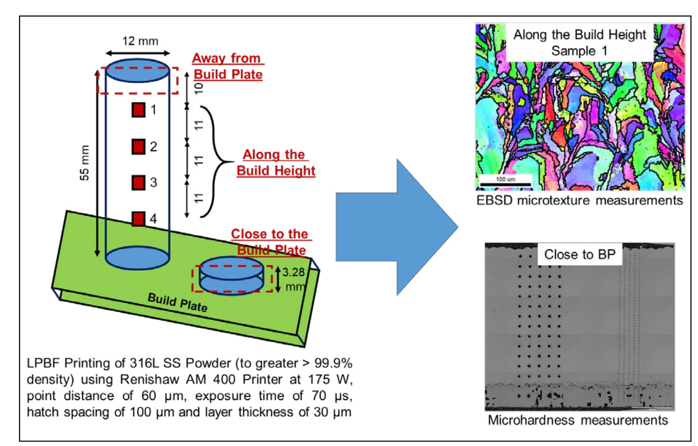
**THESIS**

1. Khobzi A. Experimental and numerical investigation of the effect of block-type support structure design on the thermal field within components fabricated by selective laser melting. University of British Columbia. **[Link]**

### SUB-PROJECT 2.1.2: MESO-SCALE THERMAL FIELD EVOLUTION IN MELT POOL SUBSTRATE

### PROGRESS

- [The University of British Columbia] The EB-PBF modeling part of the project was terminated.
- [University of Waterloo] The thermal-fluid flow modeling of L-PBF using finite element modeling was pursued under sub-project 2.1.1. The results were linked to this project and the scope of the work was expanded to investigate microstructure modeling in L-PBF.
- [University of Waterloo] Two literature reviews on microstructure modeling in L-PBF and the applications of machine learning in microstructure modeling were conducted.
- [University of Waterloo] Cylindrical samples (Ø 12 mm) were printed at full density to various heights using 316L stainless steel powder and a Renishaw AM 400 printer. Samples were characterized along the build height for variation in microstructural features and microhardness, elucidating the effect of reheating and remelting on the microstructure development during LPBF due to the deposition of subsequent powder layers.




Microstructure and mechanical characterization along the build height of L-PBF printed 316L steel samples. (Sub-project 2.1.2)

### SUB-PROJECT 2.1.3: MACRO-SCALE THERMAL FIELD EVOLUTION

### PROGRESS

Sub-project 2.1.3 was completed in 2019-2020.

### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Luo Z, Zhao Y. A survey of finite element analysis of temperature and thermal stress fields in powder bed fusion additive manufacturing. Additive Manufacturing. 2018 May 1;21:318-32. **[Link]**
2. Luo Z, Zhao Y. Numerical simulation of part-level temperature fields during selective laser melting of stainless steel 316L. The International Journal of Advanced Manufacturing Technology. 2019 Oct;104:1615-35. **[Link]**
3. Luo Z, Zhao Y. Efficient thermal finite element modeling of selective laser melting of Inconel 718. Computational Mechanics. 2020 Mar;65(3):763-87. **[Link]**

**THESIS**

1. Luo Z. Nonlinear Finite Element Modeling of Transient Thermo-Mechanical Behavior in Selective Laster Melting. McGill University (Canada); 2020. **[Link]**

### SUB-PROJECT 2.1.4 (I): MULTI-SCALE MODELING OF AM: (A) MACRO-SCALE STRESS FIELD EVOLUTION SIMULATION, (B) MESO-SCALE STRESS FIELD EVOLUTION SIMULATION, (C) RESIDUAL STRESS CHARACTERIZATION

### PROGRESS

- Tasks related to the development of an in-situ battery-powered data acquisition system for the vacuum environment and coupled thermal/meso-scale thermal stress model for EB-PBF have been completed. The meso-scale model is being used to determine the plastic strain accumulation as a function of build temperature.
- Development and experimental validation of the macro-scale thermal stress model of a component manufactured using the Arcam Q20 EB-PBF system for the prediction of in-situ and post-removal component deformation has been completed. A final test to confirm reproducibility is planned.

*Continued on next page...*

## RESEARCH OUTCOME

**JOURNAL PAPER**

- At least 3 manuscripts are in preparation for publication.

**CONFERENCE PRESENTATION**

1. Pourabdollah P, Rahimi F, Chakraborty A, Mehr FF, Maijer D, Cockcroft S. Rationalization of the Modelling of Stress and Strain Evolution in Powder Bed Fusion Additive Manufacturing—A Perspective from a Background in the Simulation of Casting Processes. InTMS 2023 152nd Annual Meeting & Exhibition Supplemental Proceedings 2023 Feb 7 (pp. 1038-1048). Cham: Springer Nature Switzerland. **[Link]**

**THESIS**

1. Rahimi F. Development of a heat transfer model of a simplified build environment in electron beam additive. University of British Columbia. **[Link]**
2. Chakraborty A. Mesoscale modeling of stress and strain evolution in electron beam powder bed fusion additive manufacturing (EB-PBF). University of British Columbia. **[Link]**

# SUB-PROJECT 2.1.4 (II): PROPERTY AND DESIGN ASSESSMENT OF A 3D-PRINTED METALLIC IMPLANT

## PROGRESS

- A new project started in September 2022 to explore the opportunity to utilize 3D-printed metallic surgical implants to treat pediatric patients in collaboration with personnel from the BC Children's Hospital (BCCH) 3D Printing Laboratory and the University of Birmingham. To this end, the researchers will:
  - Develop a demonstration component through consultations with surgeons and hospital staff focusing on mechanical performance and structural compliance.
  - Manufacture components using L-PBF and EB-PBF.
  - Characterize the mechanical properties and surface quality of the printed components.
- Literature review and Arcam EB-PBF training is underway.

# SUB-PROJECT 2.1.5: MICROSTRUCTURAL MODELING AND EXPERIMENTAL VALIDATION

## PROGRESS

- Completed the numerical modeling of eutectic growth for Al-33wt%Cu.
- Work on in situ processing of Al-33wt%Cu using hot stage in SEM has focused on exploring the coarsening of eutectic lamella using image analysis for different temperatures and times.
- A new research track on process development and solidification modeling of hybrid investment casting of lattice structures was initiated. The hybrid casting process was optimized for Al-Cu-Sc alloy with TiB2 addition. Hardness and microstructural properties of the lattice structures were evaluated. A solidification continuous cooling transform (CCT) diagram was developed for Al-10Si-0.4Sc alloy.

## RESEARCH OUTCOME

**JOURNAL PAPER**

1. Bogno AA, Hearn W, Spinelli JE, Valloton J, Henein H. Quantification of microstructure to reveal the solidification path of an alloy. In IOP Conference Series: Materials Science and Engineering 2019 May 1 (Vol. 529, No. 1, p. 012056). IOP Publishing. **[Link]**
2. Bogno AA, Valloton J, Jimenez DD, Rappaz M, Henein H. Rapid solidification of Al-Cu droplets of near eutectic composition. In IOP Conference Series: Materials Science and Engineering 2019 May 1 (Vol. 529, No. 1, p. 012021). IOP Publishing. **[Link]**

**CONFERENCE PRESENTATION**

1. D. Diaz, A. Bogno, H. Henein. Primary Si Modification via Rapid Solidification and Alloying. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
2. D. Diaz, A. Bogno, H. Henein. Modifying the Morphology of Si in Hypereutectic Al-Si Alloys. COM 2020, 59th Conference of Metallurgists - Toronto, ON, 2020.
3. D. Diaz, A. Bogno, H. Henein. Modification of Primary Si Morphology in hypereutectic Al-Si by Rapid Solidification and Alloying. COM 2021, 60th Conference of Metallurgists - Virtual, 2021.
4. J. Valloton, A. Bogno, M. Rappaz, H. Henein. Numerical Model of Al-33wt%Cu Eutectic Growth during Impulse Atomization. TMS 2022, 2021.
5. J. Valloton, N. Mahdi, L. Rabago, J. Chung, H. Henein. In situ solidification of eutectic Al-33wt%Cu droplets. ICASP6, 2022.





6. M. Dias, Y. Li, J. Valloton, A. Qureshi, H. Henein. Effects of TiB2 in an Al-Cu-Sc Alloy in the Hybrid Investment Casting Process. MS&T 2022, 2022.
7. Y. Li, A. Batool, A. Qureshi, H. Henein. Effects of TiB2 in an Al-Cu-Sc Alloy in the Hybrid Investment Casting. The 33rd Canadian Materials Science Conference - CMSC 2022, Toronto, ON, Canada, 2022.
8. H. Henein, A. Sahoo, J. Valloton. Microstructural Study of Containerless Solidification of Al-20wt%Ce Alloys. COM 2022, 61th Conference of Metallurgists, Montreal, QC, Canada, 2023.
9. J. Valloton, A. Sahoo, S.C. Vogel, H. Henein. Microstructural evaluation of containerless solidification of Al-Ce alloys. TMS 2023 Annual Meeting & Exhibition, San Diego, CA, USA, 2023.

**THESIS**

1. Diaz Jimenez D. Si modification in hypereutectic Al-Si: Combining rapid solidification and alloying. **[Link]**

## 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<br>• Mary Wells, University of Waterloo | • Arman Khobzi, The University of British Columbia, MASc<br>• Emre Ogeturk, University of Waterloo, MASc<br>• 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<br>• Farzaneh Farhang-Mehr, The University of British Columbia, RA<br>• Paresh Prakash, University of Waterloo, PDF |
| **2.1.3 Macro-scale Thermal Field Evolution (COMPLETED)** | • Yaoyao Fiona Zhao, McGill University | • Zhibo Luo, McGill University, PhD |
| **2.1.4 (i) Multi-Scale Modeling of AM:**<br>**(a) Macro-scale Stress Field Evolution Simulation**<br>**(b) Meso-scale Stress Field Evolution Simulation**<br>**(c) Residual Stress Characterization** | • Steve Cockcroft, The University of British Columbia<br>• Daan Maijer, The University of British Columbia | • Pegah Pourabdollah, The University of British Columbia, PhD<br>• Farzaneh Farhang-Mehr, The University of British Columbia, RA<br>• Asmita Chakarborty, The University of British Columbia, MASc<br>• Farhad Rahimi, The University of British Columbia, MASc |
| **2.1.4 (ii) Property and Design Assessment of a 3D-Printed Metallic Implant** | • Steve Cockcroft, The University of British Columbia<br>• Daan Maijer, The University of British Columbia | • Anushree Shah, 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<br>• Daniela Diaz, University of Alberta, MASc<br>• Jonas Valloton, University of Alberta, RA<br>• Anqi Shao, University of Alberta, MASc |

# 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.

### SUB-PROJECT 2.2.1: FAST PROCESS THERMAL-FIELD SIMULATION (COMPLETED)

## PROGRESS

- Sub-project 2.2.1 was completed in 2019-2020.

## RESEARCH OUTCOME

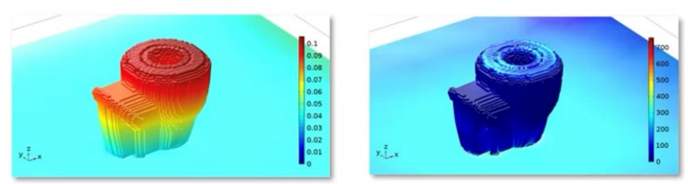
**THESIS**

1. Upadhyay M. Fast to run model for thermal fields during metal additive manufacturing simulations. University of British Columbia. **[Link]**

### SUB-PROJECT 2.2.2: FAST PROCESS STRESS-FIELD SIMULATION

## PROGRESS

- A two-dimensional thermal analysis of a single track based on an implicit finite difference method was carried out and verified. The results were verified using finite element analysis.
- The effect of process parameters, such as laser power and scan speed, on melt pool dimensions was investigated.
- The thermo-mechanical model based on an effective heat source for rapid prediction of residual stress and deformation in complex industrial geometries was completed and tested for structures such as cuboid, burner head and shroud. The model was experimentally validated for residual stress prediction. Experiments are being designed to validate the capability of the model in predicting the deformation by printing and 3D scanning cantilever parts.



