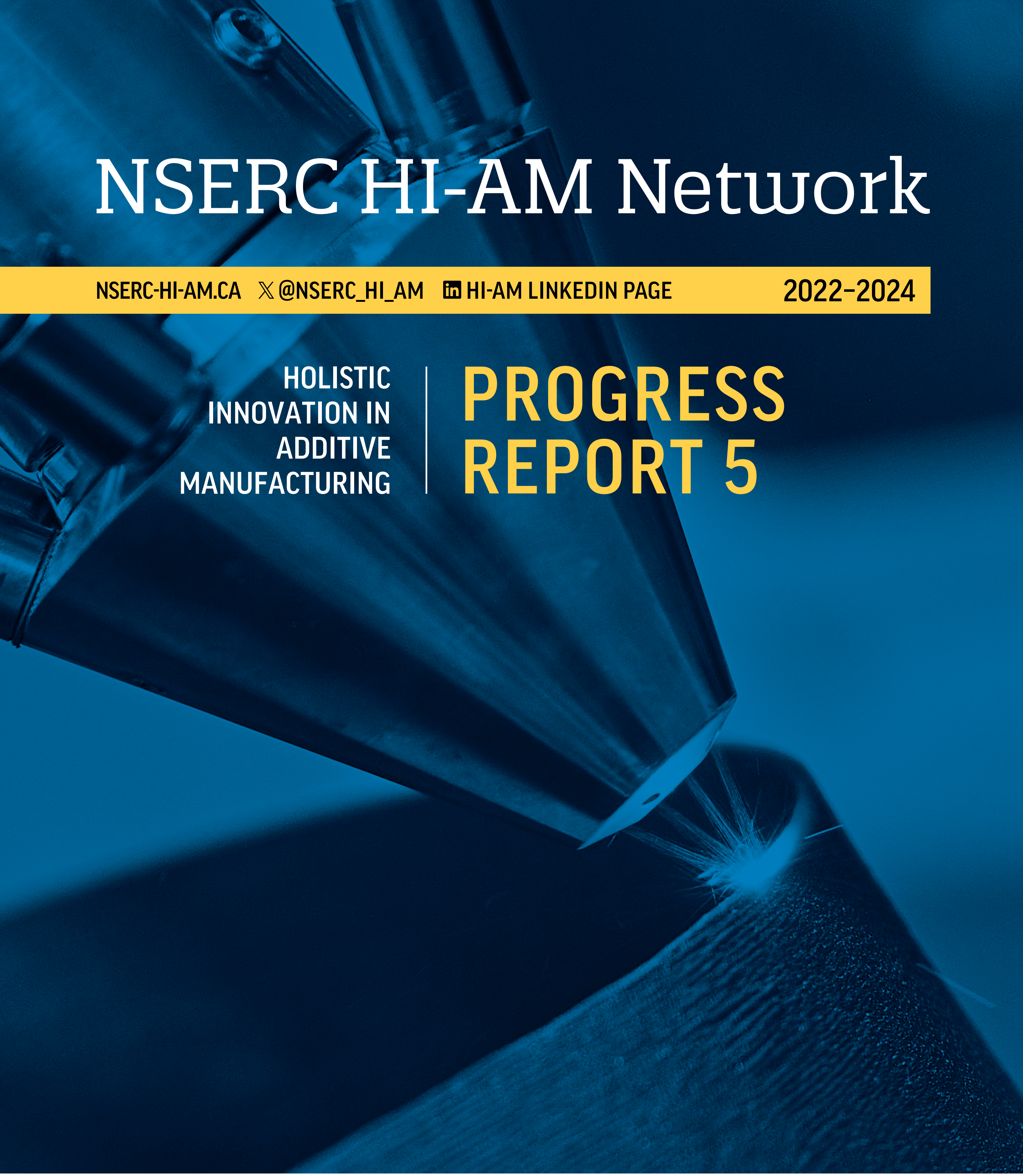

NSERC HI-AM Network

NSERC-HI-AM.CA @NSERC_HI_AM HI-AM LINKEDIN PAGE 2022–2024

HOLISTIC INNOVATION IN ADDITIVE MANUFACTURING

PROGRESS REPORT 5

NSERC HI-AM | UNIVERSITY OF WATERLOO | FACULTY OF ENGINEERING | NSERC CRSNG | INNOVATION.CA CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

PROGRESS REPORT 5

2022–2024

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READ OUR PREVIOUS PROGRESS REPORTS

Message from the Chair and Director

Ralph Resnick
Chair of the Board of Directors

Ehsan Toyserkani
Network Director

We are honored to share the fifth and final progress report of the NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM). This report provides an overview of the activities undertaken between January 2022 and June 2024, along with a summary of all research outcomes achieved over the lifespan of the Network.

As we approach the culmination of the NSERC HI-AM Network, it's a moment for reflection and celebration. For seven years, we've been dedicated to fulfilling the Network's core objectives. These include training skilled experts in additive manufacturing (AM), conducting innovative multidisciplinary research across the entire metal AM workflow, and building strong bonds between academic and industry partners. As we near the end, we can reflect on our accomplishments with pride, knowing they will continue to benefit AM in Canada and elsewhere.

The initial proposal for HI-AM Network outlined a plan to train 78 highly qualified personnel (HQP) at different stages, from undergraduate co-ops to postdoctoral fellows. However, the outcome exceeded these projections, resulting in the training of over 140 individuals, including HQP supported through grants external to HI-AM. Each HQP played a pivotal role in realizing the Network's achievements. Additionally, a substantial majority of HQP have integrated into the Canadian workforce or are currently in the process of doing so, thereby imparting their expertise in AM to the industry – a vital contribution that fosters innovation and sustains growth.

As a result of this program, we have achieved significant research milestones across 39 projects. Notably, these included the development of process-property models for over twenty novel alloys, the advancement of two cost-effective powder atomization techniques, the patenting of metrology technologies tailored for various AM platforms, and the application of advanced machine learning and modeling techniques to enhance the quality of AM systems. These accomplishments represent just a glimpse into the impact of our research and training efforts. For a comprehensive view of the Network's outcomes, we invite you to read the present report.

Collaboratively, the HI-AM researchers and HQP have contributed over 470 articles, presentations, posters, and technical reports for various journals and conferences. Additionally, we are proud to highlight other achievements such as the filing of eight invention disclosures and four patents, the establishment of three startup companies, and the submission of two ASTM/ISO standard and best practice drafts, with one already in press.

Our growth and success have been greatly bolstered by the invaluable partnerships we have forged with both industrial and government entities. These collaborations have not only enriched our research endeavors but have also laid the foundation for a robust and enduring ecosystem of cooperation within the field of AM in Canada. It's with immense pride that we announce the continuation of this collaborative spirit through our new initiative, HI-AM 2.0. Building upon our past achievements, this new project aims to further advance AM research, innovation, and industry integration across the nation. Stay tuned for more information about the HI-AM 2.0 initiative in the coming months.

We express our sincere appreciation to the faculty members, researchers, and students from the University of Waterloo, Dalhousie University, McGill University, the University of Alberta, the University of British Columbia, Université Lavel, and the University of Toronto, who led our research programs. Additionally, we extend our gratitude to their dedicated administrative staff who supported the smooth functioning of the Network. We also acknowledge the invaluable contributions of distinguished business leaders and scholars who served on the various governance committees of the Network.

We appreciate you taking the time to read this report, and we hope you find it useful. If you need any further information, please contact our Network Manager, Farzad Liravi, at **fliravi@uwaterloo.ca**.

Ralph Resnick,
Chair of the Board of Directors

Ehsan Toyserkani,
Network Director

Introduction

The University of Waterloo, represented by its Multi-Scale Additive Manufacturing Laboratory, has been proud to host and lead the **NSERC Network for Holistic Innovation in Additive Manufacturing (HI-AM)** since its establishment in 2017. With the mission of fostering collaboration among partners from diverse sectors, including academia, industry, and the public sphere, the focus of our research programs has been on advancing the development of innovative materials, processes, control systems, and products for metal AM.

The formation of the HI-AM Network stemmed from a recognition of the barriers impeding the widespread industrial adoption of metal AM. These challenges include the demand for an expanded range of feedstock metal alloys, faster build rates and greater build volumes, increased process repeatability and reliability, and quality education on design practices, among others. In response, a comprehensive research program was designed with a goal to address some of these challenges, providing practical solutions through a holistic approach.

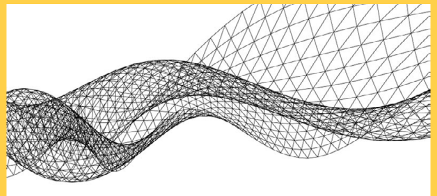
This endeavour brought together a consortium of Canada's leading researchers, boasting diverse and complementary expertise from seven universities, including Waterloo, McGill, UBC, Dalhousie, Laval, Toronto and Alberta. Subsequently, the University of Windsor and ETS Montreal joined the Network as collaborative partners. With funding totalling $5.5 million from the **Natural Resources and Engineering Research Council of Canada (NSERC)**, supplemented by an additional $2 million contributed by member universities and industrial partners, this initiative was empowered to drive meaningful progress in the field of metal AM.

The research endeavors within the NSERC HI-AM Network were complemented by a parallel $15 million initiative, which focused on enhancing AM laboratory facilities and infrastructure across Canada. Funded by the **Canada Foundation for Innovation (CFI)**, along with support from the Governments of Ontario, British Columbia, Quebec, and Nova Scotia, this endeavor, known as the **CFI Canadian Additive Manufacturing Network: HI-AM**, was spearheaded by the University of Waterloo. Participating institutions included UBC, McGill, and Dalhousie.

As both these networks reach their conclusion in 2024, their impact on fostering a collaborative ecosystem driven by multidisciplinary research and state-of-the-art research equipment has been evident. Their efforts have laid a strong foundation for ongoing collaboration and innovation within the field. We anticipate that their legacy will continue to yield benefits for Canada in the years to come, facilitating further advancements and discoveries in AM and related domains.

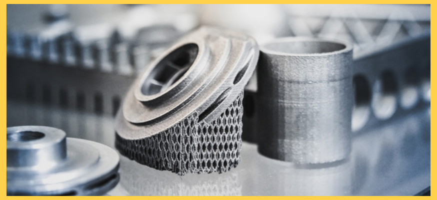
HI-AM Research Themes

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



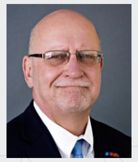
THEME 4: Innovative AM Processes and AM-made Parts

Governance

BOARD OF DIRECTORS

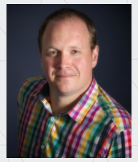
The **Board of Directors** oversees the global direction of the Network, providing bi-annual input on the research program quality and emerging research topics. The Board is also responsible for reviewing the Network's finances to ensure its success within the NSERC's financial guidelines.

VOTING MEMBERS

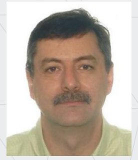


Ralph Resnick
Chair
America Makes, USA
Founding Director, President and Executive Director of NCDMM (Retired)

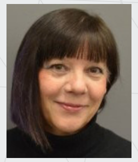
Ehsan Toyserkani
University of Waterloo, Canada
Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Mechanical and Mechatronics Engineering



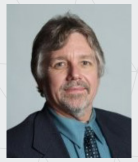
Mathieu Brochu
McGill University, Canada
Associate Director, NSERC HI-AM Network & CFI Can-AMN
Professor of Materials Engineering



Stefano Chiovelli
Syncrude, Canada
Senior Technical Advisor



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

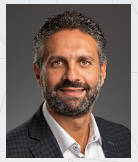


Ian Donaldson
GKN Sinter Metals, USA
Director, Advanced Engineering Applications

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

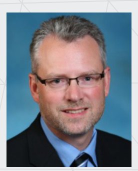
Nancy Sej
University of Waterloo, Canada
Financial Manager, NSERC HI-AM Network & CFI Can-AMN

Governance

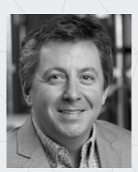
SCIENTIFIC ADVISORY COMMITTEE

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



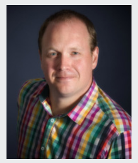
Paul Bishop
Dalhousie University, Canada
Professor of Mechanical Engineering



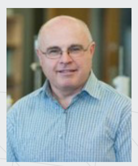
Carl Blais
Université Laval, Canada
Professor of Mining, Metallurgy and Materials Engineering

Ali Bonakdar
The University of North Carolina at Charlotte, USA
Associate Professor, Mechanical Engineering and Engineering Science

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



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

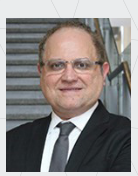


Steve Cockcroft
The University of British Columbia, Canada
Professor of Materials Engineering

Ian Gibson
UT Twente, The Netherlands
Professor of Design Engineering

Mahdi Habibnejad
AP&C (Colibrium Additive – A GE Aerospace Company)
Senior External R&D Manager

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

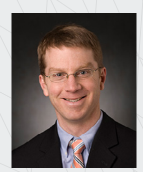


Hani Naguib
University of Toronto, Canada
Professor of Materials Science and Engineering

Behrang Poorganji
Morf3D, USA
CTO

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

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



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

Priti Wanjara
National Research Council Canada
Principal Research Officer

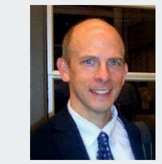
Tonya Wolfe
Elementiam Materials and Manufacturing Inc., Canada
CEO and Co-founder

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

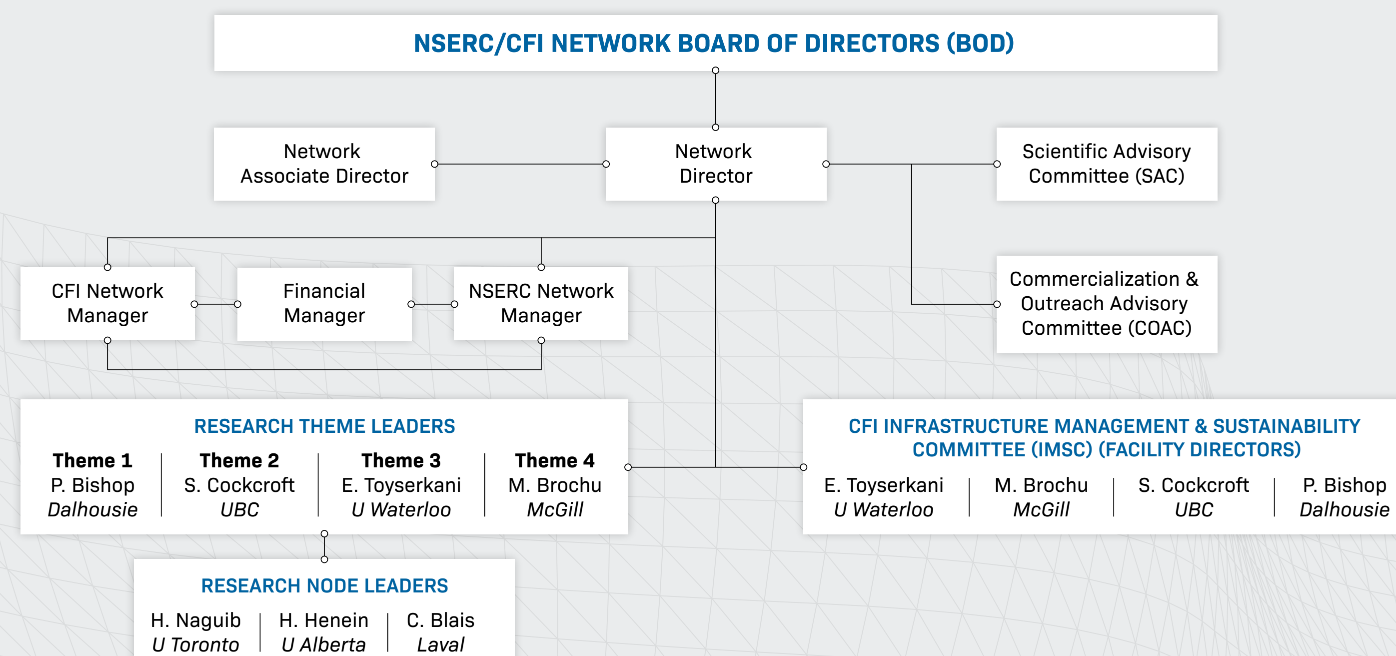
Michael Barré
IRAP - NRC, Canada
Industrial Technology Advisor