Residual stress and strain results for burner head geometry obtained from the effective heat source model. (Sub-project 2.2.2)

## 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 | • Shahriar Imani Shahabad, University of Waterloo, PhD |





# 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.

- Develop a macro-scale finite element model to simulate the deviation of SLM processes and the developed GD&T quantification methods. A complete case study has been conducted on a pin-hole assembly component, leading to the experimental validation of the skin model shapes methodology for geometric tolerance prediction of metal AM parts.

### SUB-PROJECT 2.3.1: PRE-PROCESSING FOR DIMENSIONAL CONTROL

## PROGRESS

- A macro-scale finite element model was developed for thermo-mechanical deviation calculation considering GD&T characteristics and the effect of build plate removal.
- Experimental test artefacts were developed to generate statistical data for assembly analysis using the hybrid statistical-FEM approach. A thermal camera was installed in the L-PBF system to collect manufacturing temperature data as the artefacts are built.
- The analysis scope was expanded from macro shape deviation to micro shape deviation to develop metrics for micro porosities. All models and methods were experimentally validated by printing the structured micro-porosity in L-PBF at a scale of 50 microns and shape deviation analysis of the shape memory alloys.

## RESEARCH OUTCOME

**JOURNAL PAPER**

1. Rupal BS, Anwer N, Secanell M, Qureshi AJ. Geometric tolerance and manufacturing assemblability estimation of metal additive manufacturing (AM) processes. Materials & Design. 2020 Sep 1;194:108842. **[Link]**
2. Rupal BS, Singh T, Wolfe T, Secanell M, Qureshi AJ. Tri-Planar Geometric Dimensioning and Tolerancing Characteristics of SS 316L Laser Powder Bed Fusion Process Test Artifacts and Effect of Base Plate Removal. Materials. 2021 Jun 26;14(13):3575. **[Link]**

- 1 manuscript accepted by Metals (MDPI).

**CONFERENCE PRESENTATION**

1. B. Rupal, A. Qureshi. Establishing Guidelines for Variation Management in Additive Manufacturing. 2nd Seminar of the European Group of Research in Tolerancing - Metz, France, 2017.
2. B. Rupal, A. Qureshi. Geometric Quality Control for Metal AM. Additive Manufacturing Alberta by Innotech Alberta -Edmonton, AB, 2018.
3. S. Toguem, B. Rupal, C. Mehdi-Souzani, A. Qureshi, N. Anwar. A Review of AM Artifact Design Methods. ASPE and euspen Summer Topical Meeting on Advancing Precision in Additive Manufacturing - Berkeley, CA, 2018.
4. B. Rupal, R. Ahmad, A. Qureshi. Feature-Based Methodology for Design of Geometric Benchmark Test Artifacts for Additive Manufacturing Processes. 28th CIRP Design Conference 2018, Nantes, France, 2018.
5. B. Rupal, N. Anwer, M. Secanell, A. Qureshi. Geometric Tolerance Characterization of Laser Powder Bed Fusion Processes Based on Skin Model Shapes. CIRP CAT 2020 - Charlotte, NC, 2020. **[Link]**

**THESIS**

1. Rupal BS. Geometric tolerance quantification and prediction framework for additive manufacturing processes. University of Alberta. **[Link]**

## SUB-PROJECT 2.3.2: LATTICE STRUCTURE DESIGN FOR AM PROCESSING

### PROGRESS

- The lattice structure design projects related to metal AM were completed. The project scope was expanded to include polymer-based lattices to show the impact of soft inclusions and loading deviations on spatial deformation and material behavior.
- A parametric model accounting for the nonlinearities and hyperelasticity of the base polymeric material was developed.
- Polymeric lattices with rationally embedded defects (soft inclusions of the same base material) were manufactured and characterized under unconventional loading settings to validate the numerical results.
- The experimental results highlighted how imperfections can be exploited to generate novel functionalities for soft materials. Further experiments are planned to investigate the correlation between the local and global responses of the system.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Liu L, Kamm P, García-Moreno F, Banhart J, Pasini D. Elastic and failure response of imperfect three-dimensional metallic lattices: the role of geometric defects induced by Selective Laser Melting. Journal of the Mechanics and Physics of Solids. 2017 Oct 1; 107:160-84. **[Link]**
2. Moussa A, Rahman S, Xu M, Tanzer M, Pasini D. Topology optimization of 3D-printed structurally porous cage for acetabular reinforcement in total hip arthroplasty. Journal of the mechanical behavior of biomedical materials. 2020 May 1; 105:103705. **[Link]**
3. El Elmi A, Melancon D, Asgari M, Liu L, Pasini D. Experimental and numerical investigation of selective laser melting–induced defects in Ti–6Al–4V octet truss lattice material: the role of material microstructure and morphological variations. Journal of Materials Research. 2020 Aug;35(15):1900-12. **[Link]**
4. Zhang Y, Yang S, Zhao YF. Manufacturability analysis of metal laser-based powder bed fusion additive manufacturing—a survey. The International Journal of Advanced Manufacturing Technology. 2020 Sep; 110:57-78. **[Link]**
5. Moussa A, Melancon D, El Elmi A, Pasini D. Topology optimization of imperfect lattice materials built with process-induced defects via powder bed fusion. Additive Manufacturing. 2021 Jan 1;37:101608. **[Link]**
6. Zhang Y, Yang S, Dong G, Zhao YF. Predictive manufacturability assessment system for laser powder bed fusion based on a hybrid machine learning model. Additive Manufacturing. 2021 May 1;41:101946. **[Link]**
7. Zhang Y, Zhao YF. Hybrid sparse convolutional neural networks for predicting manufacturability of visual defects of laser powder bed fusion processes. Journal of Manufacturing Systems. 2022 Jan 1;62:835-45. **[Link]**
8. Zhang Y, Zhao YF. A Web-based automated manufacturability analyzer and recommender for additive manufacturing (MAR-AM) via a hybrid Machine learning model. Expert Systems with Applications. 2022 Aug 1;199:117189. **[Link]**

- At least 1 more manuscript is in preparation for publication.

#### CONFERENCE PRESENTATION

1. Zhang Y, Dong G, Yang S, Zhao YF. Machine learning assisted prediction of the manufacturability of laser-based powder bed fusion process. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2019 Aug 18 (Vol. 59179, p. V001T02A008). American Society of Mechanical Engineers.
2. El Elmi A, Pasini D, Team AE, Team DP. Harnessing imperfections to elicit functionality in soft mechanical metamaterials. In APS March Meeting Abstracts 2022 (Vol. 2022, pp. W21-004).
3. Qiao C, El Elmi A, Pasini D. Bi-shell valve inspired by shell snapping interaction for rapid actuation of soft pneumatic actuators. In APS March Meeting Abstracts 2022 (Vol. 2022, pp. D21-011).

#### THESIS

1. Zhang Y. Development of hybrid machine learning models for assessing the manufacturability of designs for additive manufacturing processes. **[Link]**

## SUB-PROJECT 2.3.3: MISMATCH DETERMINATION DURING AM OF THIN STRUCTURES

### PROGRESS

- Various aspects of the mechanical response of the micro and meso-scale stainless steel struts resulting from surface heterogeneity and dimensional variations were studied as part of an independent doctoral research linked to this sub-project (2019-2021). A new HQP joined the project in Jan 2021 to work on determining the mismatch of thin structures during AM.





- A literature review on the surface defects and localized deformation on thin-walled structures considering fatigue and surface morphology was completed.
- Thin rods with different cross sections were manufactured from aluminum and titanium alloys and their surfaces were characterized.
- A testing method was developed for carrying out extreme low cycle fatigue tests on AM-made small-scale rods. Monotonic, dynamic, and cyclic mechanical response tests for cylindrical/thin-wall struts are progressing. The effect of mechanical tests on mill annealed and hot isostatic pressed (HIPed) specimens were compared in terms of surface roughness, porosity, and microstructure.
- A prediction machine learning model is being developed based on the dynamic mechanical response data.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Ghosh A, Biswas S, Turner T, Kietzig AM, Brochu M. Surface, microstructure, and tensile deformation characterization of L-PBF SS316L microstruts micromachined with femtosecond laser. Materials & Design. 2021 Nov 15;210:110045. **[Link]**
2. Ghosh A, Kumar A, Joy N, Kietzig AM, Brochu M. Characterization of femtosecond laser micromachined specimens extracted from PBF-LB/M microstruts: Analyzing surfaces fabricated via internally linked machined kerfs. Materialia. 2021 Dec 1;20:101260. **[Link]**
3. Ghosh A, Kumar A, Harris A, Kietzig AM, Brochu M. Fatigue behavior of stainless steel 316L microstruts fabricated by laser powder bed fusion. Materialia. 2022 Dec 1;26:101591. **[Link]**
4. Ghosh A, Kumar A, Wang X, Kietzig AM, Brochu M. Analysis of the effect of surface morphology on tensile behavior of L-PBF SS316L microstruts. Materials Science and Engineering: A. 2022 Jan 13; 831:142226. **[Link]**

#### CONFERENCE PRESENTATION

1. Ghosh A, Joy N, Kietzig AM, Brochu M. Enhancing Tensile Performance of Laser Powder Bed Fusion Stainless Steel Micro-struts Using Femtosecond Laser Micromachining. In Laser Applications Conference 2020 Oct 13 (pp. JTu5A-20). Optica Publishing Group.
2. M. Kumar, M. Brochu, Y.F. Zhao. Extreme low cycle fatigue behavior comparison between L-PBF and wrought Al7SiMg alloys for small-scale specimen. Journée des Étudiants REGAL, Saguenay, Canada, 2022.
3. M. Kumar, M. Brochu, Y.F. Zhao. Extreme low cycle fatigue behavior comparison between L-PBF and wrought Al7SiMg alloys for small-scale specimen. International Materials, Applications & Technologies (IMAT 2022), New Orleans, USA, 2022.

#### THESIS

- Ghosh A. Surface morphological effects of laser powder bed fusion and laser micromachining in micro-scale parts. McGill University (Canada); 2021. **[Link]**

### RESEARCHERS

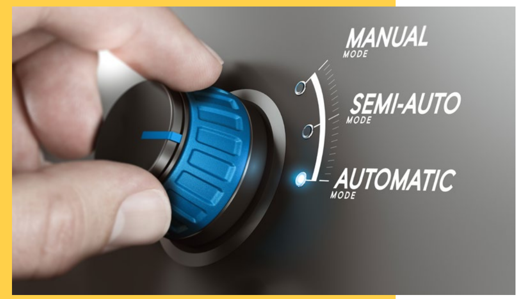
| SUB-PROJECT | PRINCIPAL INVESTIGATOR(S) | HIGHLY QUALIFIED PERSONNEL |
|---|---|---|
| **2.3.1 Pre-processing for Dimensional Control** | • Ahmed Qureshi, University of Alberta | • Baltej Rupal, University of Alberta, PhD<br>• Shirin Dehgahi, University of Alberta, PDF (Collaborator)<br>• Shokoufeh Sardarian, University of Alberta, MASc (Collaborator) |
| **2.3.2 Lattice Structure Design for AM Processing** | • Damiano Pasini, McGill University<br>• Yaoyao Fiona Zhao, McGill University | • Asma El Elmi, McGill University, PhD<br>• Ying Zhang, McGill University, PhD |
| **2.3.3 Mismatch Determination During AM of Thin Structures** | • Mathieu Brochu, McGill University<br>• Yaoyao Fiona Zhao, McGill University | • Abhi Ghosh, McGill University, PhD (Collaborator)<br>• Muralidharan Kumar, McGill University, PhD |

# 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.

### SUB-PROJECT 3.1.1: DEVELOPMENT OF NON-CONTACT DYNAMIC MELT POOL CHARACTERISTIC MEASUREMENT VIA RADIOMETRIC MONITORING FOR LPB- AND LPF-AM

### PROGRESS

- Machine learning was implemented with multi-layer cladding to predict the geometry of multi-layer AM for adjacent layers, allowing more complex parts to be monitored.
- A second unit has been built for wire-fed laser welding.
- Hardware to capture visible and infrared light images simultaneously to effectively make a 2-color camera and reduce the effect of emissivity changes in high temperature applications was developed. The camera transformation was determined to overlay the images.
- Gas metal arc welding experiments were conducted and results analyzed to determine the thermal dynamics and geometry of the weld bead from the captured images.

### RESEARCH OUTCOME

#### CONFERENCE PRESENTATION

1. Botelho L, van Blitterswijk RH, Khajepour A. Multi-track Geometry Prediction in Powder Fed Laser Additive Manufacturing Using Machine Learning. 2021 International Solid Freeform Fabrication Symposium 2021. University of Texas at Austin. **[Link]**

### SUB-PROJECT 3.1.2: DEVELOPMENT OF CONTINUOUS AND LAYER-INTERMITTENT IMAGING CAPABILITIES FOR WAAM

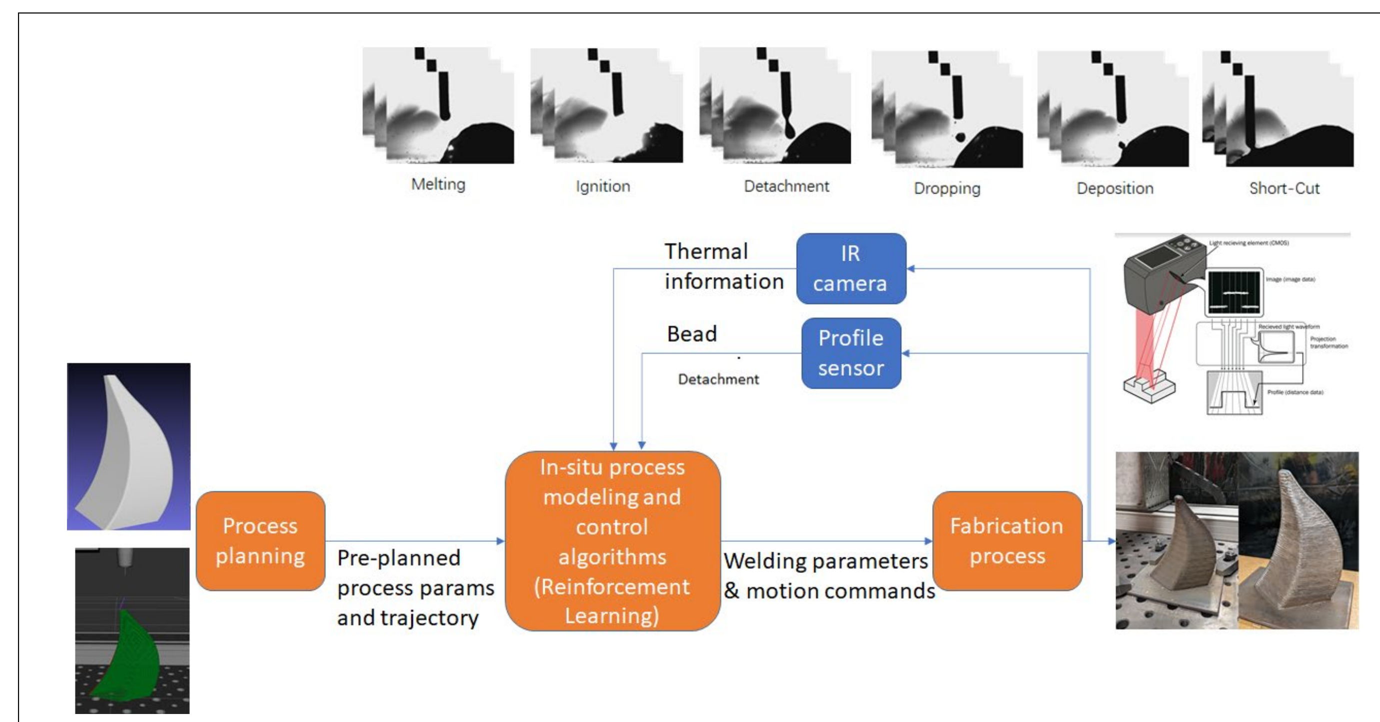
### PROGRESS

- An AI-based bead tracking and optimization algorithm has been developed using the reinforcement learning method Twin Delayed Deep Deterministic Policy Gradients (TD3).
- An infrared camera of temperature range above 600 deg C was implemented to observe the bead temperature in real time. In-situ emissivity variation detection and tracking were completed.
- An in-situ profiler sensor was implemented into the control system. The profile data accuracy was improved by utilizing feedstock material with lower reflectivity.
- Closed loop controlling, capable of inputting action command to the AM toolchain to change process parameters for every layer being deposited, was implemented and improved by inputting more state parameters to the experiment, including temperature, height, standard deviation of the layered beads, and others.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Lehmann T, Rose D, Ranjbar E, Ghasri-Khouzani M, Tavakoli M, Henein H, Wolfe T, Jawad Qureshi A. Large-scale metal additive manufacturing: a holistic review of the state of the art and challenges. International Materials Reviews. 2022 May 19; 67(4):410-59. **[Link]**
2. Teng S, Dehgahi S, Henein H, Wolfe T, Qureshi A. Effect of surface texture, viewing angle, and surface condition on the emissivity of wire arc directed energy deposition manufactured 7075 nano treated aluminum alloy. The International Journal of Advanced Manufacturing Technology. 2023 Mar 20: 1-5. **[Link]**




Schematic view of the monitoring and control system developed for WAAM process. (Sub-project 3.1.2)

## SUB-PROJECT 3.1.3: DEVELOPMENT OF NON-CONTACT CAPABILITY TO DETECT SUB-SURFACE PROPERTIES USING EDDY CURRENT INDUCTIVE MEASUREMENTS

### PROGRESS

- An analytical model of the coil impedance change on top of a plate with a defect was completed.
- The sensitivity of the design was improved to achieve the capability to detect smaller blind holes.
- The Eddy current design was tested using samples with different surface roughness, random defects with unknown sizes, and defects of the same size at different depths.
- Correlation of the Eddy current inductive sensor data and part quality metrics was completed.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. E. Farag H, Toyserkani E, Khamesee MB. Non-destructive testing using eddy current sensors for defect detection in additively manufactured titanium and stainless-steel parts. Sensors. 2022 Jul 21;22(14):5440. **[Link]**

#### THESIS

1. Farag H. Eddy Current Probes Design for Defect Detection in Metallic Parts Made by Additive Manufacturing Processes. **[Link]**

## SUB-PROJECT 3.1.4: LASER ULTRASONIC SENSING FOR LPB- AND LPF-AM

### PROGRESS

- An ultrasonic powder focusing project, which stems from the HI-AM project but is being conducted independently, has been progressing.
- Data processing was completed for AlSi10Mg and Ti6Al4V samples containing trapped powder, side hole, and bottom hole artificial defects.
- Defect locations were reconstructed and compared to defect images and CT data.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Martinez-Marchese A, Klumpp M, Toyserkani E. Directed energy deposition powder stream modeling using a Gaussian beam ray representation. Powder Technology. 2022 Nov 1;412:117965. **[Link]**
2. Martinez-Marchese A, Ansari M, Wang M, Marzo A, Toyserkani E. On the application of sound radiation force for focusing of powder stream in directed energy deposition. Ultrasonics. 2023 Jan 1;127:106830. **[Link]**

- At least 1 more manuscript is in preparation for publication. 2 manuscripts are under review.

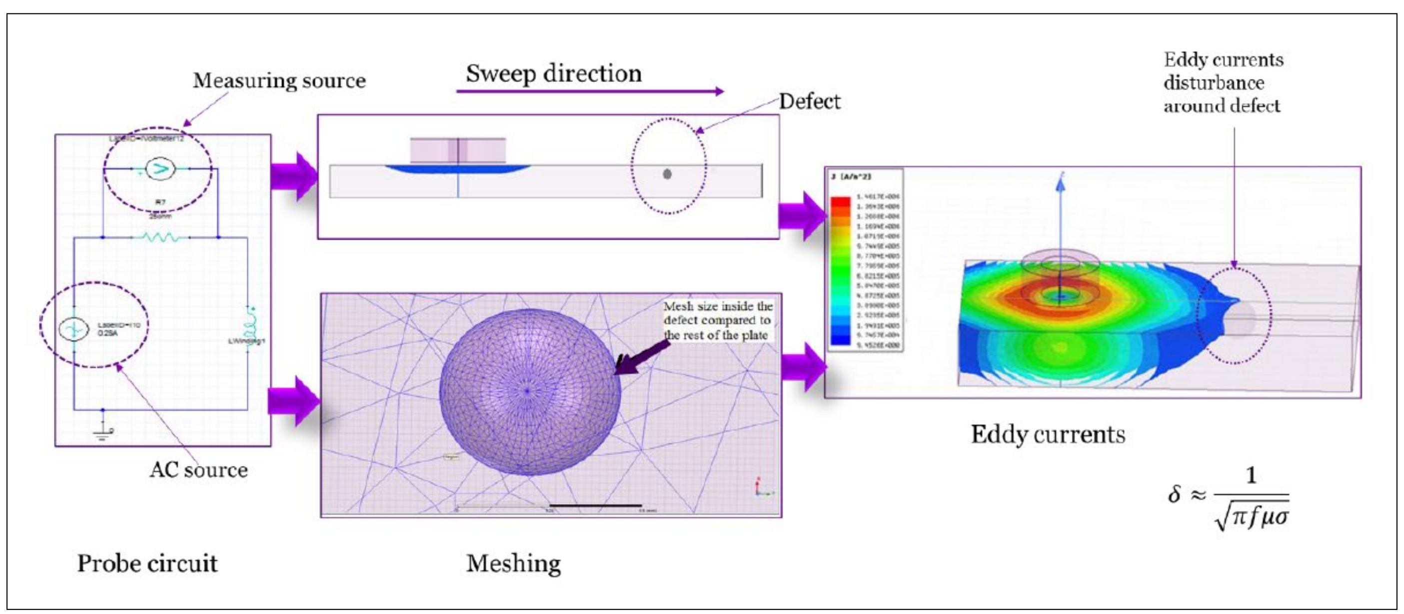



Diagram of the absolute probe modeled using ANSYS Maxwell. (Sub-project 3.1.3)