Dave Dietz
University of Waterloo, Canada
Director of Engineering Research

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

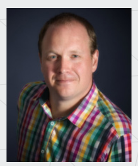
GOVERNANCE STRUCTURE



Principal Investigators

THEME/NODE LEADERS

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



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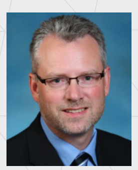

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NODE LEADER
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NODE LEADER
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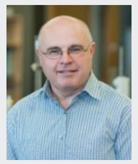
Département de la métallurgie et des matériaux



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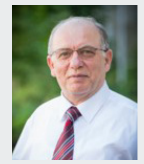
Hani Naguib
PhD, PEng
NODE LEADER
University of Toronto
Dept. of Materials Science and Engineering
Dept. of Mechanical and Industrial Engineering

CO-INVESTIGATORS



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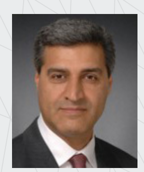

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Yaoyao Fiona Zhao
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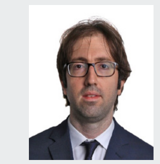
COLLABORATORS



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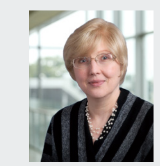
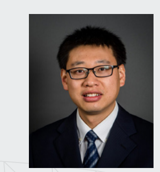
Dept. of Mechanical Engineering

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



Jill Urbanic
PhD, PEng
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) – Université du Québec
- 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
- 39 PROJECTS
- 22 PRINCIPAL INVESTIGATORS
- 148 HIGHLY QUALIFIED PERSONNEL*
- 116 JOURNAL PAPERS
- 71 CONFERENCE PAPERS/ PRESENTATIONS
- 231 HI-AM CONFERENCE PAPERS/ PRESENTATIONS
- 59 THESES
- 11 OTHER PUBLICATIONS**
- 8 INVENTION DISCLOSURE
- 6 EVENTS

* Includes HQP funded by external sources or a combination of HI-AM and external grants.
** Technical reports, patents, standard drafts

HIGHLY QUALIFIED PERSONNEL (HQP) BY THEME

	Undergraduate	MASc	PhD	PDF/RA
THEME 1	10	18	16	8
THEME 2	0	9	9	5
THEME 3	3	16	18	6
THEME 4	6	8	10	6
TOTAL	**19**	**51**	**53**	**25**

Research Progress

THEME 1

Material Development Tailored with Optimum Process Parameters

Paul Bishop
PhD, PEng
THEME 1 LEADER

Dalhousie University
Dept. of Mechanical Engineering

While tremendous progress has been made in 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.

Project 1.1: Development of Next Generation Alloys

DESCRIPTION

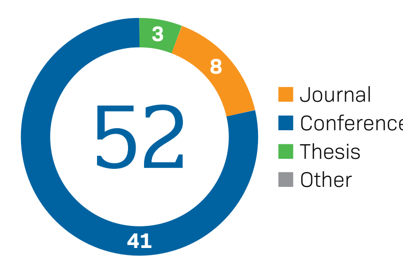
The objective of this project is to generate new powder metal feedstocks, with compositions strategically chosen to have a widespread and immediate impact on the global AM community. These new materials will broaden the mechanical, physical, and corrosion properties attainable within metallic products.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

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

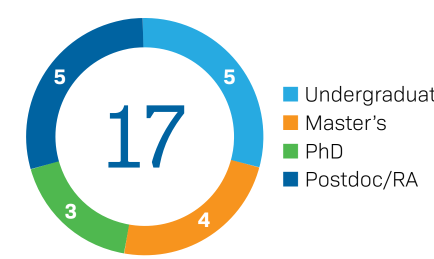
PROGRESS

This subproject represented a significant research endeavour within the Network, spanning across three universities: Dalhousie University, McGill University, and the University of Alberta. It involved the active participation of 17 HQP. Approaching its conclusion, the subproject has met its objectives, including the expansion of aluminum alloy applications for commercialized LPBF by addressing solidification cracking (in conjunction with subproject 2.1.5). Additionally, it has contributed to the creation of comprehensive datasets detailing the mechanical and physical properties achievable from more than ten feedstocks.

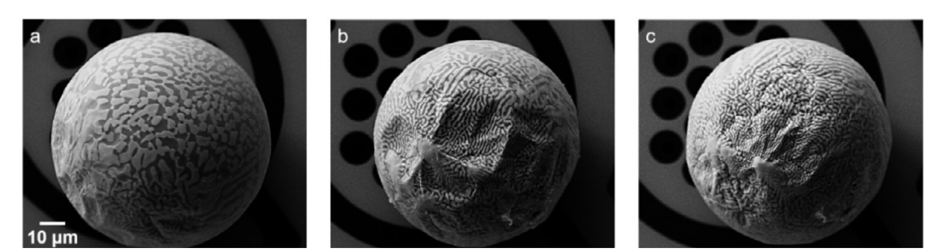
RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



*Please note that the statistics presented in the HQP Profile charts represent actual individual counts, not full-time equivalents (FTE). There may be instances where an HQP has withdrawn from the program or had only a brief collaboration with the Network.



SEM micrographs of Al-33wt%Cu droplets solidified at (a) 5 K/s, (b) 10 K/s, and (c) 20 K/s.
(Subproject 1.1.1 | Valloton, J., et al. "In situ solidification of eutectic Al-33wt% Cu droplets."
IOP Conference Series: Materials Science and Engineering. Vol. 1274. No. 1. IOP Publishing, 2023.)

RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Paul Bishop, Dalhousie University
- Mathieu Brochu, McGill University
- Hani Henein, University of Alberta

HIGHLY QUALIFIED PERSONNEL

- An Fu, McGill University, PhD
- Jon Heirly, Dalhousie University, PhD
- Quentin Champdoizeau, University of Alberta, MASc
- Daniela Diaz, University of Alberta, RA, MASc
- Abdoul-Aziz Bogno, University of Alberta, RA
- Jose Marcelino Da Silva Dias Filho, University of Alberta, PDF (Collaborator)
- Akankshya Sahoo, University of Alberta, PhD (Collaborator)
- Matthew Harding, Dalhousie University, PDF
- Greg Sweet, Dalhousie University, PDF
- Maéva Chrzaszcz, McGill University, Co-op
- Ryan Ley, Dalhousie University, Co-op (Collaborator)
- Jon Comhaire, Dalhousie University, MASc
- Loraine Rabago, University of Alberta, Co-op/URA (Collaborator)
- Batool Aleeza, University of Alberta, Co-op/URA (Collaborator)

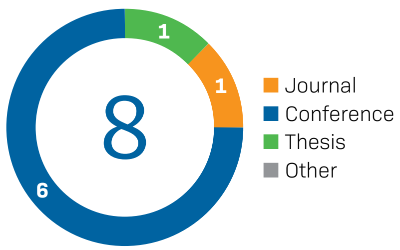
RESEARCH OUTCOMES

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

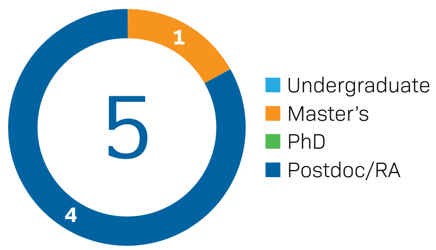
PROGRESS

Concluded in 2023, this subproject conducted at Dalhousie University has effectively delved into feedstock atomization, process optimization, and development of metallurgical database aimed at optimizing products built with Ti55511 alloy using DED technology.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Paul Bishop, Dalhousie University

HIGHLY QUALIFIED PERSONNEL

- Matthew Harding, Dalhousie University, PDF
- Greg Sweet, Dalhousie University, PDF
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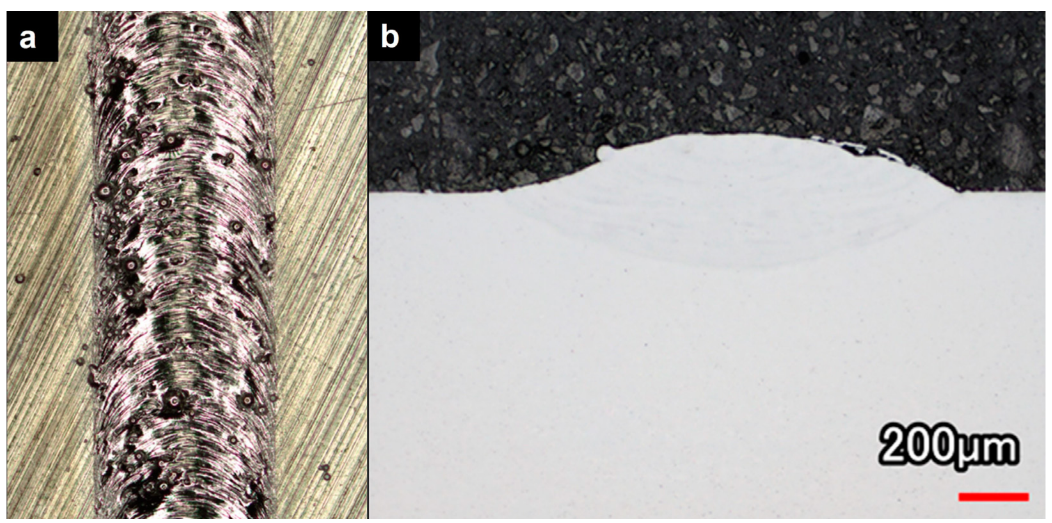
- Addison Rayner, Dalhousie University, PDF



DED single track of Ti-55511: (a) as-deposited top view and (b) polished cross-section. (Subproject 1.1.2 | Rayner, Addison J., et al. "Investigation of Deposition Parameters for Near-Beta Alloy Ti-55511 Fabricated by Directed Energy Deposition." Journal of Manufacturing and Materials Processing 8.2 (2024): 72.)

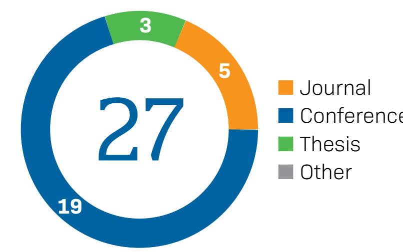
RESEARCH OUTCOMES

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

PROGRESS

The objective of this subproject was to explore AM options for tool steels other than H13. At Université Laval, research efforts led to impactful results in the production and characterization of near-spherical ferrous powders via water atomization, with a focus on A8 and S7 grades, intended for PBF and DED processes. Concurrently, researchers at the University of Alberta concentrated on characterizing 17-4 precipitation-hardened stainless steel. As an ancillary project targeting applications in energy and mining sectors, the same Alberta team conducted microstructure analysis of Ni-WC metal matrix composites deposited using PTA-DED employing convolutional neural networks. Both research threads concluded in 2023, with final publications currently under review.

RESEARCH DISSEMINATION
(to date)



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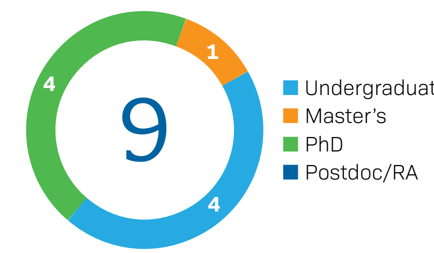
(member and collaborator)



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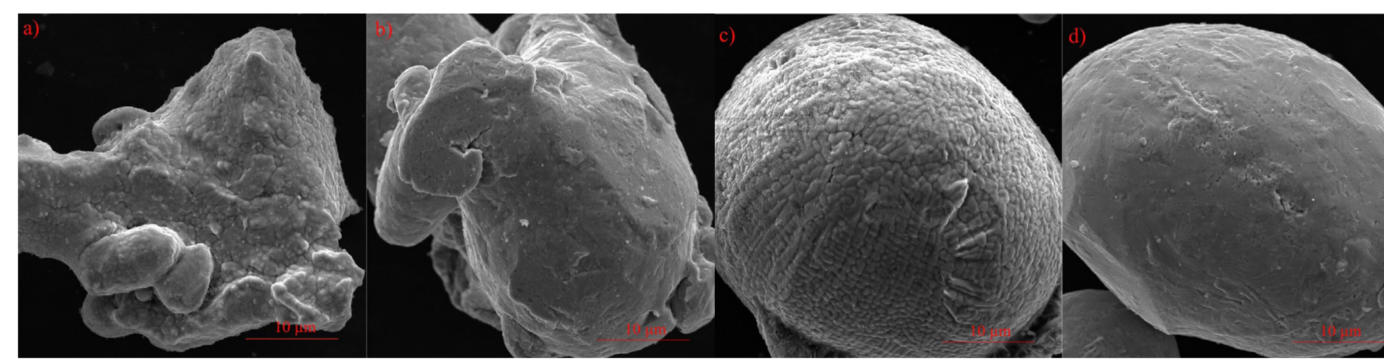
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Carl Blais, Université Laval
- Hani Henein, University of Alberta

HIGHLY QUALIFIED PERSONNEL

- Denis Mutel, Université Laval, PhD
- William Chaîné, Université Laval, MASc
- Anne McDonald, University of Alberta, URA
- Dylan Rose, University of Alberta, PhD (Collaborator)
- Nasim Navid Moghadam, University of Alberta, PhD
- Swalihah Noorani, University of Alberta, URA
- Yume Bhutia, University of Alberta, URA (Collaborator)
- Jolene Borrelli, University of Alberta, URA (Collaborator)
- Justin Plante, Université Laval, PhD (Collaborator)



SEM images of particle surface of (a) and (c) as-atomized powders, and (b) and (d) powders after thermo-mechanical spheroidization treatment. (Subproject 1.1.3 | Mutel, Denis, Simon Gélinas, and Carl Blais. "Rheological characterisation of water atomised tool steel powders developed for laser powder bed fusion by supervised and unsupervised machine learning." Powder Metallurgy 66.3 (2023): 195-207.)