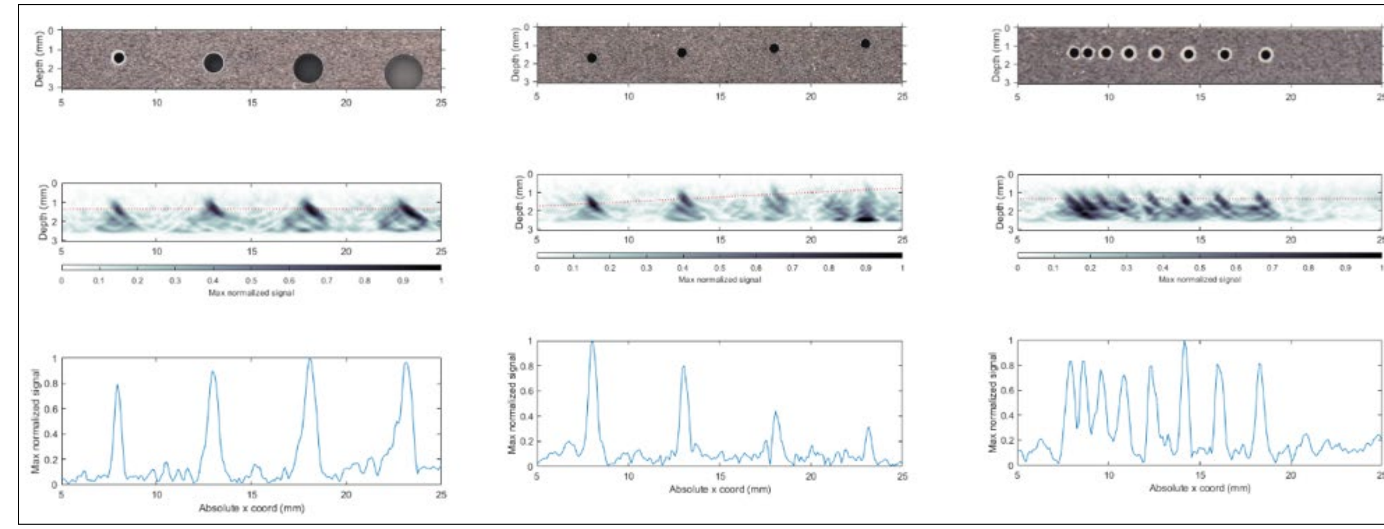


#### CONFERENCE PRESENTATION

1. A. Martinez, M. Ansari, A. Marzo, M. Wang, E. Toyserkani. Ultrasound metal powder stream focusing for producing variable track widths in directed energy deposition. 2021 Solid Freeform Fabrication (SFF) Symposium - Austin, TX, 2021.

#### THESIS

1. Martinez A. Monitoring and Control of Metal Additive Manufacturing Processes Using Ultrasound. **[Link]**



Reconstructed defect locations for AlSi10Mg parts containing side hole artificial defects. (Sub-project 3.1.4)

### 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<br>• Neel Bhatt, University of Waterloo, MASc (Collaborator)<br>• Shuchen Huang, University of Waterloo, MASc (Collaborator)<br>• Hamid Tahir, University of Waterloo, MASc (Collaborator)<br>• Hasan Askari, University of Waterloo, PhD (Collaborator)<br>• Richard van Blitterswijk, 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<br>• Thomas Lehmann, University of Alberta, PDF (Collaborator)<br>• Yeon Kyu Kwak, University of Alberta, PhD<br>• Shiyu Teng, University of Alberta, MASc (Collaborator) |
| **3.1.3 Development of Non-contact Capability to Detect Sub-surface Properties Using Eddy Current Inductive Measurements** | • Behrad Khamesee, University of Waterloo<br>• 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<br>• Soyazhe Khan, University of Waterloo, Co-op |

# 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.

## SUB-PROJECT 3.2.1: KNOWLEDGE-BASED LUMPED MODELS

### PROGRESS

- A study on the effect of the preheat stage in EB-PBF on the geometric fidelity and de-powdering of complex lattice architectures was completed.
- A beam path planning study based on modeling theory for improvement of the surface quality and part density was completed.

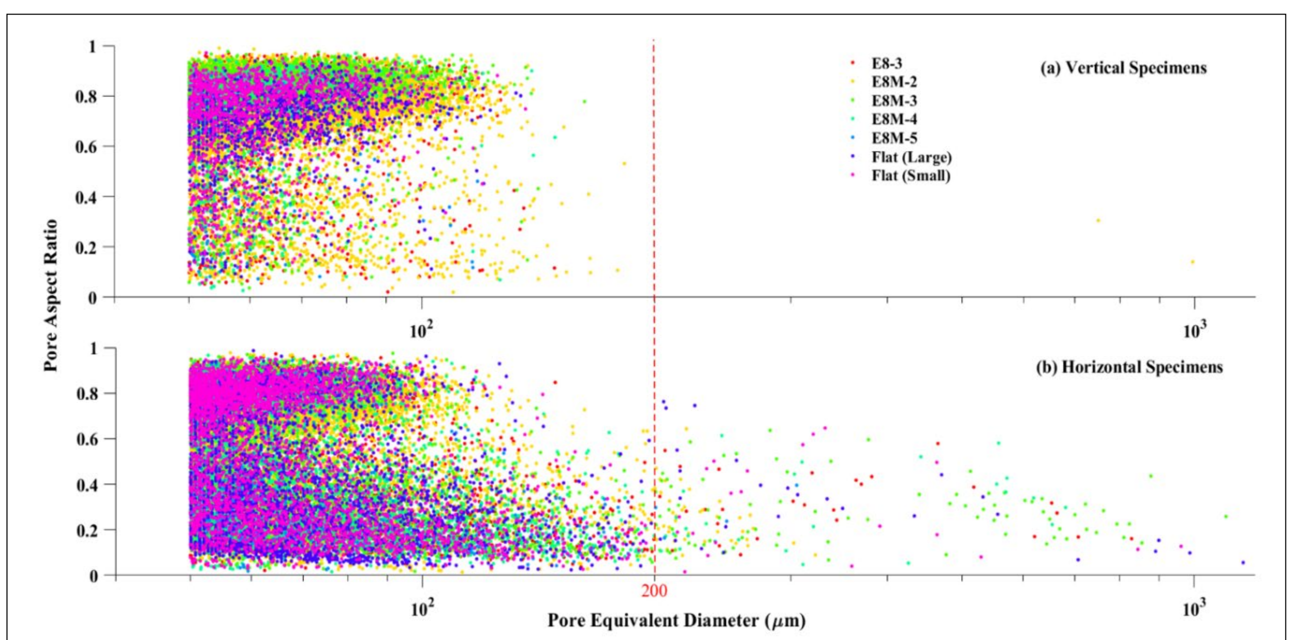
### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Shanbhag G, Vlasea M. The effect of reuse cycles on Ti-6Al-4V powder properties processed by electron beam powder bed fusion. Manufacturing Letters. 2020 Aug 1;25:60-3. **[Link]**
2. Shanbhag G, Wheat E, Moylan S, Vlasea M. Effect of specimen geometry and orientation on tensile properties of Ti-6Al-4V manufactured by electron beam powder bed fusion. Additive Manufacturing. 2021 Dec 1;48:102366. **[Link]**
3. Shanbhag G, Vlasea M. Powder reuse cycles in electron beam powder bed fusion—Variation of powder characteristics. Materials. 2021 Aug 16;14(16):4602. **[Link]**
4. Shanbhag G, Vlasea M. Effect of varying preheating temperatures in electron beam powder bed fusion: Part I Assessment of the effective powder cake thermal conductivity. arXiv preprint arXiv:2107.14684. 2021 Jul 30. **[Link]**

#### THESIS

1. Shanbhag G. Performance Analytics for Electron Beam Powder Bed Fusion of Ti-6Al-4V. **[Link]**




Pore equivalent diameter vs. aspect ratio for all pores > 50 μm. (Sub-project 3.2.1)





## SUB-PROJECT 3.2.2: DEVELOPMENT OF INTELLIGENT CONTROLLERS

### PROGRESS

- An intermittent closed-loop controller was designed to increase the laser power for healing/minimizing the lack of fusion defects.
- The process was simulated in four phases using LabVIEW, MATLAB, and Python to: (1) obtain real-time data from the DAQ system, (2) apply geometry and intensity corrections on data to avoid any deviation, (3) apply the SOM algorithm to identify defect position, and (4) apply the intermittent controller to change the laser power on top of the detected defect.
- A Message Queuing Telemetry Transport (MQTT) broker was used to connect the data acquisition system, the defect detection algorithm, the LCF calculation algorithm, and the actuator.
- The work is progressing on testing and refining the performance of the process control system. Two sets of experiments incorporating intentional and randomized defects were manufactured to evaluate the performance of the control system.
- A Best Practice Standard draft (ASTM WK76983) for in-situ defect detection and analysis based on the results of this sub-project was submitted to ASTM/ISO to be placed on ballot voting.

### RESEARCH OUTCOME

#### JOURNAL PAPER

1. Taherkhani K, Sheydaeian E, Eischer C, Otto M, Toyserkani E. Development of a defect-detection platform using photodiode signals collected from the melt pool of laser powder-bed fusion. Additive Manufacturing. 2021 Oct 1;46:102152. **[Link]**
2. Taherkhani K, Eischer C, Toyserkani E. An unsupervised machine learning algorithm for in-situ defect-detection in laser powder-bed fusion. Journal of Manufacturing Processes. 2022 Sep 1;81:476-89. **[Link]**

- At least 1 more manuscript is in preparation for publication. 1 manuscript is under review.

#### THESIS

1. Taherkhani K. In-Situ Monitoring and Quality Assurance Algorithms for Laser Powder-Bed Fusion. **[Link]**

## RESEARCHERS

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

# 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.

## SUB-PROJECT 3.3.1: MEASUREMENT SYSTEM DEVELOPMENT AND VALIDATION OF COMBINED POWDER SPREAD, COMPACTION AND BINDER FLUID DYNAMICS LINKED WITH SINTERING MODEL

### PROGRESS

- Modeling of the powder compaction and spread using discrete element modeling followed by experimental validation and tuning of the developed models was completed.
- The sintering theory was adapted to a 1D, 2D, 3D densification and distortion model.
- A high fidelity and high-resolution pore network model was developed and validated as a framework to liquid-powder imbibition simulations using statistics and machine learning.
- The molecular dynamics literature as it relates to the BJ-AM powder-binder systems was reviewed.

### RESEARCH OUTCOME

**JOURNAL PAPER**

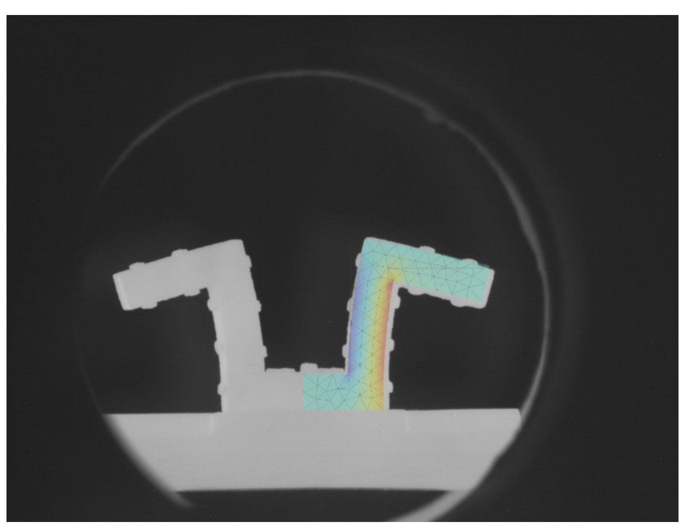
- At least 2 manuscripts are in preparation for publication.

**CONFERENCE PRESENTATION**

1. A. Groen, M. Vlasea, K. Erkorkmaz. Optimization of Powder Bed Compaction Consistency for Binder Jetting. 34th Annual Meeting of American Society for Precision Engineering (ASPE) - Pittsburgh, PA, 2019.

**THESIS**

1. Wang M. Part Performance Measurement, Analysis and Optimization for Binder Jetting Additive Manufacturing (Master's thesis, University of Waterloo). **[Link]**



Overlay of the simulated result and experimental validation data for the cantilever part with 3mm wall thickness and 10mm overhang, at the end of solid-phase sintering. (Sub-project 3.3.1)





## SUB-PROJECT 3.3.2: CLOSED-LOOP CONTROL OF COMPACTION DENSITY AND BINDER IMBIBITION AND EXPERIMENTAL VALIDATION

### PROGRESS

- The originally proposed objectives related to the development of closed-loop control system using a feedback vision-based detector and/or strain gauge array were canceled due to feasibility issues. The following new objectives were proposed in their place: (1) to simulate and quantify the effect of powder compaction methods on part densification and test the feasibility to design a reliable closed-loop control system for compaction density testing; (2) to explore the application of nano-ink formulations and Boron-based ink to improve part density and to achieving variable density gradients without a need for latticing.
- Algorithms for geometry compensation were investigated. Initial algorithmic compensation with 3D part scans was attempted.
- A literature review on binders, powder-binder systems, and powder-binder interactions in metal and ceramic BJ-AM is ongoing.

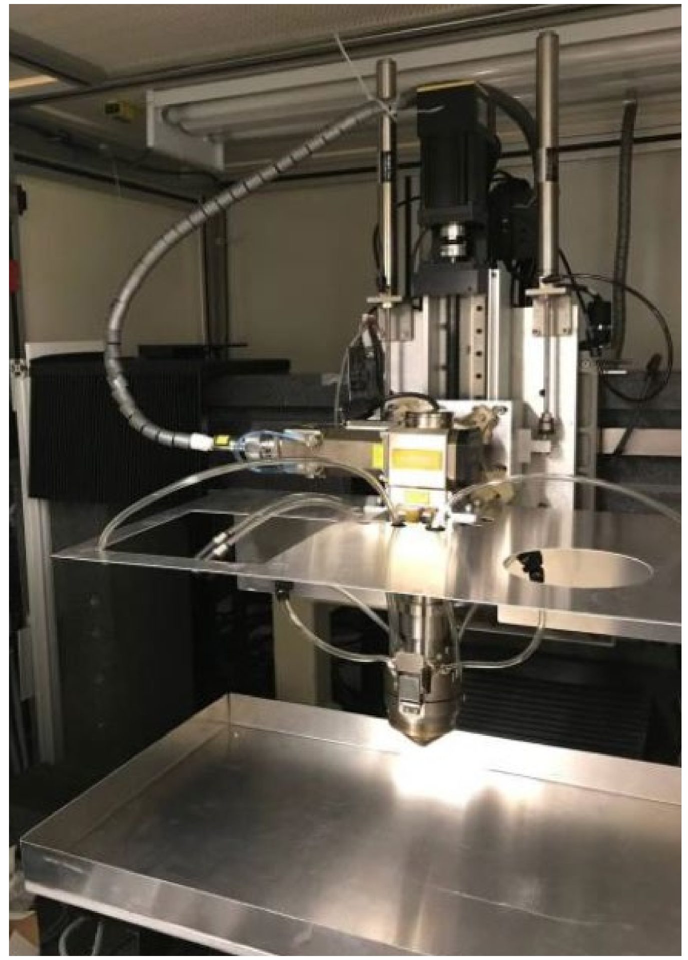
## RESEARCHERS

| 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<br>• Mihaela Vlasea, University of Waterloo | • Alex Groen, University of Waterloo, MASc<br>• Marc Wang, University of Waterloo, MASc (Collaborator)<br>• Justin Memar-Makhsous, University of Waterloo, Co-op<br>• Roman Boychuk, University of Waterloo, MASc<br>• Daniel Juhasz, University of Waterloo, MASc (Collaborator) |
| **3.3.2 Closed-loop Control of Compaction Density and Binder Imbibition and Experimental Validation** | • Mihaela Vlasea, University of Waterloo<br>• Kaan Erkorkmaz, University of Waterloo | • Alex Groen, University of Waterloo, MASc<br>• Marc Wang, University of Waterloo, MASc (Collaborator)<br>• Roman Boychuk, University of Waterloo, MASc<br>• Daniel Juhasz, University of Waterloo, MASc (Collaborator) |

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

## DESCRIPTION

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



UBC's in-house-built L-PBF system controlled by open architecture research CNC. (Sub-project 3.4.1)

### SUB-PROJECT 3.4.1: COMBINED TRAJECTORY OPTIMIZATION AND THERMAL ANALYTICAL MODELS

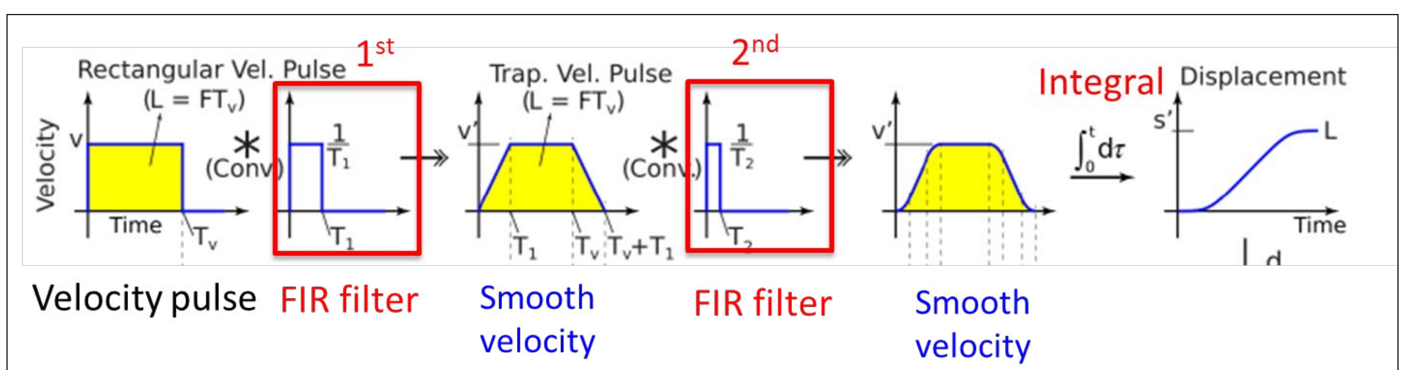
## PROGRESS

- Cascaded FIR filter-based motion trajectory profiling was developed to control the laser melting rate along the tool path based on the method used in commercial CNC machines. Cycle time (printing time) algorithm was developed from NC programs and experimentally validated.
- A 3-axis machine was retrofitted with a laser head and powder bed controlled by the UBC team's in-house developed CNC.

## RESEARCH OUTCOME

**THESIS**

1. Parks S. Modelling of electron beam deflection system for beam position control in metal additive manufacturing. University of British Columbia. **[Link]**




Dual cascaded Finite Impulse Response (FIR) filter-based velocity trajectory smoothing. (Sub-project 3.4.1)



THEME 3

### SUB-PROJECT 3.4.2: ADAPTIVE PATH PLANNING PROTOCOLS/CONTROLLERS AND EXPERIMENTAL VALIDATION

## PROGRESS

- An experimentally driven semi-supervised machine learning model was developed for DED to reduce the amount of annotation for new datasets. Work on a combined AI and batch selection methodology is underway.
- Offline validation and testing of the performance of classifier and segmentation models using the annotated datasets is progressing.
- VIS high-speed detector and VIS/NIR HDR-based sensors were used for process signature detection in powder-fed DED. Datasets have been collected to apply similar systems to L-PBF.
- Work on defining process stability based on in-process signatures by developing correlations between sensor data, characterization data, and experimental datasets is progressing. The team has been investigating (1) process stability from predictions made by vision-based ML for DED, (2) porous defects morphology for use in training ML models for L-PBF and DED, (3) surface roughness artefacts for use in training ML models for L-PBF, and (4) melt pool morphology for use in training ML models for L-PBF.

## RESEARCH OUTCOME

**JOURNAL PAPER**

1. van Houtum GJ, Vlasea ML. Active learning via adaptive weighted uncertainty sampling applied to additive manufacturing. Additive Manufacturing. 2021 Dec 1;48:102411. [Link]

- At least 4 more manuscripts are in preparation for publication.

**CONFERENCE PRESENTATION**

1. S. Patel, J. Patel, M. Yang, M. Vlasea, J. Barnes, C. Aldridge, W. King, J. Coyne. Laser additive manufacturing of high reflectivity metallic materials using pore-free non-equiaxed powders. RAPID+TCT 2022 - Detroit, MI, USA, 2022.

**THESIS**

1. Ertay DS. Modeling, performance evaluation, and post-process planning for directed energy deposition. **[Link]**

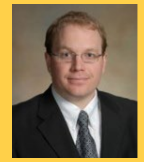
## RESEARCHERS

| 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<br>• Varun Jacob-John, The University of British Columbia, MASc (Collaborator)<br>• Graham Williamson, The University of British Columbia, MEng (Collaborator)<br>• Randy Yuwono, The University of British Columbia, MEng (Collaborator)<br>• Kirubakarann Srenevasan, The University of British Columbia, MEng (Collaborator)<br>• Sharon Tam, The University of British Columbia, MASc |
| **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<br>• Deniz Sera Ertay, University of Waterloo, PhD (Collaborator)<br>• Jigar Patel, University of Waterloo, PhD<br>• Andrew Katz, University of Waterloo, RA |

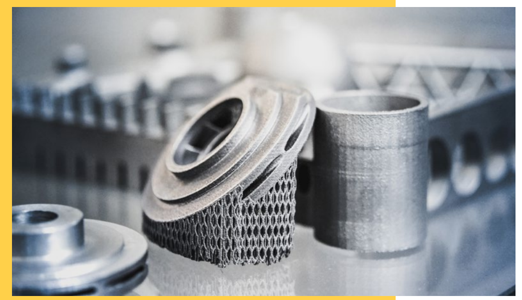
# Research Progress

## 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.

### SUB-PROJECT 4.1.1(I): MAGNETICALLY DRIVEN VACUUM-BASED POWDER DELIVERY PROCESSING HEAD FOR LPF-AM

### PROGRESS

- Sub-project 4.1.1(i) was completed in 2018.

### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Huang Y, Khamesee MB, Toyserkani E. Electrodynamic concentration of non-ferrous metallic particles in the moving gas-powder stream: Mathematical modeling and analysis. International Journal of Magnetics and Electromagnetism. 2019;5(1). **[Link]**
2. Huang Y, Ansari M, Asgari H, Farshidianfar MH, Sarker D, Khamesee MB, Toyserkani E. Rapid prediction of real-time thermal characteristics, solidification parameters and microstructure in laser directed energy deposition (powder-fed additive manufacturing). Journal of Materials Processing Technology. 2019 Dec 1;274:116286. **[Link]**

**CONFERENCE PRESENTATION**

1. Y. Huang, B. Khamesee, E. Toyserkani. A Time efficient Analytical Model of Laser Directed Energy Deposition for Functionally Graded Materials Fabrication. 2019 Solid Freeform Fabrication (SFF) Symposium - Austin, TX, 2019.