RESEARCH OUTCOMES

TABLE OF CONTENTS

Subproject 1.1.4: Development of Nickel Alloys for LPB-AM

PROGRESS

With the aim of exploring defect-free LPBF processing of difficult to weld nickel-based alloys, this subproject conducted at McGill University has successfully compiled a database of process-microstructure-property models focused on Rene 41 and Rene 77, primarily targeted for aerospace applications. Building on this progress, the investigation was extended to include LPBF processing of intermetallics such as Nicke Aluminide. The research activities were concluded in 2023, and the final articles are currently being prepared for publication.

RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Mathieu Brochu, McGill University

HIGHLY QUALIFIED PERSONNEL

- Sila Atabay, McGill University, PhD
- Kevin Lee, McGill University, PhD
- Anh Tran, McGill University, Co-op

RESEARCH DISSEMINATION
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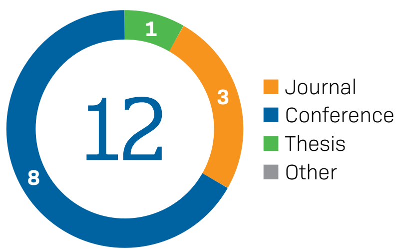
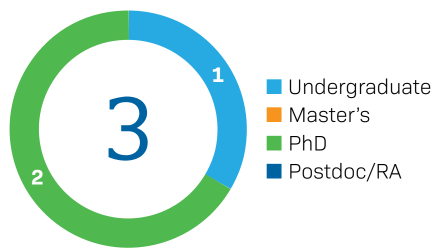


HQP PROFILE*
(member and collaborator)



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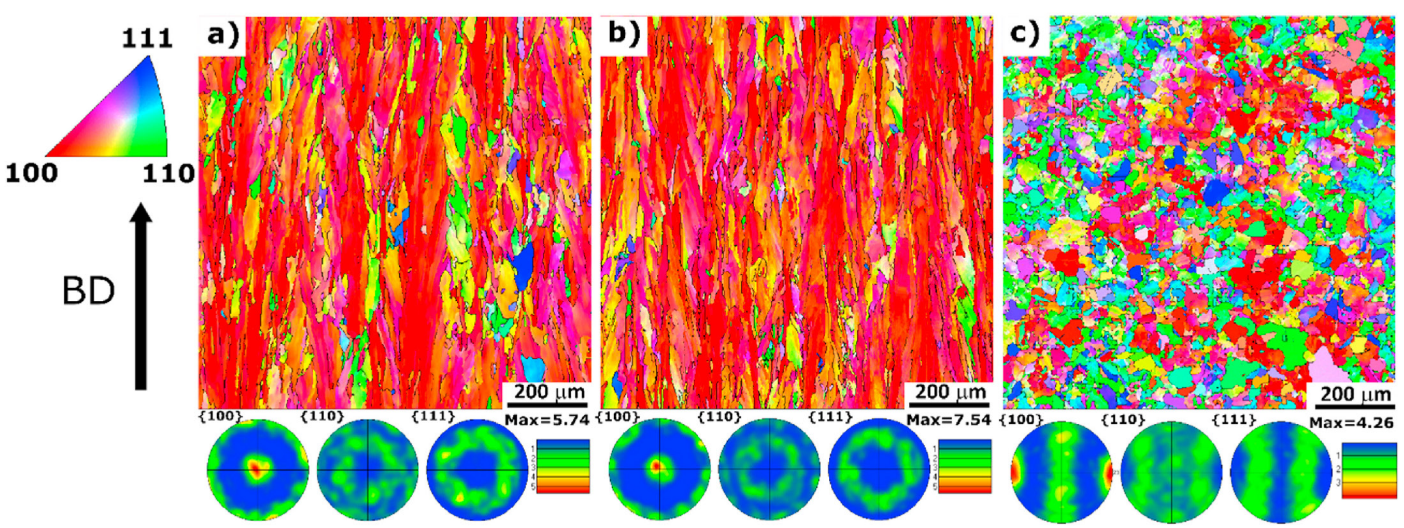


IPF orientation maps and the corresponding pole figures for Rene 41 alloy in (a) as-built, (b) and (c) heat treated conditions. (Subproject 1.1.4 | Atabay, Sila Ece, et al. "Effect of heat treatment on the microstructure and elevated temperature tensile properties of Rene 41 alloy produced by laser powder bed fusion." Journal of Alloys and Compounds 858 (2021): 157645.)

RESEARCH OUTCOMES

Subproject 1.1.5: Development of Refractory Metals for LPB-AM

PROGRESS

This subproject, concluded in 2024, focused on investigating the LPBF processing of pure molybdenum for potential applications in aerospace engines as an alternative to aluminide systems. The research team at McGill University initially delved into fundamental studies concerning rapid solidification and phase development of this material. Subsequently, mechanical and oxidation properties at elevated temperatures were characterized. Building upon successful outcomes, the scope of the research was expanded to include the investigation into LPBF of titanium-zirconium-molybdenum (TZM) exoskeleton with copper infiltration for fabrication of composite heat sinks.

RESEARCHERS

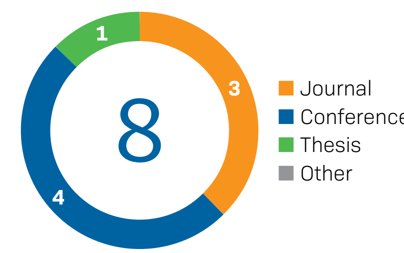
PRINCIPAL INVESTIGATOR(S)

- Mathieu Brochu, McGill University

HIGHLY QUALIFIED PERSONNEL

- Tejas Ramakrishnan, McGill University, PhD

RESEARCH DISSEMINATION
(to date)



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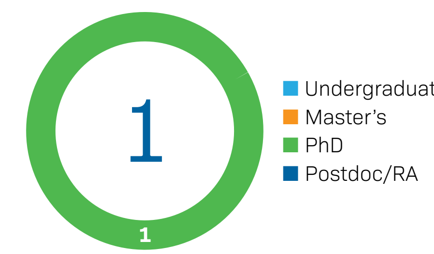
(member and collaborator)



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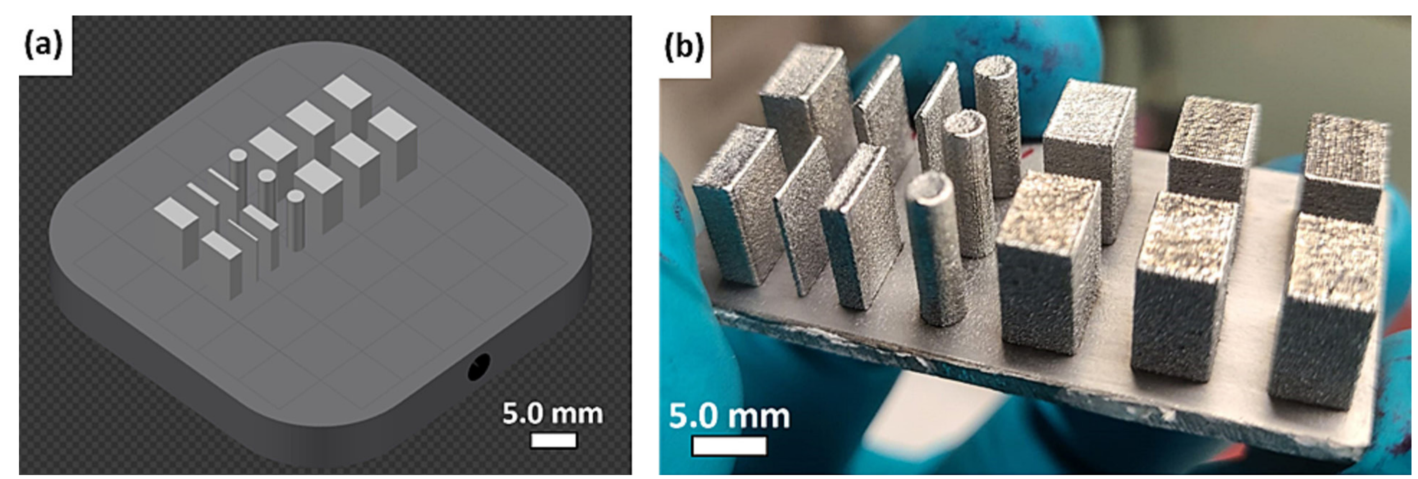


Test samples manufactured using Mo under Ar-N2 mixture build atmosphere. (Subproject 1.1.5 | Ramakrishnan, Tejas, Sunyong Kwon, and Mathieu Brochu. "Laser powder bed fusion of molybdenum under various ArN2 mixture build atmospheres." International Journal of Refractory Metals and Hard Materials 119 (2024): 106556.)

RESEARCH OUTCOMES

Project 1.2: AM Processing of Multi-Material Systems

DESCRIPTION

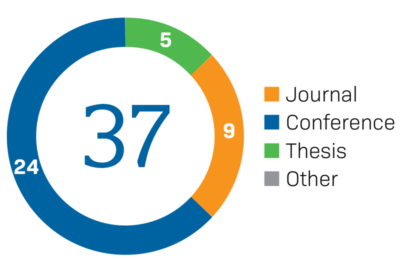
Everyday composite materials are becoming lighter and stronger due to stringent industry standards, such as CAFÉ 2025. As a result, lightweight, high strength composite structures are being used in many scenarios, ranging from small-scale biomedical industries to large-scale aerospace and tooling sectors. 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.

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

PROGRESS

Concluded in 2023 at the University of Toronto, this subproject aimed at developing and optimizing the microstructure of filler materials and their corresponding binder materials for AM of novel composites. The research involved testing and characterizing a diverse range of filler-binder-additive combinations, including graphene, PVA, copper, intrinsically conductive polymers, MXene, etc. Additionally, the team successfully developed a prototype of a robust binder jetting printer. Expanding the research scope, the team ventured into designing origami-inspired tessellated materials and tunable energy absorption through graded lattice structures.

RESEARCH DISSEMINATION
(to date)



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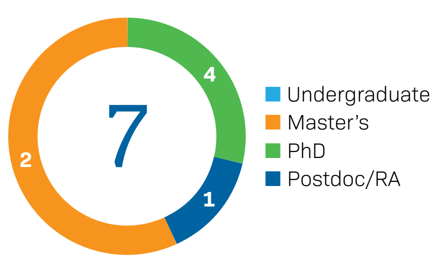
(member and collaborator)



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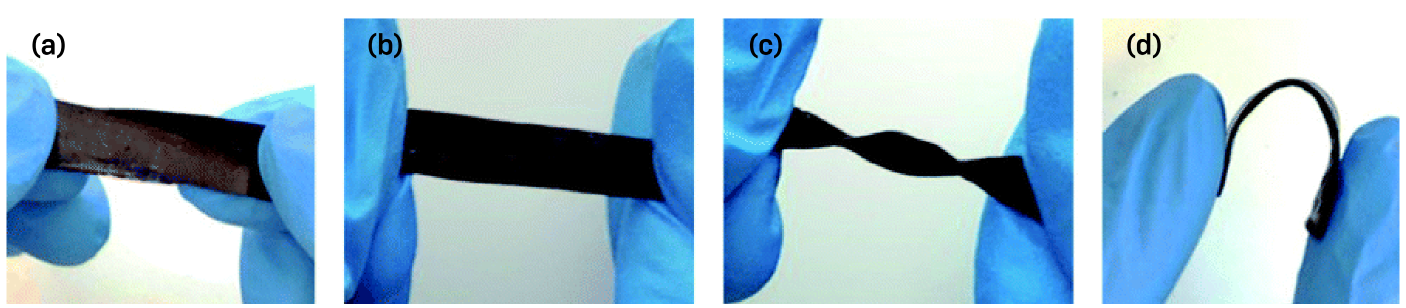
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Hani Naguib, University of Toronto

HIGHLY QUALIFIED PERSONNEL

- Anastasia Wickeler, University of Toronto, PhD
- Xuechen Shen, University of Toronto, MASc
- Tylor Morrison, University of Toronto, MASc (Collaborator)
- Kyra Mclellan, University of Toronto, MASc
- Terek Li, University of Toronto, MASc (Collaborator)
- Andrew Jo, University of Toronto, PhD
- Yu-Chen Sun, University of Toronto, PDF



(a) A binder jet printed MXene composite sensor (b) stretched by hand to ~ 50% strain, (c) twisted, and (d) bent with a radius curvature of 0.46 cm. (Subproject 1.2.1 | Li, Terek, et al. "A binder jet 3D printed MXene composite for strain sensing and energy storage application." Nanoscale Advances 4.3 (2022): 916-925.)

RESEARCH OUTCOMES

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

PROGRESS

Concluded in 2022 at Dalhousie University, this subproject focused on conducting fundamental studies to explore the properties of H13 tool steel and OFHC Cu alloys, optimizing process parameters for LDED processing of these alloys, and conducting thermal and mechanical analyses of the single-material and graded structures. The study demonstrated the successful manufacturing of functionally graded H13/Cu composites using LDED, showcasing it as an enhanced process.

RESEARCHERS

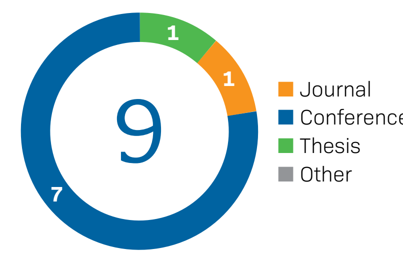
PRINCIPAL INVESTIGATOR(S)

- Kevin Plucknett, Dalhousie University

HIGHLY QUALIFIED PERSONNEL

- Owen Craig, Dalhousie University, MASc | PhD
- Riley Roache, Dalhousie University, Co-op

RESEARCH DISSEMINATION
(to date)



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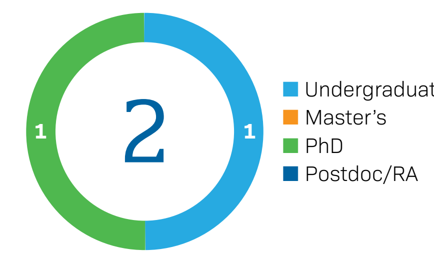

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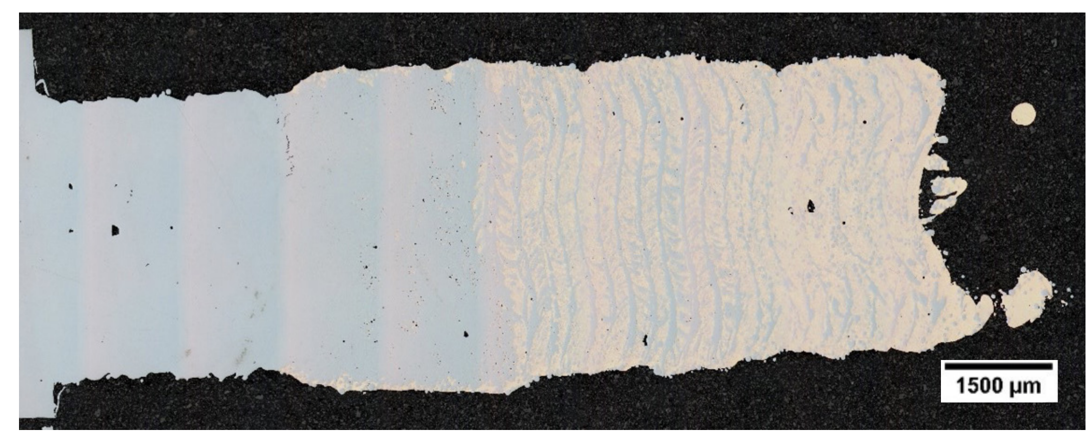


An H13-Cu FGM sample manufactured using LDED. (Subproject 1.2.2 | Craig, Owen. "MATERIAL CHARACTERIZATION OF DIRECTED ENERGY DEPOSITION OF H13 TOOL STEEL AND FUNCTIONALLY GRADED H13-COPPER." (2022).)

RESEARCH OUTCOMES

TABLE OF CONTENTS

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.

Subproject 1.3.1: Recyclability of Powder Feedstocks for LPB-AM

PROGRESS

The objective of this subproject was to investigate the printing environment and characterize the impact of recycling unfused particles in consecutive builds. Initially launched at McGill University, this subproject contributed to a deeper understanding of the relationship between cellulosic fiber filters and moisture/oxygen contents in LPBF process. Subsequently continued at the University of Toronto, the research further elucidated the effects of using recycled maraging steel powder on the microstructural and mechanical properties of parts processed via LPBF. The research scope was later broadened at UofT to explore the utilization of developing recyclable fillers such as MXene in binder jetting AM and precipitation printing technologies establishing a connection to subproject 1.2.1.

RESEARCHERS

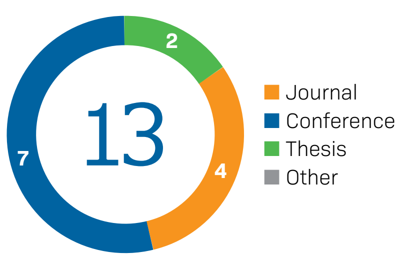
PRINCIPAL INVESTIGATOR(S)

- Mathieu Brochu, McGill University
- Gisele Azimi, University of Toronto
- Hani Naguib, University of Toronto

HIGHLY QUALIFIED PERSONNEL

- Aniruddha Das, McGill University, MASc
- Hao Kun Sun, University of Toronto, MASc
- Yu-Chen Sun, University of Toronto, PDF
- Rui Yang, University of Toronto, MASc

RESEARCH DISSEMINATION
(to date)



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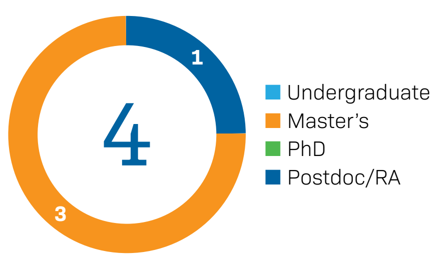
(member and collaborator)



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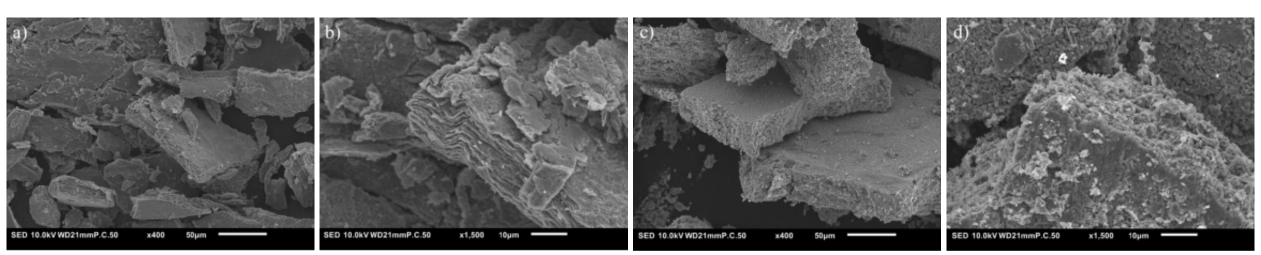


(a, c) As-printed MXene nanoparticles; (b, d) MXene nanoparticles after 6 months aging showing the surface deterioration as a result of oxides build-up. (Subproject 1.3.1 | Sun, Yu Chen, et al. "Functionalization, Oxidation, and Recyclability Study of 3D Printable MXene." The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada)

RESEARCH OUTCOMES

Subproject 1.3.2: Plasma Spheroidization of Low Cost Powders

PROGRESS

This subproject, conducted at Université Laval, aims to convert irregular-shaped particles into spherical ones suitable for AM using the inductively-coupled plasma spheroidization as a cost reduction strategy. Since 2022, the team has achieved significant advancements by enhancing the characteristics of agglomerated 316 L particles through milling and optimizing laser parameters for both virgin and deagglomerated particles to facilitate property comparison. Additionally, a secondary objective of the project is to explore the impact of recycling Ti64 powder on the mechanical properties of parts produced via LPBF. The team has recycled the powder up to 20 times, and characterized its flow/morphology properties throughout the recycling process. Due to changes in the timeline for equipment installation, the start of this subproject was delayed. Therefore, its completion is anticipated after the conclusion of the Network.

RESEARCHERS

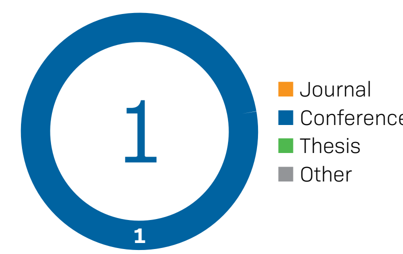
PRINCIPAL INVESTIGATOR(S)

- Carl Blais, Université Lavaly

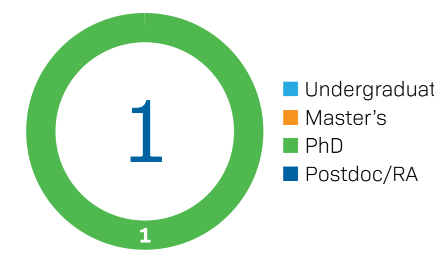
HIGHLY QUALIFIED PERSONNEL

- Tina Mohamadhassan, Université Laval, PhD

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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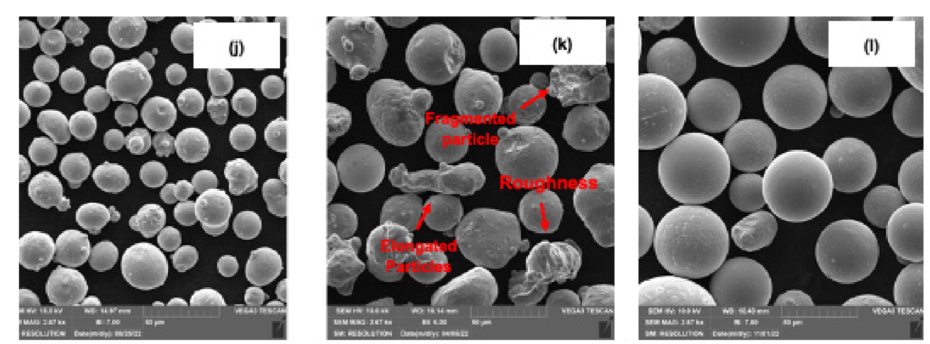


SEM micrographs showing the morphology of SS 316L powder in the (a) virgin, (b) used, and (c) spheroidized states. (Subproject 1.3.2)

RESEARCH OUTCOMES

Subproject 1.3.3: Cost-effective Steel Feedstock for AM

PROGRESS

In this subproject, research teams from the University of Alberta, Université Laval, and Dalhousie University collaborated to assess the viability of processing alloyed and tool steel powders made by low-cost atomization techniques using various AM technologies. The University of Alberta team designed and constructed an electrostatically assisted (EA) atomization technology for this purpose, followed by a fundamental investigation into atomization phenomena within the Rayleigh Regime. Concurrently, the team at Université Laval fine-tuned the binder jetting process for water-atomized D2 and AISI 4340 powders. Meanwhile, researchers at Dalhousie University concentrated on process development for binder jetting of water-atomized 42CrMo4 and AISI 5120 Chromium steel powders leading to development of master alloys to increase densification of binder jet printed steel components. In parallel, the project also pursued the LDED processing of water-atomized DP600.

RESEARCHERS

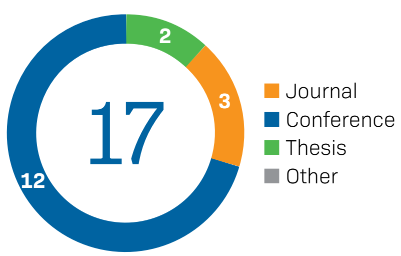
PRINCIPAL INVESTIGATOR(S)

- Carl Blais, Université Laval
- Paul Bishop, Dalhousie University
- Hani Henein, University of Alberta

HIGHLY QUALIFIED PERSONNEL

- Ryan Ley, Dalhousie University, PhD
- Bilal Bharadia, University of Alberta, MASc
- William Bouchard, Université Laval, MASc
- Addison Rayner, Dalhousie University, PDF

RESEARCH DISSEMINATION
(to date)



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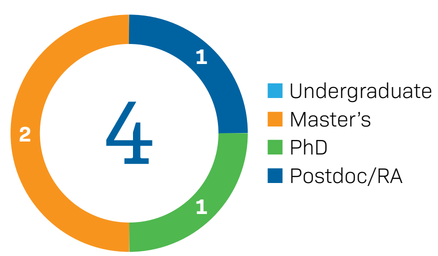

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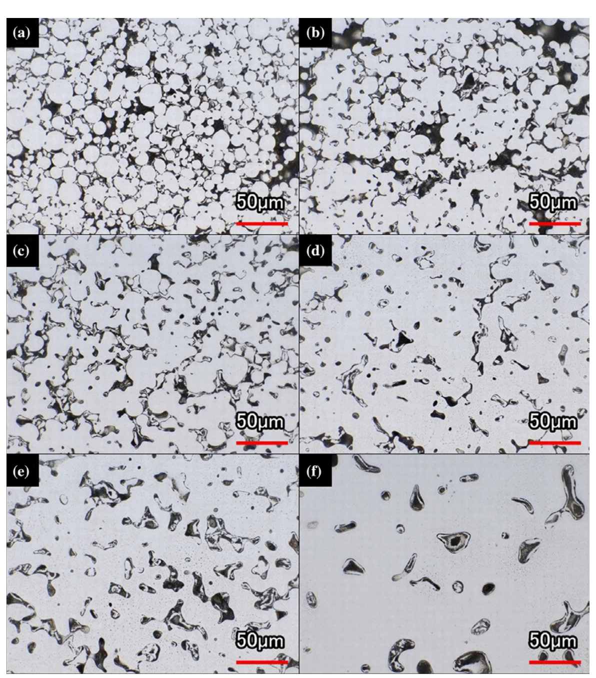
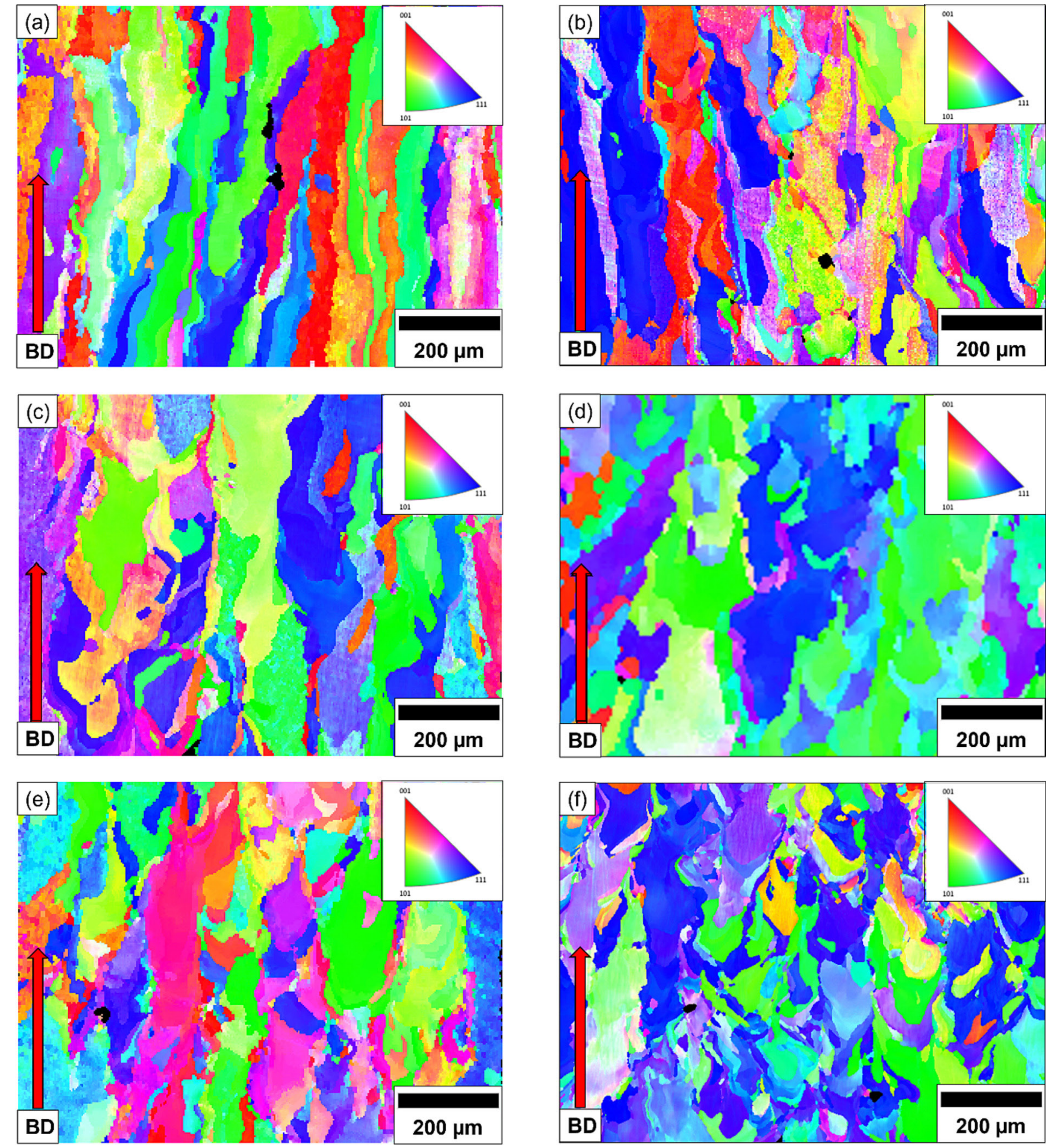


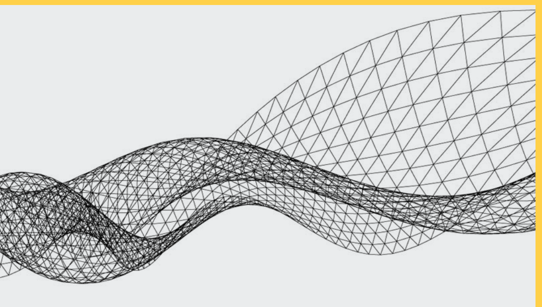
Microstructure of binder jet printed 5120 steel specimens sintered at (a) 1000 °C, (b) 1200 °C, (c) 1300 °C, (d) 1400 °C, (e) 1450 °C, and (f) 1475 °C under high vacuum for 1 hr. (Subproject 1.3.3 | Rayner, A. J., et al. "Binder Jet Printing AISI 5120 Chromium Steel Powder." Metallurgical and Materials Transactions A 54.4 (2023): 1271-1285.)