**THESIS**

1. Huang Y. Comprehensive Analytical Modeling of Laser Powder-Bed/Fed Additive Manufacturing Processes and an Associated Magnetic Focusing Module. **[Link]**

### SUB-PROJECT 4.1.1(II): EMBEDDING OPTICAL SENSORS INSIDE OPTIMIZED LIGHTWEIGHT STRUCTURE MADE BY LASER POWDER-BED FUSION

### PROGRESS

- Sub-project 4.1.1(ii) was completed in Winter 2021.

### RESEARCH OUTCOME

**CONFERENCE PRESENTATION**

1. Nsiempba, E. Toyserkani. Predicting Defects in 3D Printed Lattice Structures. Rapid+TCT 2019 - Detroit, MI, 2019.

**THESIS**

1. Nsiempba KM. Coupled Experimentally-Driven Constraint Functions and Topology Optimization utilized in Design for Additive Manufacturing (Master's thesis, University of Waterloo). **[Link]**
2. Son K. Embedding Optical Sensors in Additively Manufactured Parts for In-Situ Performance Measurement (Master's thesis, University of Waterloo). **[Link]**

### SUB-PROJECT 4.1.2: LEVITATED ADDITIVE MANUFACTURING

### PROGRESS

- An analytical relationship between current input and average levitation height output for control strategies was established.
- A literature review on the impact of environmental disturbances on the stability of the levitated substrate was completed. The review indicated that the use of low frequencies (50 Hz) resulted in faster achievement of steady state and stable levitation.
- An enclosure for safe operation at high voltage inputs with 2 degrees of freedom (levitation and flipping of the substrate) was designed and built to facilitate deposition of material on any desired surface of the substrate.
- The compatibility of the magnetic levitation system with the AM system was verified. Multiple experiments were carried, and modifications to the experimental setup were made to optimize the levitation system.
- The effect of powder deposition on the levitation of the substrate was tested in the lab and inside the AM machine.

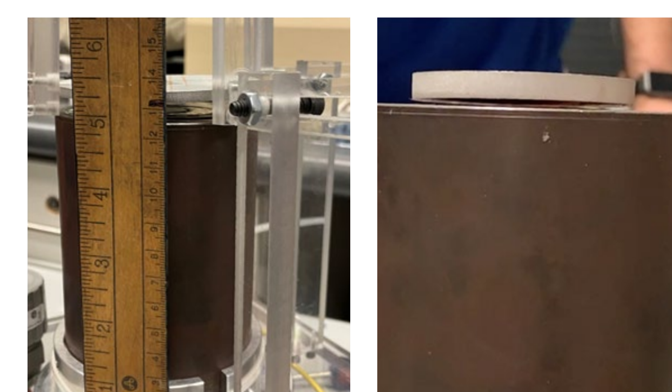
### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Kumar P, Huang Y, Toyserkani E, Khamesee MB. Development of a magnetic levitation system for additive manufacturing: Simulation analyses. IEEE Transactions on Magnetics. 2020 May 29;56(8):1-7. **[Link]**
2. Kumar P, Khamesee MB. Development and Analysis of a Novel Magnetic Levitation System with a Feedback Controller for Additive Manufacturing Applications. In Actuators 2022 Dec 3 (Vol. 11, No. 12, p. 364). MDPI. **[Link]**
3. Kumar P, Malik S, Toyserkani E, Khamesee MB. Development of an Electromagnetic Micromanipulator Levitation System for Metal Additive Manufacturing Applications. Micromachines. 2022 Apr 9;13(4):585. **[Link]**

**THESIS**

1. Malik S. Hardware Design and Implementation of an Electromagnetic Levitation System in an Additive Manufacturing Environment (Master's thesis, University of Waterloo). **[Link]**
2. Kumar P. Development of a Magnetic Levitation System for Additive Manufacturing Processes. **[Link]**



Successful levitation experiment without and with added payload. (Sub-project 4.1.2)

## 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<br>• Behrad Khamesee, University of Waterloo | • Kelvin Jisoo Son, University of Waterloo, MASc<br>• Yuze Huang, University of Waterloo, PhD / PDF<br>• 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<br>• Yuze Huang, University of Waterloo, PhD, PDF<br>• Ken Nsiempba, University of Waterloo, MASc<br>• Farid Ahmed, University of Waterloo, PDF (Collaborator) |
| **4.1.2 Levitated Additive Manufacturing** | • Behrad Khamesee, University of Waterloo<br>• Ehsan Toyserkani, University of Waterloo | • Parichit Kumar, University of Waterloo, PhD<br>• Yuze Huang, University of Waterloo, PDF<br>• Saksham Malik, University of Waterloo, MASc |

# 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.

### SUB-PROJECT 4.2.1: METAL AM FOR ORTHOPAEDIC AND IMPLANTS TECHNOLOGIES

## PROGRESS

- Sub-project 4.2.1 was completed in 2021.

## RESEARCH OUTCOME

**JOURNAL PAPER**

1. Moussa A, Rahman S, Xu M, Tanzer M, Pasini D. Topology optimization of 3D-printed structurally porous cage for acetabular reinforcement in total hip arthroplasty. Journal of the mechanical behavior of biomedical materials. 2020 May 1;105:103705. **[Link]**
2. Moussa A, Melancon D, El Elmi A, Pasini D. Topology optimization of imperfect lattice materials built with process-induced defects via powder bed fusion. Additive Manufacturing. 2021 Jan 1;37:101608. **[Link]**

**THESIS**

1. Moussa AE. Topology Optimization of Cellular Materials: Application to Bone Replacement Implants. McGill University (Canada); 2020. **[Link]**





### SUB-PROJECT 4.2.2: DEVELOPMENT OF SMART MOLDS WITH EMBEDDED OPTICAL SENSORS AND CONFORMAL CHANNELS

## PROGRESS

- The sensitivity of the Fiber Bragg Grating (FBG) sensors to changes in temperature under different curvature conditions was investigated.
- Channel properties were optimized and characterized using CT scanning and surface profilometry.
- Thermal distribution and mechanical strain under compression (as low as 1 kN) were measured for test coupons.
- Temperature calibration was completed and the effect of curvature on the calibration curves was studied.
- To validate the developed systems and models, an FBG sensor was embedded inside a complex geometry to create a small part. The internal temperature distribution was successfully measured.

## RESEARCH OUTCOME

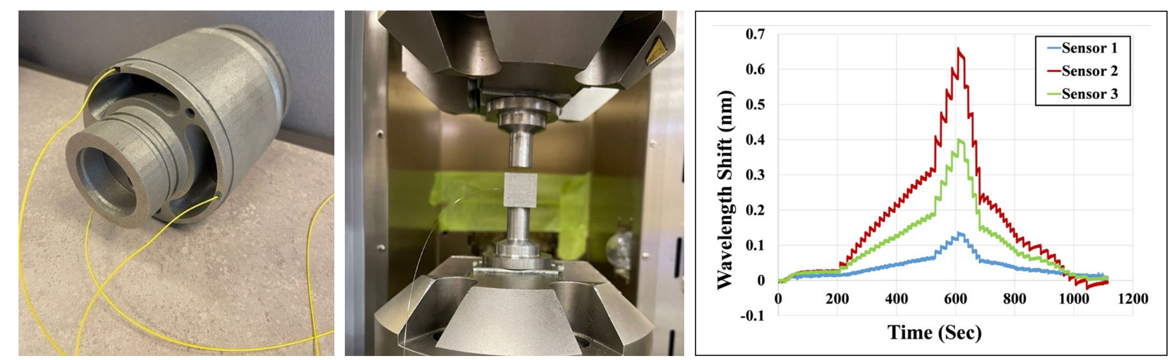
**JOURNAL PAPER**

1. Tang Y, Gao Z, Zhao YF. Design of conformal porous structures for the cooling system of an injection mold fabricated by Additive Manufacturing Process. Journal of Mechanical Design. 2019 Oct 1;141(10). **[Link]**
2. Gao Z, Dong G, Tang Y, Zhao YF. Machine learning aided design of conformal cooling channels for injection molding. Journal of Intelligent Manufacturing. 2021 Oct 9:1-9. **[Link]**

- At least 1 more manuscript is in preparation for publication.

**THESIS**

1. Gao Z. Machine Learning Aided Design of Conformal Cooling Channels for Injection Molding. McGill University. **[Link]**




(Left) A smart industrial part with three single and multiple sensors for measuring the temperature and mechanical loading during service. (Right) Strain measurements of the cubes during compression testing using FBGs.

## 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<br>• 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<br>• Ehsan Toyserkani, University of Waterloo | • Tang Yunlong, McGill University, PDF<br>• Zhenyang Gao, McGill University, MASc<br>• Danièle Sossou, McGill University, Co-op<br>• Bahareh Marzbanrad, University of Waterloo, PDF (collaborator) |

# 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.

## SUB-PROJECT 4.3.1: DIRECT MANUFACTURING OF FGM ADVANCED PART USING PTA-AM

### PROGRESS

- The auxiliary thermal model of PTA-AM was completed and compared with experimental results. Using the model, the temperature and velocity history of nickel alloy and tungsten carbide spherical powder particles are predicted as they are injected into an argon plasma transferred arc.
- The influence of the operating parameters on the heating of powders in a PTA plume was studied followed by a sensitivity analysis of the model.
- The PTA-AM of Functionally Graded Coatings (FGCs) was simulated using ABAQUS in order to predict the deposition process temperature history and the resulting residual stress trends. The mesh and time step refinement were completed for the finite element model.
- Experimental trials had been planned to compare the performance of a set of different FGM material systems with residual stress profiles obtained experimentally and numerically. Due to delays in the installation of the PTA-AM system, the experimental portion of the project could not be completed before the HQP graduated. Instead, the focus was shifted to improving the model and obtaining more precise predictions.

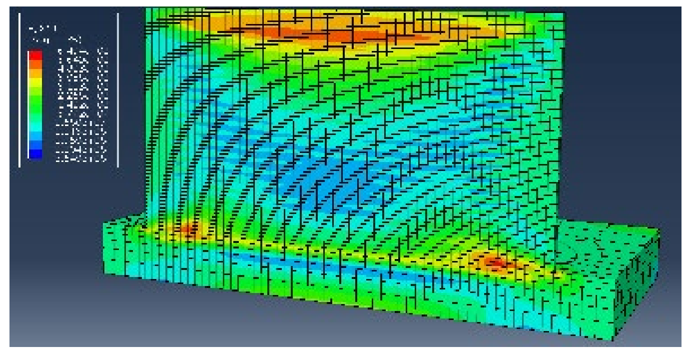
## RESEARCH OUTCOME

### JOURNAL PAPER

- At least 3 manuscripts are in preparation for publication. 1 manuscript has been accepted by IOP.

### THESIS

1. Bonias G. Thermal and residual stress modeling of functionally graded deposits using the PTAAM. **[Link]**

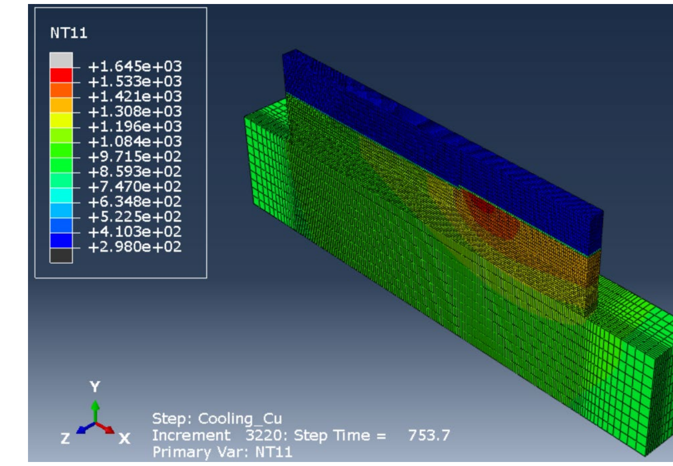


Residual stress field (Pa) after printing the non-graded wall. (Sub-project 4.3.1)

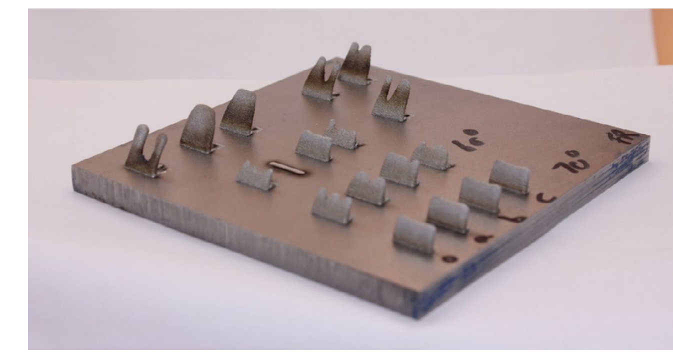
## SUB-PROJECT 4.3.2: DIRECT MANUFACTURING OF FGM MOLDS USING LPF-AM

### PROGRESS

- The research scope was modified to only include process development for one alloy (D2 tool steel). The milestones related to DED processing of copper for manufacturing FGM molds were not completed due to lack of time. Modeling efforts for multi-material DED were pursued instead.
- XRD analysis of as-printed and heat-treated DED samples was completed.
- A study investigating the effect of heat treatment on the mechanical properties of the wrought D2 tool steel was completed.
- A study on the feasibility of printing internal hollow structures using DED by production of inclined thin walls was competed. The influence of varying process parameters and angles of inclination on the side surface roughness was examined. Further experiments indicated the maximum angle of inclination that could be reached before failure.
- Samples were printed to examine the effect of different process parameters and heat treatment scenarios on the wear resistance of as-printed and heat-treated DED D2 tool steel relative to wrought (as-received and heat-treated) tool steel. Further characterization using SEM and EDS mapping of the wear tracks was carried out.
- A finite element model of the DED process, through the deposition of Cu on H13 tool steel while using an Ni-based alloy as a buffering layer, was developed. The model temperature evolution was validated using experimental results from the literature. Mechanical validation is planned to be conducted in the future.




Example of temperature distribution during DED of copper layers. (Sub-project 4.3.2)



Typical instances of DED processed inclined thin walls. (Sub-project 4.3.2)

## RESEARCH OUTCOME

### JOURNAL PAPER

1. Omar SM, Plucknett KP. The influence of DED process parameters and heat-treatment cycle on the microstructure and hardness of AISI D2 tool steel. Journal of Manufacturing Processes. 2022 Sep 1;81:655-71. **[Link]**

- At least 2 more manuscripts are in preparation for publication.

### CONFERENCE PRESENTATION

1. O. Craig, S. Omar, K. Plucknett. Material Characterization Comparison of D2 and H13 Tool Steels Manufactured using Directed Energy Deposition. COM 2021, 60th Conference of Metallurgists - Virtual, 2021.
2. Omar SM, Plucknett KP. Influence of Layer Thickness Upon the Dimensional Accuracy and Surface Roughness of AISI D2 Tool Steel Manufactured Using Directed Energy Deposition. InProceedings of the 61st Conference of Metallurgists, COM 2022 2023 Jan 6 (pp. 39-42). Cham: Springer International Publishing.

## 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<br>• Geoffrey Bonias, University of Alberta, MASC |
| **4.3.2 Direct Manufacturing of FGM Molds Using LPF-AM** | • Kevin Plucknett, Dalhousie University | • Samer Tawfik Omar, Dalhousie University, PhD<br>• Riley Roache, Dalhousie University, Co-op (collaborator) |

# 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.

## SUB-PROJECT 4.4.1: REPAIR STRATEGIES WITH LPF-AM

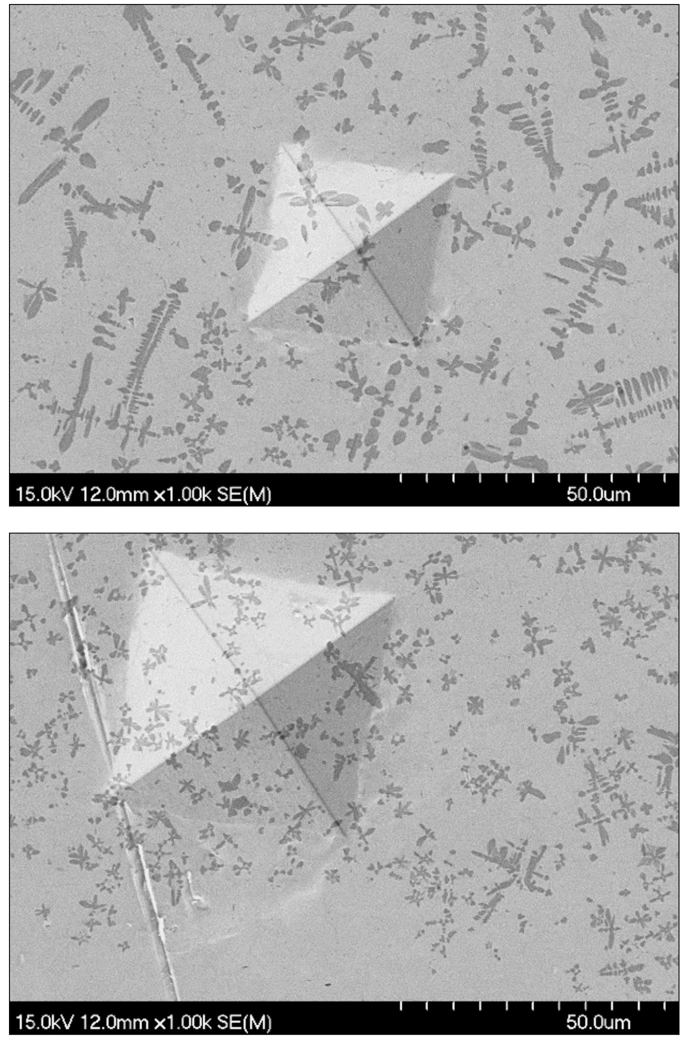
### PROGRESS

- The methodology was updated in the areas of powder preparation, chemical composition, gelation kinetics and cladding action. The generated procedure was refined for successful pre-deposition and DED processing of TiC-Ni3Al cermet coatings on tool steel.
- The repeatability of microstructural and mechanical performance of protective coatings manufactured by the proposed method was examined.
- The compatibility of the gelation-based pre-position route with varying coating feedstock and substrate compositions was verified for several scenarios as a path forward for generalization of this application method.
- The effectiveness of fabricated coatings on mechanical and corrosion enhancement of the DED processed D2 tool steel surface was examined. Micro Vickers indentation, scratch hardness tests and corrosion evaluation, including Electrochemical Impedance Spectroscopy (EIS), were completed for coated specimens. Experiments were replicated for each test in order to ensure reproducibility of the data.

### RESEARCH OUTCOME

**JOURNAL PAPER**

- At least 3 manuscripts are in preparation for publication.




Example SEM images of Vickers indents under 3 N applied normal force: (Left) at top of the clad coating, and (Right) near the coating/substrate interface. (Sub-project 4.4.1)

## SUB-PROJECT 4.4.2: REPAIR STRATEGIES USING EWF-AM

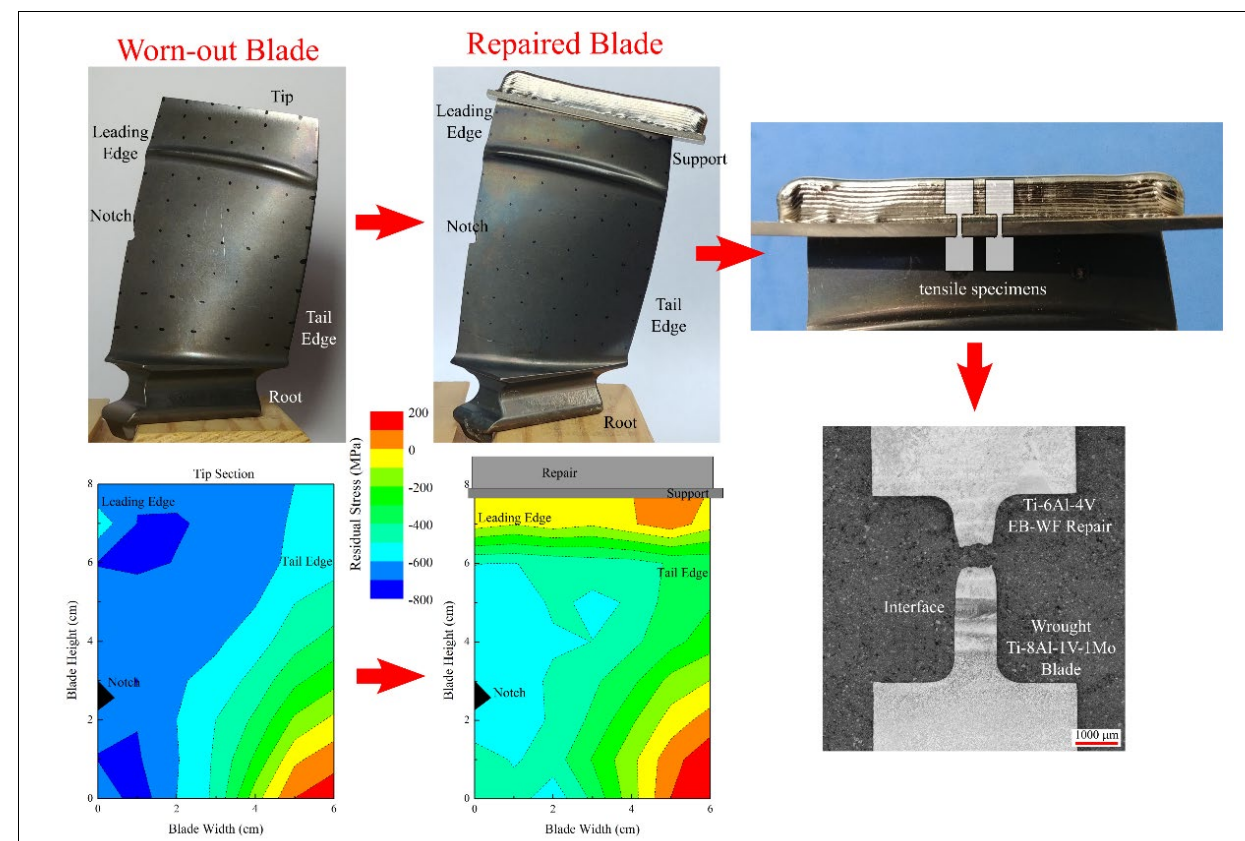
### PROGRESS

- A study on the effect of initial substrate condition on EWF-AM process was completed.
- The residual stress profile of each substrate condition was investigated before and after deposition and analyzed in correlation with the previously developed thermo-mechanical model.