RESEARCH OUTCOMES



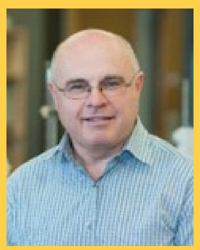
IPF maps from EBSD analysis showing the influence of the N2 gas on the grain structure in LPBF processing of molybdenum: (a) MoAr, (b) Mo10B, (c) Mo60N, and (d) Mo95N, and (f) Mo—N sample. (Subproject 1.1.5 | Ramakrishnan, Tejas, Sunyong Kwon, and Mathieu Brochu. "Laser powder bed fusion of molybdenum under various ArN2 mixture build atmospheres." International Journal of Refractory Metals and Hard Materials 119 (2024): 106556.)

Research Progress



THEME 2

Advanced Process Modeling and Coupled Component/Process Design



Steven Cockcroft
PhD, PEng
THEME 2 LEADER

University of British Columbia
Dept. of Materials Engineering

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

Project 2.1: Multi-scale Modeling of AM

DESCRIPTION

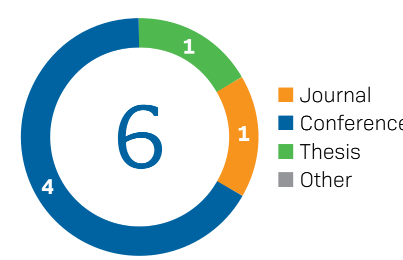
Currently, the energy transport characteristics of the beam/feedstock interaction in powder-bed based AM processes are not well understood. Physics-based process models are critically needed to describe the energy input profile and powder bed/substrate thermal diffusion and advection (when liquid is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

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

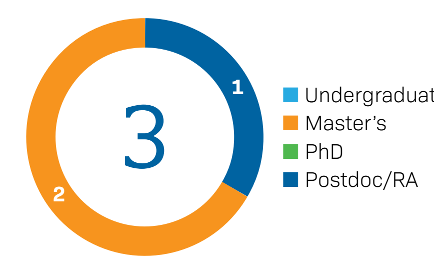
PROGRESS

This subproject was undertaken by two teams at the University of British Columbia and University of Waterloo. The UBC team designed experiments aimed at investigating the impact of support structure design on component formation, in collaboration with Nanyang Technological University. The experiments were followed by finite element modeling of the process with focus on quantification of heat transport. The Waterloo team focused on developing models describing the beam/powder/melt pool interaction in LPBF process by leveraging data collected by a thermocouple-embedded build plate designed by the team, coupled with inverse heat conduction analysis.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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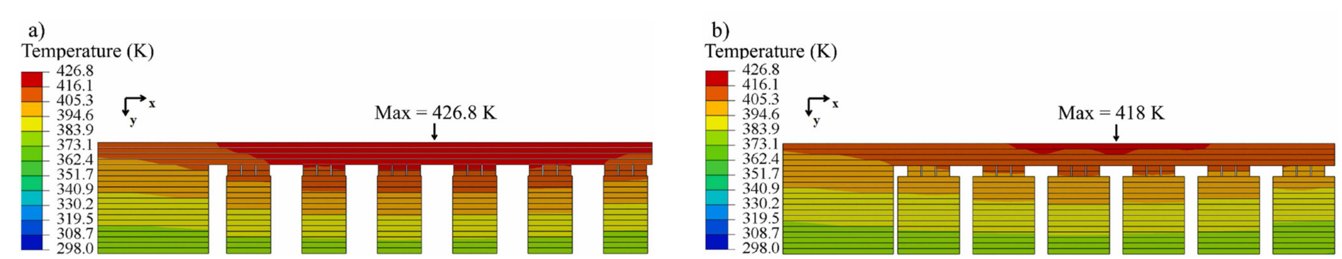
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Steve Cockcroft, The University of British Columbia
- Mary Wells, University of Waterloo
- Daan Maijer, The University of British Columbia

HIGHLY QUALIFIED PERSONNEL

- Arman Khobzi, The University of British Columbia, MASc
- Emre Ogeturk, University of Waterloo, MASc
- Farzaneh Farhang-Mehr, The University of British Columbia, RA



End of build temperature contours for the produced cantilevered plate using support structures with a total support base area of (a) 240 mm2, (b) 336 mm2. (Subproject 2.1.1 | Khobzi, Arman, et al. "The role of block-type support structure design on the thermal field and deformation in components fabricated by Laser Powder Bed Fusion." Additive Manufacturing 51 (2022): 102644.)

RESEARCH OUTCOMES

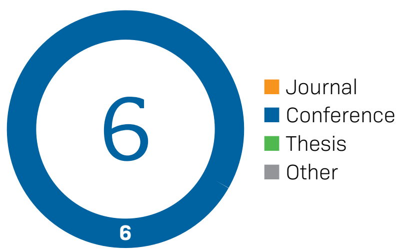
TABLE OF CONTENTS

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

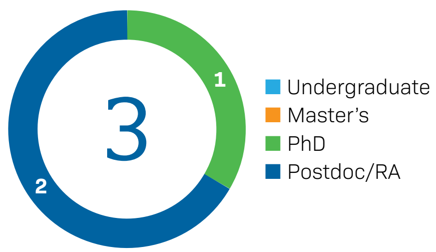
PROGRESS

This subproject was undertaken by two teams at the University of British Columbia and University of Waterloo. Following the development of preliminary thermal-fluid flow models of the melt pool dynamics and powder consolidation in EB-PBF process, the UBC portion of the project was canceled due to unforeseen circumstances. The team at Waterloo proposed and tested a new methodology to study layer wise microstructure in metallic materials during LPBF process. This subproject was completed in 2023.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Steve Cockcroft, The University of British Columbia
- Mary Wells, University of Waterloo

HIGHLY QUALIFIED PERSONNEL

- Eiko Nishimura, The University of British Columbia, PhD
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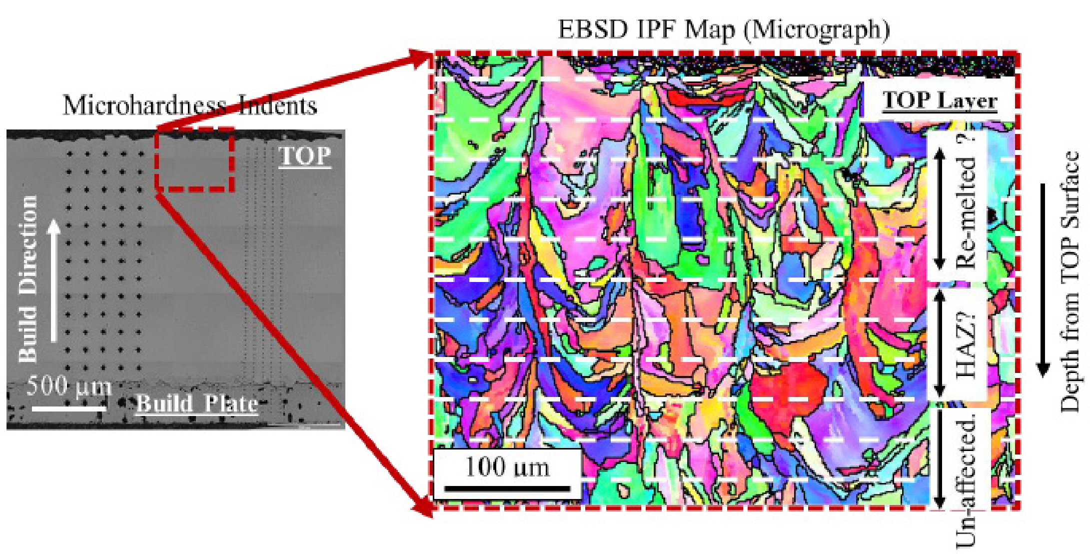
- Paresh Prakash, University of Waterloo, PDF



View of microhardness and layer wise microstructure characterization of 316 L stainless steel samples manufactured using a pulsed LPBF system. (Sub-project 2.1.2 | Prakash, Paresh, et al. "Microstructure and Microhardness Variation with Build Height in Laser Powder Bed Fusion Fabricated 316L Stainless Steel." The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada)

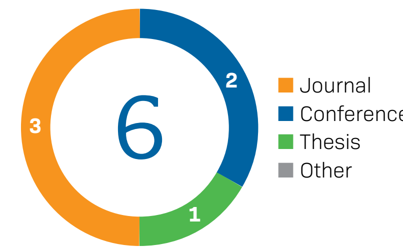
RESEARCH OUTCOMES

Subproject 2.1.3: Macro-scale Thermal Field Evolution

PROGRESS

This Subproject, completed in 2020 at McGill University, developed an efficient 3D model to simulate thermal field evolution at the part scale in an LPBF system as well as a customized mesh refinement strategy. The model was tested using 316 L and IN718 materials.

RESEARCH DISSEMINATION
(to date)



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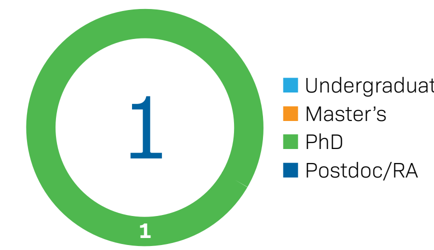
(member and collaborator)



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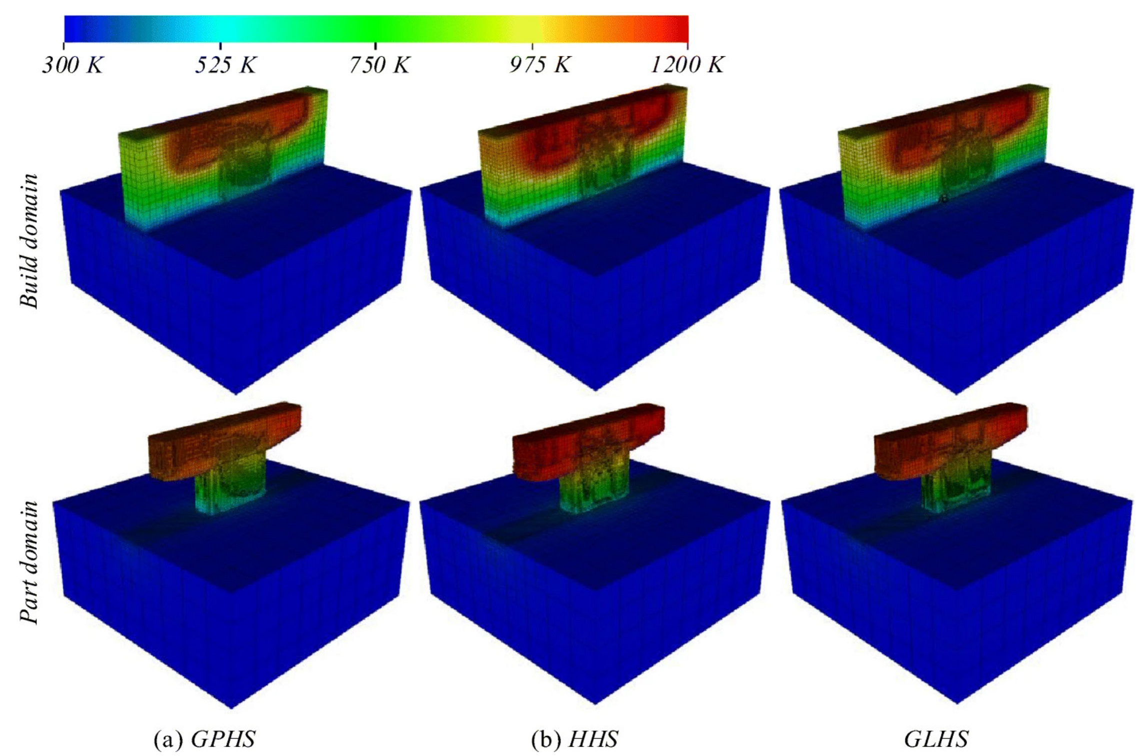
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Yaoyao Fiona Zhao, McGill University

HIGHLY QUALIFIED PERSONNEL

- Zhibo Luo, McGill University, PhD



Temperature distribution at the end of the LPBF building process after cooling for 1 s for (a) Gaussian point heat source, (b) hybrid heat source, and (c) Gaussian line heat source. (Subproject 2.1.3 | Luo, Zhibo, and Yaoyao Zhao. "Numerical simulation of part-level temperature fields during selective laser melting of stainless steel 316L." The International Journal of Advanced Manufacturing Technology 104 (2019): 1615-1635.)

RESEARCH OUTCOMES

TABLE OF CONTENTS

Subproject 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

Completed in 2024 at the University of British Columbia, this subproject aimed to shed light on the complex physics of electron beam-based PBF technology. It involved developing and validating two models for EB-PBF process: a macro-scale coupled thermal-stress model and a meso-scale coupled thermal-stress model. Additionally, the project focused on characterizing and modeling the radiation within the EB-PBF build chamber. To accomplish this, the team designed and built a custom, in-situ data acquisition system capable of operating in a vacuum environment.

RESEARCHERS

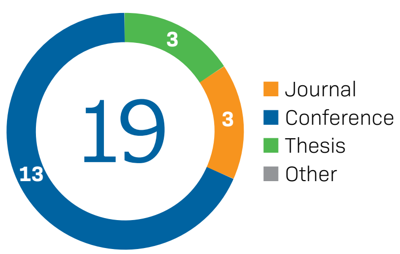
PRINCIPAL INVESTIGATOR(S)

- Steve Cockcroft, The University of British Columbia
- Daan Maijer, The University of British Columbia

HIGHLY QUALIFIED PERSONNEL

- Pegah Pourabdollah, The University of British Columbia, PhD
- Farzaneh Farhang-Mehr, The University of British Columbia, RA
- Asmita Chakarborty, The University of British Columbia, MASc
- Farhad Rahimi, The University of British Columbia, MASc

RESEARCH DISSEMINATION
(to date)



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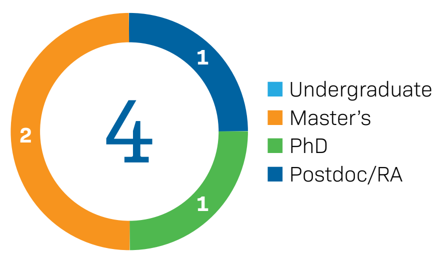
(member and collaborator)



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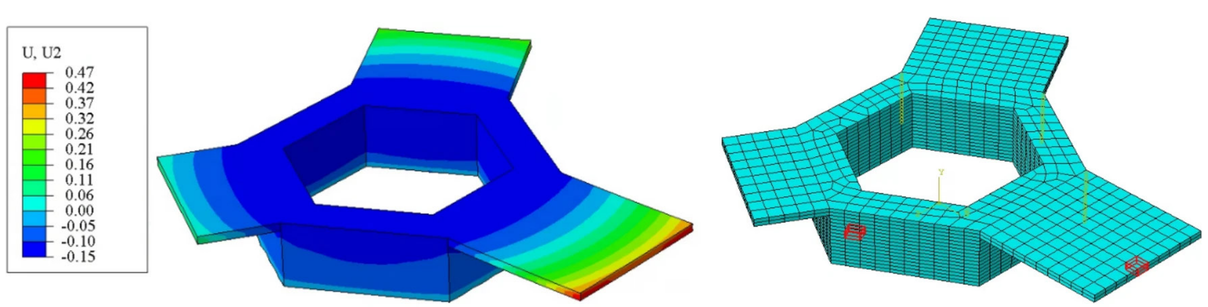


The total displacement distribution following removing the EB-PBF built component from the start plate as simulated at part-scale using a new variant of the inherent strain method. (Subproject 2.1.4(i) | Pourabdollah, Pegah, et al. "A new variant of the inherent strain method for the prediction of distortion in powder bed fusion additive manufacturing processes." The International Journal of Advanced Manufacturing Technology (2024): 1-20.)

RESEARCH OUTCOMES

Subproject 2.1.4 (ii): Property and Design Assessment of a 3D-Printed Metallic Implant

PROGRESS

This subproject began in the fifth year of the Network as an additional research endeavor aimed at exploring the potential use of 3D-printed metallic surgical instruments and implants for treating pediatric patients. In the current reporting period, the team at the University of British Columbia has finished conducting a literature review and is currently in the process of finalizing the design of a test implant based on sample CT scans. Manufacturing and geometric tolerance analyses are expected to be completed after the Network's end date.

RESEARCHERS

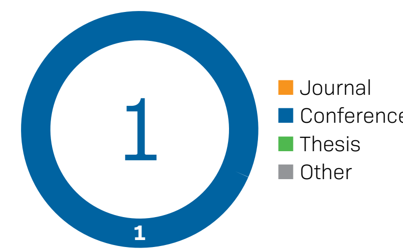
PRINCIPAL INVESTIGATOR(S)

- Steve Cockcroft, The University of British Columbia
- Daan Maijer, The University of British Columbia

HIGHLY QUALIFIED PERSONNEL

- Anushree Shah, The University of British Columbia, MASc

RESEARCH DISSEMINATION
(to date)



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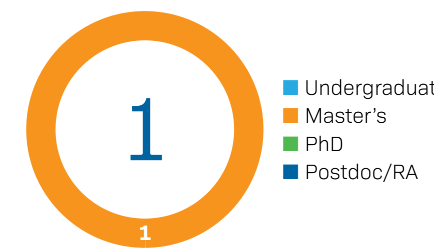

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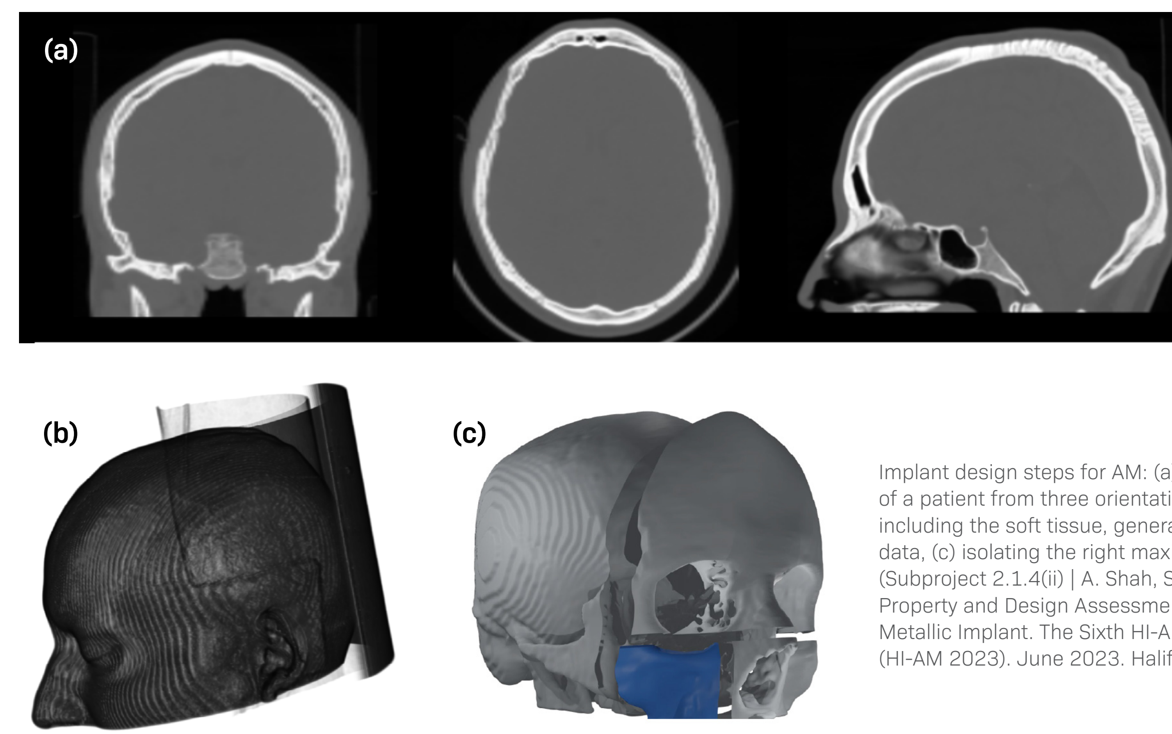


Implant design steps for AM: (a) Craniofacial CT scan of a patient from three orientations, (b) 3D model, including the soft tissue, generated from the CT data, (c) isolating the right maxilla in BlenderTM. (Subproject 2.1.4(ii) | A. Shah, S. Cockcroft, D. Maijer. Property and Design Assessment of a 3D-Printed Metallic Implant. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.)

RESEARCH OUTCOMES

Subproject 2.1.5: Microstructural Modeling and Experimental Validation

PROGRESS

The aim of this subproject was to explore the relationship between microstructure, properties, and the AM processes for specific aluminum alloys investigated in subproject 1.1.1, including Al-Cu, Al-Si, and Al-Ce alloys. In pursuit of this goal, the team at the University of Alberta developed solidification continuous cooling transformation (CCT) diagrams for different binary Al alloys and conducted numerical simulations to model eutectic growth in Al-33wt%Cu alloy. The project was completed in 2023.

RESEARCHERS

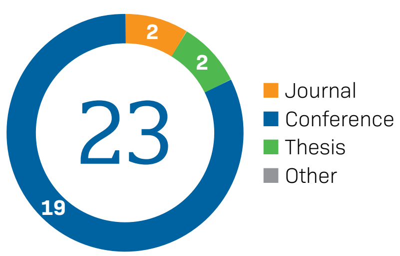
PRINCIPAL INVESTIGATOR(S)

- Hani Henein, University of Alberta

HIGHLY QUALIFIED PERSONNEL

- Quentin Champdoizeau, University of Alberta, MASc
- Daniela Diaz, University of Alberta, MASc
- Jonas Valloton, University of Alberta, RA
- Anqi Shao, University of Alberta, MASc

RESEARCH DISSEMINATION
(to date)



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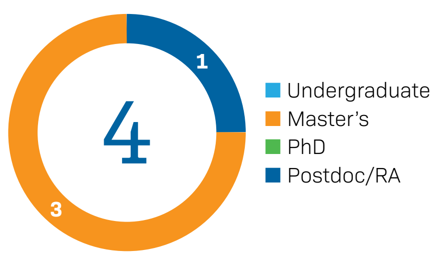
(member and collaborator)



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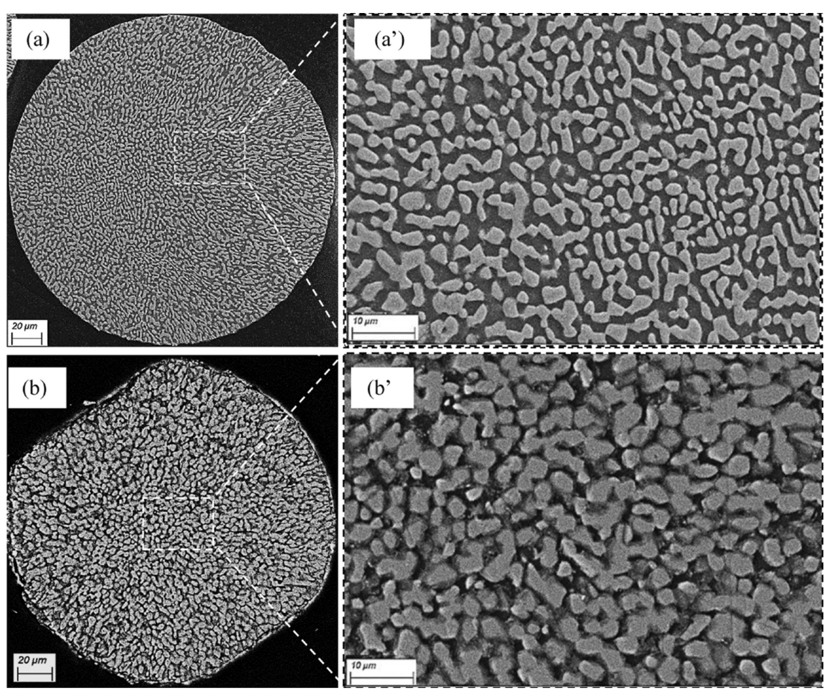


SEM (BSD) of heat-treated Al-Cu powder of near eutectic composition, after (a-a') 0% plastic deformation, (b-b') 30% plastic deformation. (Subproject 2.1.5 | Bogno, A. A., et al. "Tailored solidification microstructures for innovative use of high-density materials in lightweight products." Journal of Alloys and Metallurgical Systems (2024): 100061.)

RESEARCH OUTCOMES

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 is planned to be developed and deployed for process predictive and process feedback control. Fast process predictive thermo-mechanical models for stress field simulation have the potential to be used in digital topology design optimization and in predictive control approaches.

Subproject 2.2.1: Fast Process Thermal-Field Simulation

PROGRESS

This subproject was concluded in 2020. The research team at the University of British Columbia developed fast-to-run (FTR) simulations and reduced-ordered macro-scale thermal models capable of high-speed process predictions, building upon and complementing the findings from project 2.1.

RESEARCHERS

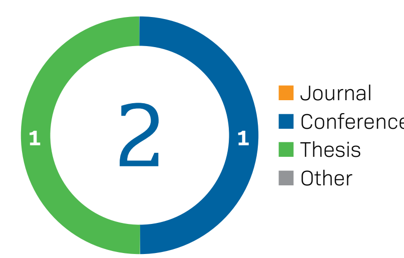
PRINCIPAL INVESTIGATOR(S)

- Daan Maijer, The University of British Columbia

HIGHLY QUALIFIED PERSONNEL

- Meet Uphadhyay, The University of British Columbia, MASc (Collaborator)

RESEARCH DISSEMINATION
(to date)



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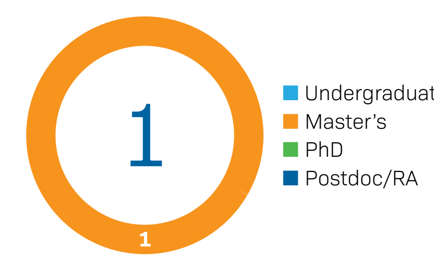

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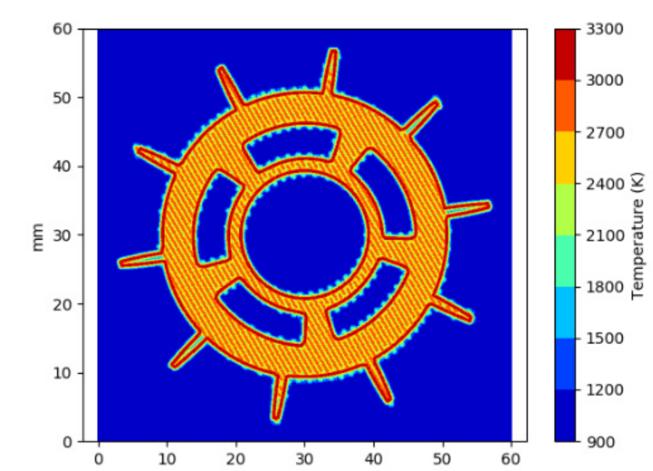


Maximum temperatures for a simulated centrifugal impeller at layer z = 4 mm using the developed FTR model. (Subproject 2.2.1 | Upadhyay, Meet. Fast to run model for thermal fields during metal additive manufacturing simulations. Diss. University of British Columbia, 2020.)

RESEARCH OUTCOMES

Subproject 2.2.2: Fast Process Stress-Field Simulation

PROGRESS

The research team at the University of Waterloo developed and verified an effective heat source model of the LPBF process. This model was then integrated into macro- and part-scale finite element models, significantly expediting simulation time for accurate predictions of residual stress and deformation. To validate these models, a comprehensive experimental approach was adopted, employing techniques such as optical scanning and X-ray diffraction. The project concluded in 2023, and the team subsequently filed its findings for patent protection.

RESEARCHERS

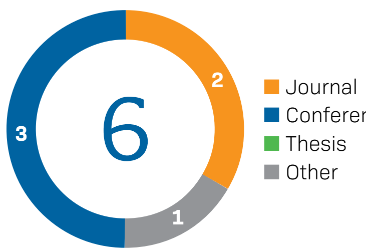
PRINCIPAL INVESTIGATOR(S)

- Ehsan Toyserkani, University of Waterloo

HIGHLY QUALIFIED PERSONNEL

- Shahriar Imani Shahabad, University of Waterloo, PhD | PDF

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
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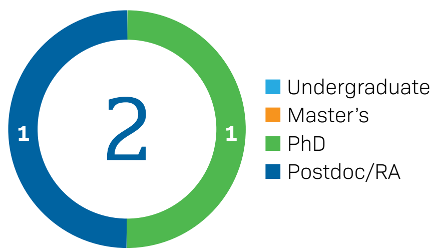

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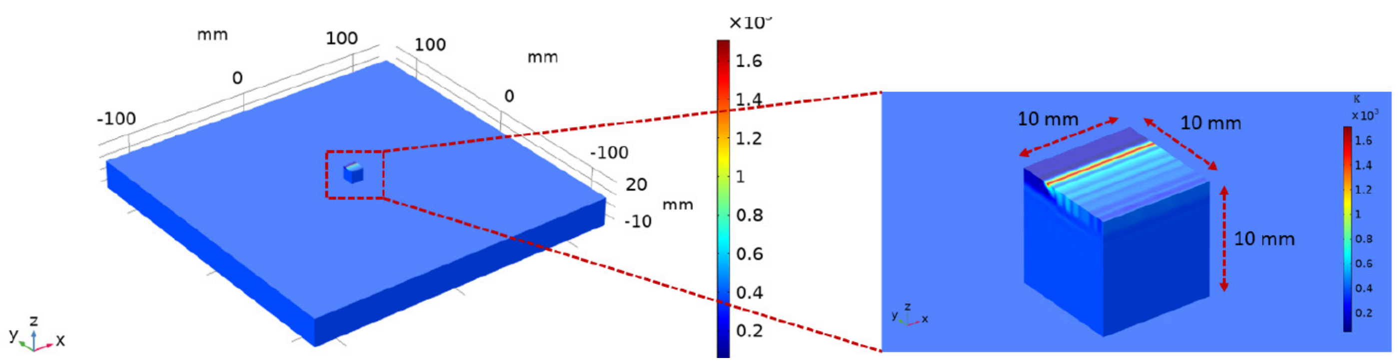


Accelerated thermo-mechanical simulation of a simple geometry using an effective heat source. (Subproject 2.2.2 | Imani Shahabad, Shahriar, et al. "Novel Accelerated Thermo-mechanical LPBF Modelling Using an Effective Heat Source". The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada)

RESEARCH OUTCOMES

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.