- Out of plane distortion was measured using 3D optical scanning before and after deposition and correlated with the initial stresses and microstructural features.
- Microstructural alterations on the grain structure due to heat accumulation during deposition were characterized and correlated with the initial microstructure.
- Small scale mechanical testing was performed to understand the variation in microstructure and mechanical properties of an EWF-deposited Ti-6Al-4V alloy. The results were compared with the mechanical performance of the wrought and cast counterpart.
- The capability of the developed technique was demonstrated by repairing worn Ti-8Al-1V-1Mo compressor blade tips after 20,000 hours of service. The residual stress and distortion profiles of the compressor blade were analyzed before and after the repair to ascertain the changes resulting from the additive repair process and to assess the viability of the blade geometry against the tolerance requirements for return-to-service.




Repair and characterization of the worn-out blade made from Ti-8Al-1V-1Mo using EWF-AM. (Sub-project 4.4.2)

### RESEARCH OUTCOME

**JOURNAL PAPER**

1. Sikan F, Wanjara P, Gholipour J, Kumar A, Brochu M. Thermo-mechanical modeling of wire-fed electron beam additive manufacturing. Materials. 2021 Feb 15;14(4):911. **[Link]**
2. Sikan F, Wanjara P, Gholipour J, Atabay SE, Brochu M. Effect of substrate condition on wire fed electron beam additive deposition. Materials Science and Engineering: A. 2022 Aug 1;849:143448. **[Link]**
3. Sikan F, Wanjara P, Gholipour J, Brochu M. Use of miniature tensile specimens for measuring mechanical properties in the steady-state and transient zones of Ti–6Al–4V wire-fed electron beam deposits. Materials Science and Engineering: A. 2023 Jan 18;862:144487. **[Link]**
4. Sikan F, Wanjara P, Atabay SE, Gholipour J, Brochu M. Evaluation of electron beam wire-fed deposition technology for titanium compressor blade repair. Materials Today Communications. 2023 Jun 1;35:105701. **[Link]**

# Project 4.4: Advanced LPF-, EWF-, and PTA-AM for Repair and Remanufacturing (Continued)

**CONFERENCE PRESENTATION**

1. F. Sikan, P. Wanjara, J. Gholipour, M. Brochu. Thermo-mechanical Modelling of Electron Beam Additive Manufacturing Process for Repair and Remanufacturing Purposes. EBAM 2020, 3rd International Conference on Electron Beam Additive Manufacturing - Erlangen, Germany (moved online), 2020.
2. F. Sikan, P. Wanjara, J. Gholipour, M. Brochu. Thermo-mechanical Modelling of Wire fed Electron Beam Additive Manufacturing. Aeromat 2021 - 32nd Conference and Exposition, 2021.
3. F. Sikan, P. Wanjara, J. Gholipour, M. Brochu. Influence of Substrate Condition and Initial Residual Stresses on Wire Fed Electron Beam Additive Deposition. MS&T 2022, 2022.

## SUB-PROJECT 4.4.3: REPAIR STRATEGIES USING PTA- AND FFF-AM

### PROGRESS

- The integration of the PTA into the gantry system was finalized by setting up remote control for ARC/Pilot/gas on/off signal using G-Code, setting up electrical and gas connections for the PTA power supply, installing a transformer, and testing for Pilot ignition using direct and remote control.
- A new fast hybrid calibration process for part identification and localization based on fiducial marker and inverse kinematics was designed and implemented.
- Surface preparation tests were run using aluminum samples with different damage types: attrition, abrasion, cavity, and fracture. The algorithm generated toolpaths for automated repair, leading to conclusive results in terms of accuracy and precision.
- Repair process was tested using polymer samples. The team is working on addressing the slight geometric deviation and adhesion issues observed during the tests.
- The project on repair strategies using FFF-AM was completed.

### RESEARCH OUTCOME

**CONFERENCE PRESENTATION**

1. N. Bhardwaj, H. Henein, T. Wolfe. Fused Filament Fabrication (FFF) of Metal Matrix Composites (MMC). Materials Science and Technology 2020 (MS&T) - Online, 2020.

**THESIS**

1. Bhardwaj N. Fused Filament Fabrication of Metal-Ceramic High-Density Polyethylene Composites. **[Link]**

### 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<br>• Kerilyn Kennedy, Dalhousie University, Co-op |
| **4.4.2 Repair Strategies Using EWF-AM** | • Mathieu Brochu, McGill University | • Fatih Sikan, McGill University, PhD<br>• Camila Gutierrez, McGill University, Co-op |
| **4.4.3 Repair Strategies Using PTA- and FFF-AM** | • Hani Henein, University of Alberta | • Nancy Bhardwaj, University of Alberta, MASc (Collaborator)<br>• Remy Samson, University of Alberta, MASc |

# Finances

The HI-AM Network receives funding mainly from NSERC. The Network received $1 million in its first year, and has received $1.125 million for years 2-5. This funding is matched by both industry funds, and institutional support from the universities participating in the Network. The pandemic has caused some delay in spending travel-related expenses; including exchanges, other conferences, and the annual HI-AM conference.

**YEAR ONE TO FIVE NSERC FUNDING (2017-2022)**

| | BUDGET | EXPENSES AND COMMITMENTS* |
|---|---|---|
| THEME 1 | $1,927,567 | $1,403,596 |
| THEME 2 | $916,240 | $783,978 |
| THEME 3 | $614,348 | $533,458 |
| THEME 4 | $762,356 | $597,743 |
| ADMINISTRATIVE AND KNOWLEDGE TRANSFER | $1,459,490 | $938,503 |
| **TOTAL** | **$5,680,000** | **$4,257,278** |


**YEAR ONE TO FIVE INDUSTRY/GOVERNMENT PARTNER AND INSTITUTIONS CONTRIBUTIONS (2017-2022)**

| | BUDGET | EXPENSES AND COMMITMENTS |
|---|---|---|
| THEME 1 | $671,397 | $397,554 |
| THEME 2 | $415,334 | $142,407 |
| THEME 3 | $454,224 | $340,044 |
| THEME 4 | $464,614 | $327,468 |
| ADMINISTRATIVE AND KNOWLEDGE TRANSFER | $106,932 | $190,399 |
| **TOTAL** | **$2,112,501** | **$1,397,871** |


*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 within and beyond the Network in numerous ways, including through Network events, via our online presence, participation in international engineering conferences, training undergraduate and graduate students, and domestic and international student exchanges.

# HI-AM Conference 5th | 2022

Over the past six years, the HI-AM Conference has developed into a dynamic event, providing a platform for additive manufacturing researchers and experts from Canada and internationally to exchange ideas and discuss the latest trends and developments in metal AM. With attendees from various institutions and organizations, the conference consistently provides participants with a unique opportunity to network across sectors, and to connect with and learn from leading researchers and AM professionals from across the globe.

# HI-AM Conference 2022 *continued*

The 5th HI-AM Conference, held on June 21-22 in Montreal and co-chaired by Mathieu Brochu of McGill University and Ehsan Toyserkani of University of Waterloo was very well received by the AM community, with approximately 200 participants from more than 100 organizations. The conference was opened by Professor Jim Nicell, Dean of the Faculty of Engineering at McGill University, with opening remarks also provided by the Conference Chairs. The 2022 conference follows past HI-AM conferences, hosted by the University of Waterloo in 2018 (Waterloo, ON), the University of British Columbia in 2019 (Vancouver, BC), McGill University in 2020 (virtual), and Dalhousie University in 2021 (virtual).


Opening remarks by (left to right): Jim Nicell, Dean of Engineering, McGill University, Mathieu Brochu, HI-AM 2022 Chair, McGill University and Ehsan Toyserkani, HI-AM 2022 Chair, University of Waterloo

A total of 105 research work were presented at HI-AM 2022 in oral and poster formats. 4 keynote presentations were delivered by James Sears, Technology Fellow, AMAERO, United States; Animesh Bose, VP Special Projects, Desktop Metal, United States; Sebastian Piegert, Technology Field Lead Additive Manufacturing, Siemens Energy, Germany; and Wayne King, Principal ADDvisor®, The Barnes Global Advisors, United States.

The conference was supported by partners and exhibitors from industry and academia: Natural Sciences and Engineering Research Council Canada, University of Waterloo, McGill University, Multi-Scale Additive Manufacturing Lab, Canada Makes, Leichtbau BW, Metal AM Magazine, EOS, GE Additive, AP&C, Promation, Desktop Metal, Keyence, Phaseshift Technologies, GA3D, Opti-Tech Scientific, Retinex, C-Therm, Xact Metal, and Tronos. These partners significantly enhanced the value of the conference by showcasing their latest technologies, products and services at the HI-AM Exhibition. The Exhibition provides Network HQP and other attendees with the opportunity to get a firsthand look at the latest developments in the field, to network in an intimate setting with industry leaders, experts, and peers, and to gain valuable insights into the future of the industry.

2022 Exhibition

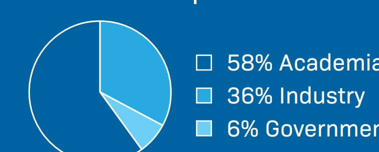
The conference dinner at Hotel Place D'Armes was the highlight of the event, providing the guests with a perfect opportunity to unwind and connect with colleagues after two years of virtual events. Participants enjoyed exquisite French-Canadian cuisine in a beautiful setting with a view of old Montreal. Mr. Ralph Resnick, the Chairman of the Board of Directors of the HI-AM Network, commended the Network researchers for their progress during the pandemic and thanked NSERC for their continued support of the HI-AM's research activities during the difficult pandemic years. He highlighted the importance of the work being done at HI-AM Network and thanked the members for their resilience and perseverance. Overall, his remarks were a fitting tribute to the hard work and dedication of the Network researchers, and a reminder of the importance of science and research in times of crisis.

2022 conference dinner

## 2022 HI-AM Conference at a Glance

### AT A GLANCE

- 200 Participants




- 100+ Organizations

### EDUCATION

- 4 Keynote Talks
- 64 Oral Presentations
- 41 Posters

### NETWORKING

- 18 Exhibitors
- Tradeshow
- Networking Session
- Social Event

### KEYNOTE SPEAKERS

**James Sears**
Technology Fellow
AMAERO,
United States

**Animesh Bose**
VP, Special Projects
Desktop Metal, Inc.,
United States

**Sebastian Piegert**
Technology Field Lead Additive Manufacturing
Siemens Energy GmbH & Co KG, Germany

**Wayne King**
Principal ADDvisor®
The Barnes Global Advisors

# HI-AM Conference 2022 *continued*

The conference closing remarks were given by HI-AM Network's Theme 1 Leader, Paul Bishop, who is chairing the 2023 HI-AM Conference hosted by Dalhousie University in Halifax, NS. The conference concluded with the announcement of the recipients of student presentation competition awards. The 2022 winners are:

## ORAL PRESENTATION COMPETITION:

**First Place:**
- William Chaine, Université Laval
- Farzaneh Kaji, University of Waterloo

**Second place:**
- Sahar Toorandaz, University of Waterloo
- An Fu, McGill University
- Sharon Tam, The University of British Columbia

**Third place:**
- Amanda Rossi, Federal University of ABC
- Kudakwashe Nyamuchiwa, University of New Brunswick
- Dylan Rose, University of Alberta
- Jason Guy, Arts et Metiers Institute of Technology

## POSTER PRESENTATION COMPETITION:

**First place:**
- Etienne Moquin, École de technologie supérieure
- Nadia Azizi, University of Waterloo

**Second place:**
- Ali Safdel, McMaster University
- William Bouchard, Université Laval

**Third place:**
- Mohammad Azimi, Concordia University
- Jonathan Comhaire, Dalhousie University
- Ali Zardoshtian, University of Waterloo

2022 student presentation award winners