Subproject 2.3.1: Pre-processing for Dimensional Control

PROGRESS

In this subproject, the research team at the University of Alberta aimed to advance part build geometry assessment methods. To achieve this goal, the team devised a geometric assessment framework for LPBF process based on the geometric tolerancing and dimensioning (GD&T) standards. The work included creating a novel macro-scale thermo-mechanical model that incorporated GD&T characteristics.

RESEARCHERS

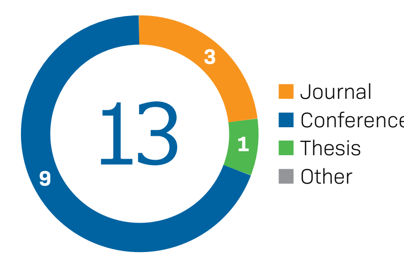
PRINCIPAL INVESTIGATOR(S)

- Ahmed Qureshi, University of Alberta

HIGHLY QUALIFIED PERSONNEL

- Baltej Rupal, University of Alberta, PhD
- Shirin Dehghani, University of Alberta, PDF (Collaborator)
- Shokoufeh Sardarian, University of Alberta, MASc (Collaborator)

RESEARCH DISSEMINATION
(to date)



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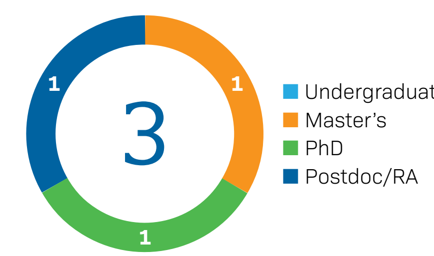

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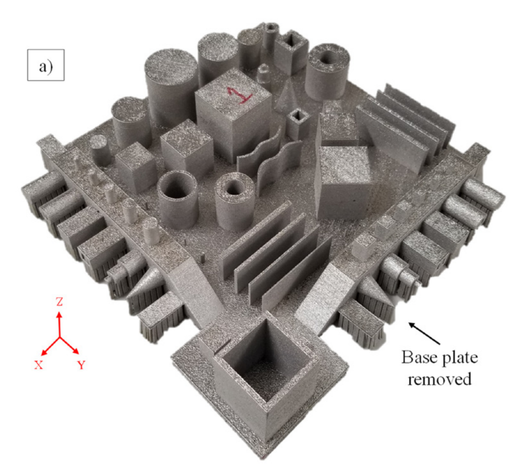


Geometric benchmark test artifacts manufactured to test the developed geometric assessment framework. (Subproject 2.3.1 | Rupal, Baltej Singh, et al. "Tri-Planar Geometric Dimensioning and Tolerancing Characteristics of SS 316L Laser Powder Bed Fusion Process Test Artifacts and Effect of Base Plate Removal." Materials 14.13 (2021): 3575.)

RESEARCH OUTCOMES

Subproject 2.3.2: Lattice Structure Design for AM Processing

PROGRESS

Two research teams from McGill University independently contributed to this subproject. One team focused on studying the mechanical behavior of AM-made lattice materials in the presence of defects. The second team worked on modeling the LPBF constraints and capabilities for lattice structure design. Their efforts led to the development of a new computational predictive tool for capturing the role of geometric and material defects in the response of metallic and soft lattices, as well as a machine learning method for predicting the manufacturability of lattice structures in LPBF and suggesting corrective measures. This subproject was concluded in 2024, with final publications currently in preparation.

RESEARCHERS

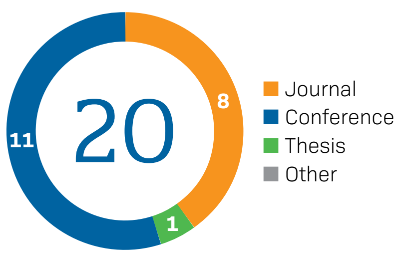
PRINCIPAL INVESTIGATOR(S)

- Damiano Pasini, McGill University
- Yaoyao Fiona Zhao, McGill University

HIGHLY QUALIFIED PERSONNEL

- Asma El Elmi, McGill University, PhD
- Ying Zhang, McGill University, PhD

RESEARCH DISSEMINATION
(to date)



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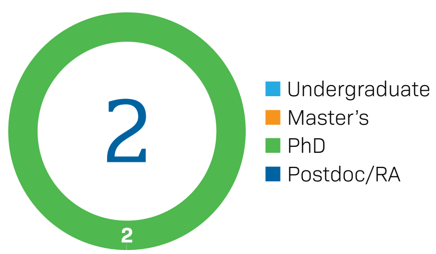

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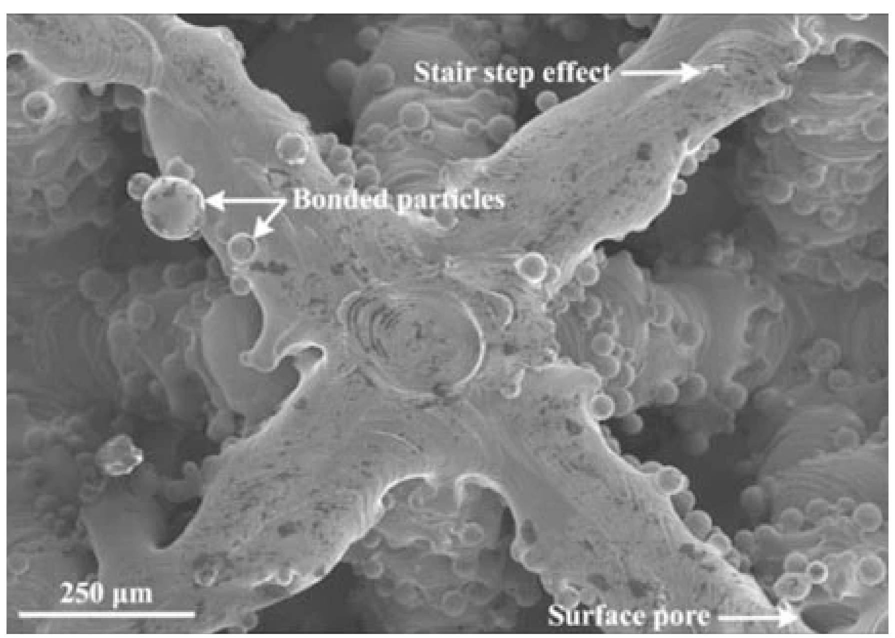


SEM image of a representative region of the manufactured sample showing typical surface defects. (Subproject 2.3.2 | El Elmi, Asma, et al. "Experimental and numerical investigation of selective laser melting–induced defects in Ti–6Al–4V octet truss lattice material: the role of material microstructure and morphological variations." Journal of Materials Research 35.15 (2020): 1900-1912.)

RESEARCH OUTCOMES

Subproject 2.3.3: Mismatch Determination During AM of Thin Structures

PROGRESS

In this subproject, the research team at McGill University explored the processing window for manufacturing of small-scale features and examined the mismatch between the anticipated properties of LPBF-made thin features, as predicted by simulations, and the actual outcomes. The printed microstruts underwent comprehensive mechanical and physical characterization, including fatigue, tensile, and surface morphology analyses.

RESEARCHERS

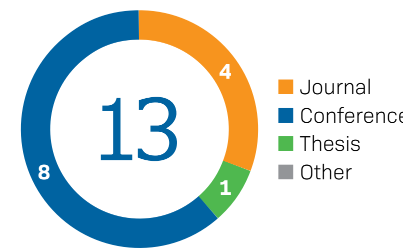
PRINCIPAL INVESTIGATOR(S)

- Mathieu Brochu, McGill University
- Yaoyao Fiona Zhao, McGill University

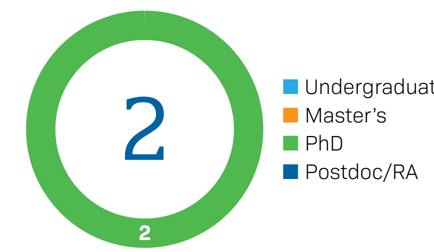
HIGHLY QUALIFIED PERSONNEL

- Abhi Ghosh, McGill University, PhD (Collaborator)
- Muralidharan Kumar, McGill University, PhD

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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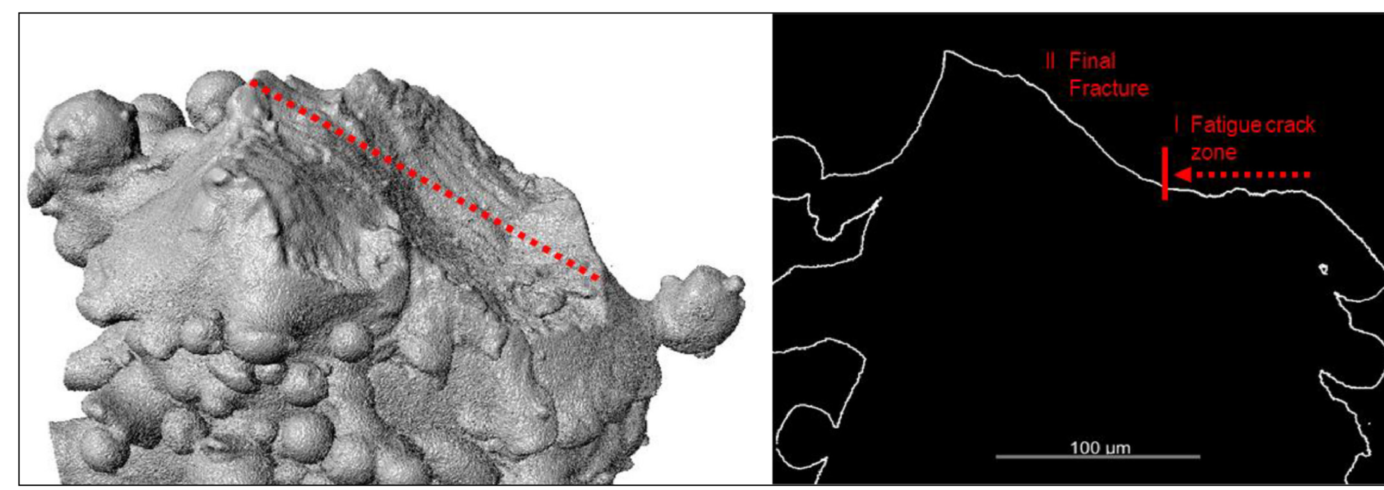

Post-fatigue failure characterization for the LPBF-made thin microstruts subjected to a σmax of 298 MPa. (subproject 2.3.3 | Ghosh, Abhi, et al. "Fatigue behavior of stainless steel 316L microstruts fabricated by laser powder bed fusion." Materialia 26 (2022): 101591.)

RESEARCH OUTCOMES

Research Progress

THEME 3

In-Line Monitoring/Metrology and Intelligent Process Control Strategies

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Insufficient process reliability and repeatability, resulting from random and environmental disturbances, are critical impediments for widespread AM adoption. A key solution to compensate for these disturbances is using closed-loop control systems and algorithms to monitor the process, and to tune actuating signals accordingly. However, implementing this approach is challenging as there are many input physical parameters that govern metal AM processes. Furthermore, the output of the process is 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

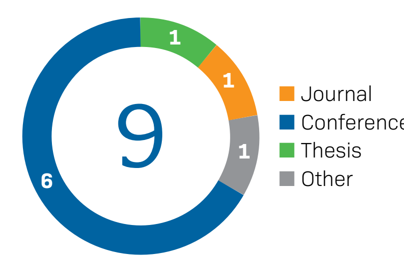
Implementing control algorithms in metal AM systems is challenging due to the high number of parameters involved and narrow temporal opportunity to capture perturbations. This lack of control results in build defects such as porosity. Currently, most quality control measurements are conducted offline, 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.

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

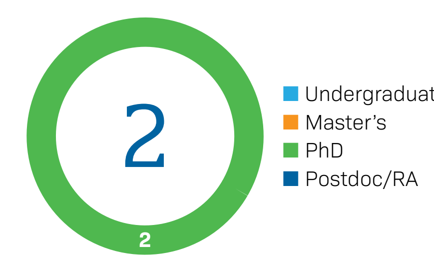
PROGRESS

In this subproject, the research team at the University of Waterloo innovated a sensor monitoring system for capturing and processing both visible and infrared data. This system extracts critical process parameters from laser-material interactions. Additionally, the team has designed a real-time physics-based model, integrated with a controller, to ensure reliable predictive control of thermal material processing. This monitoring system has been patented and a startup company (Retinex - retinex.ca) has been established by the HQP based on the results of this subproject and background IP from the team.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



*Please note that the statistics presented in the HQP Profile charts represent actual individual counts, not full-time equivalents (FTE). There may be instances where an HQP has withdrawn from the program or had only a brief collaboration with the Network.

RESEARCHERS

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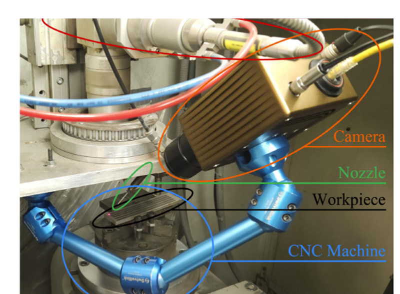


The monitoring system for laser material processing developed at the University of Waterloo. (Subproject 3.1.1 | van Blitterswijk, Richard H., et al. "Adaptive thermal model for real-time peak temperature and cooling rate prediction in laser material processing." Journal of Manufacturing Processes 101 (2023): 1301-1317.)

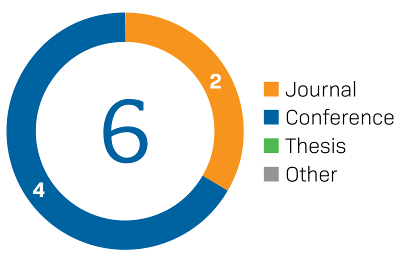
RESEARCH OUTCOMES

Subproject 3.1.2: Development of Continuous and Layer-intermittent Imaging Capabilities for WAAM

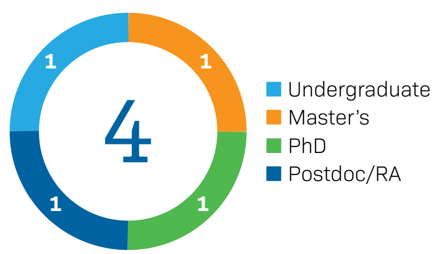
PROGRESS

In this subproject, the research team at the University of Alberta aimed to develop hardware, control, and assessment tools and methods to enable precise layer height control for DED systems, with a specific focus on wire arc and plasma-based AM. The team devised a continuous and layer-intermittent vision monitoring strategy (profiler and infrared camera with CMOS sensor) for controlling material layer height in WAAM, taking into account toolpath considerations and accumulated errors in manufacturing operations. This framework facilitates quasi-real-time error detection during the build process and employs advanced toolpath correction strategies to mitigate these errors effectively.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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RESEARCHERS

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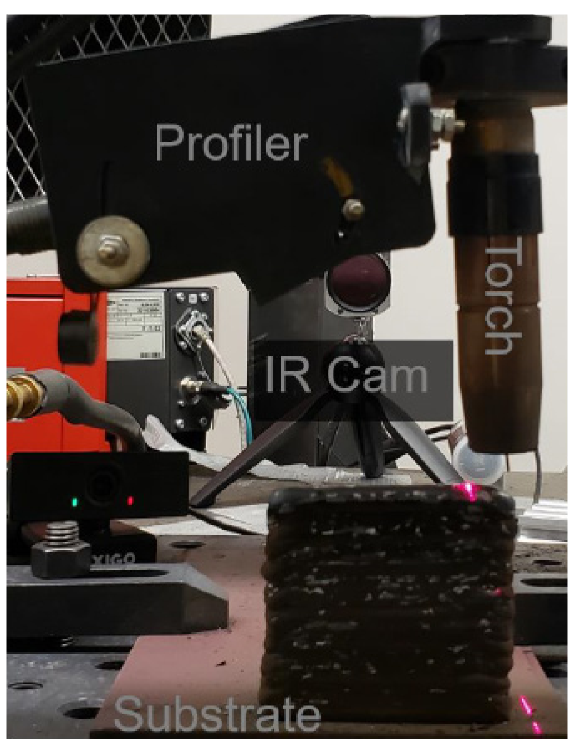

The monitoring system for layer height control developed at the University of Alberta. (Subproject 3.1.2 | Kwak, Yeon Kyu, et al. Policy Gradient Optimization of Bead Geometry in Robotic Wire Arc Additive Manufacturing. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.)

RESEARCH OUTCOMES

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

PROGRESS

In this subproject, completed in 2023, the research team at the University of Waterloo demonstrated the feasibility of utilizing Eddy current inductive sensors as a non-destructive monitoring solution for detecting sub-surface defects and features in parts manufactured through LPBF. The research included the design, development, and calibration of an experimental sensor setup, alongside comprehensive modeling efforts, including analytical modeling for crack detection.

RESEARCH DISSEMINATION
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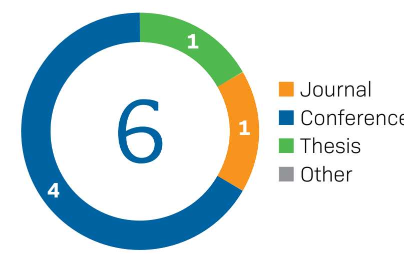

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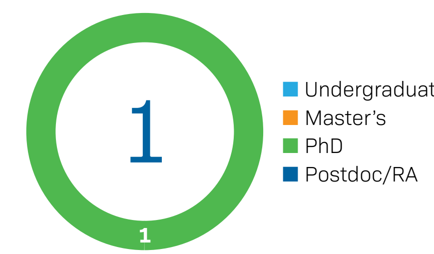
(member and collaborator)



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RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

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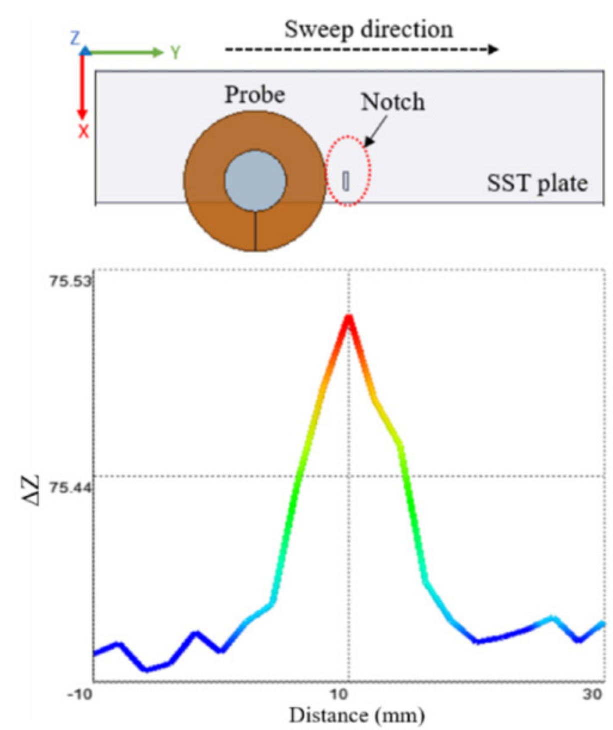

Detecting sub-surface defects near the edge using the developed Eddy current inductive sensor. (Subproject 3.1.3 | E. Farag, Heba, Ehsan Toyserkani, and Mir Behrad Khamesee. "Non-Destructive Testing Using Eddy Current Sensors for Defect Detection in Additively Manufactured Titanium and Stainless-Steel Parts." Sensors 22.14 (2022): 5440.)

RESEARCH OUTCOMES

Subproject 3.1.4: Laser Ultrasonic Sensing for LPB- and LPF-AM

PROGRESS

In this subproject completed in 2024 at the University of Waterloo, researchers explored using ultrasonic sensing to detect porosity defects in each layer of manufactured parts. The method involved using laser irradiation to stimulate ultrasonic waves through rapid thermal expansion or medium ablation. These waves were then utilized to inspect the area of interest on the test part. Additionally, as a complementary endeavor, the team investigated using ultrasound for focusing the powder stream in DED systems. The team has filed for a patent based on the technology developed in this project, and is currently progressing with plans for a startup.

RESEARCHERS

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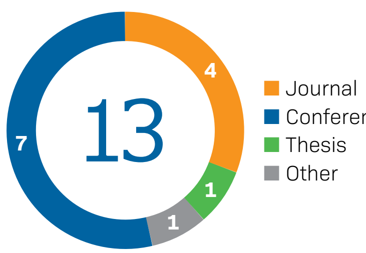
- Soyazhe Khan, University of Waterloo, Co-op

RESEARCH DISSEMINATION
(to date)



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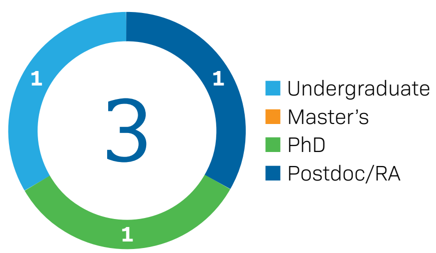
(member and collaborator)



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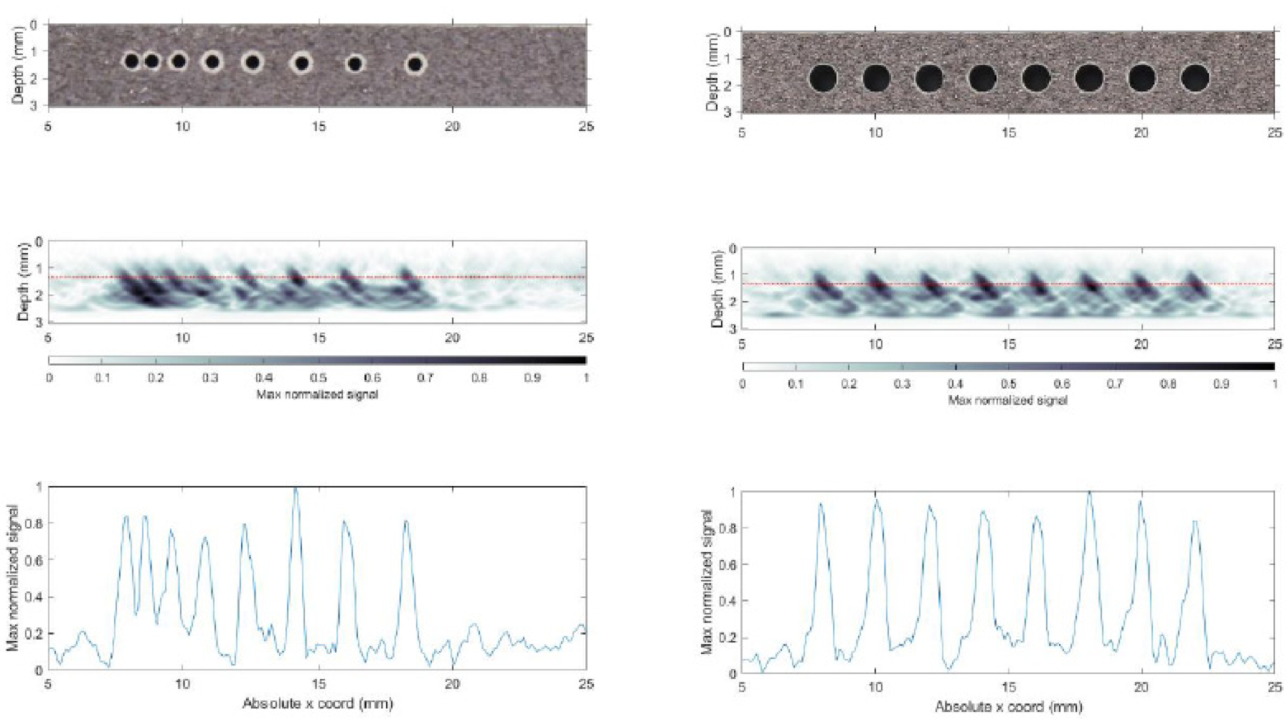

Defect reconstructions based on laser ultrasonics B scans. (Subproject 3.1.4 | Martinez-Marchese, Alexander, et al. "Detection of Defects in Additively Manufactured AlSi10Mg and Ti64 Samples Using Laser Ultrasonics and Phase Shift Migration". The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada)

RESEARCH OUTCOMES

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.

Subproject 3.2.1: Knowledge-based Lumped Models

PROGRESS

In this subproject, the team at the University of Waterloo focused on developing both experimentally driven and physics-driven models to enhance understanding of the EB-PBF process. These models aimed to uncover the relationships between pre-heating process parameters, process variables, and quality outcomes like density, surface roughness, and tensile strength, as well as the effect of powder recycling on characteristics of EBM-grade Ti6Al4V. As a result, processing parameters for PSD 45-150 µm and 38-180 µm were derived. Additionally, the team developed models to comprehend the melting mode transition in LPBF technology, spanning lack of fusion, conduction, and keyhole modes. This subproject was completed in 2021.

RESEARCHERS

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- Ahmet Okyay, University of Waterloo, RA
- Andrew Katz, University of Waterloo, RA
- Tomisin Oluwajuyigbe, University of Waterloo, MASc (Collaborator)

RESEARCH DISSEMINATION
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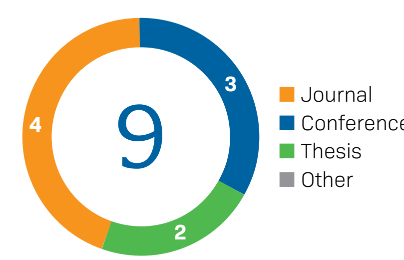

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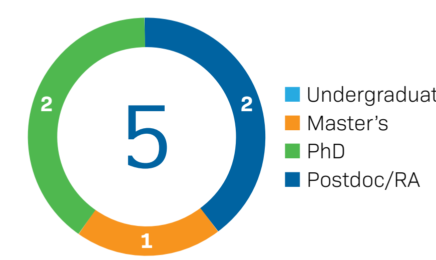

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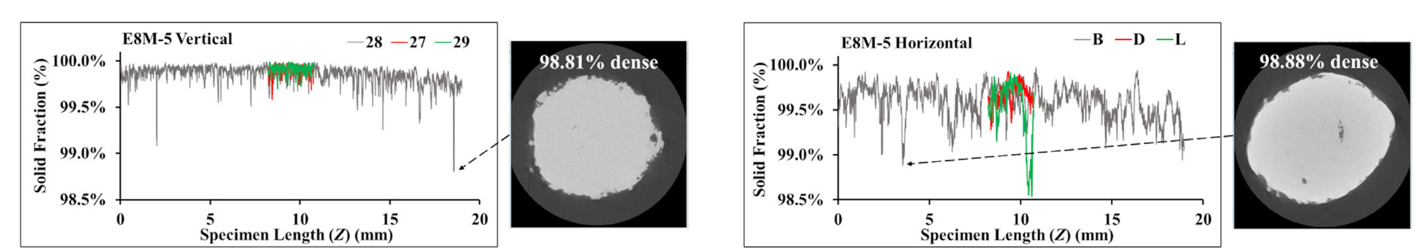

Layer-wise density for vertical and horizontal EBM specimens. (Subproject 3.2.1 | Shanbhag, Gitanjali, et al. "Effect of specimen geometry and orientation on tensile properties of Ti-6Al-4V manufactured by electron beam powder bed fusion." Additive Manufacturing 48 (2021): 102366.)

RESEARCH OUTCOMES

TABLE OF CONTENTS

Subproject 3.2.2: Development of Intelligent Controllers

PROGRESS

The research team at the University of Waterloo utilized photo-diode based sensors to gather and analyze light intensity signals from the LPBF melt pool. By employing machine learning, they correlated signal disturbances with defects in parts. These findings were integrated into a control system, facilitating intermittent defect correction. The data collection method developed in this subproject is currently under review for inclusion in an ASTM best practice guideline. This subproject concluded in 2022.

RESEARCH DISSEMINATION
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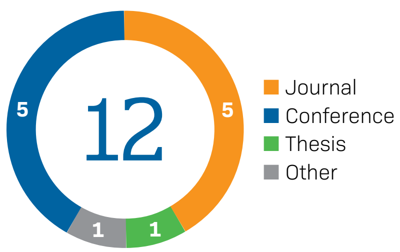

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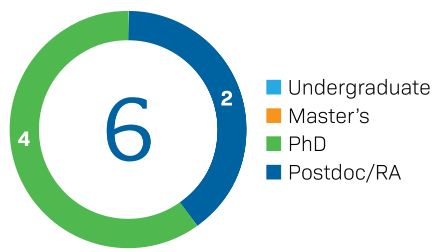

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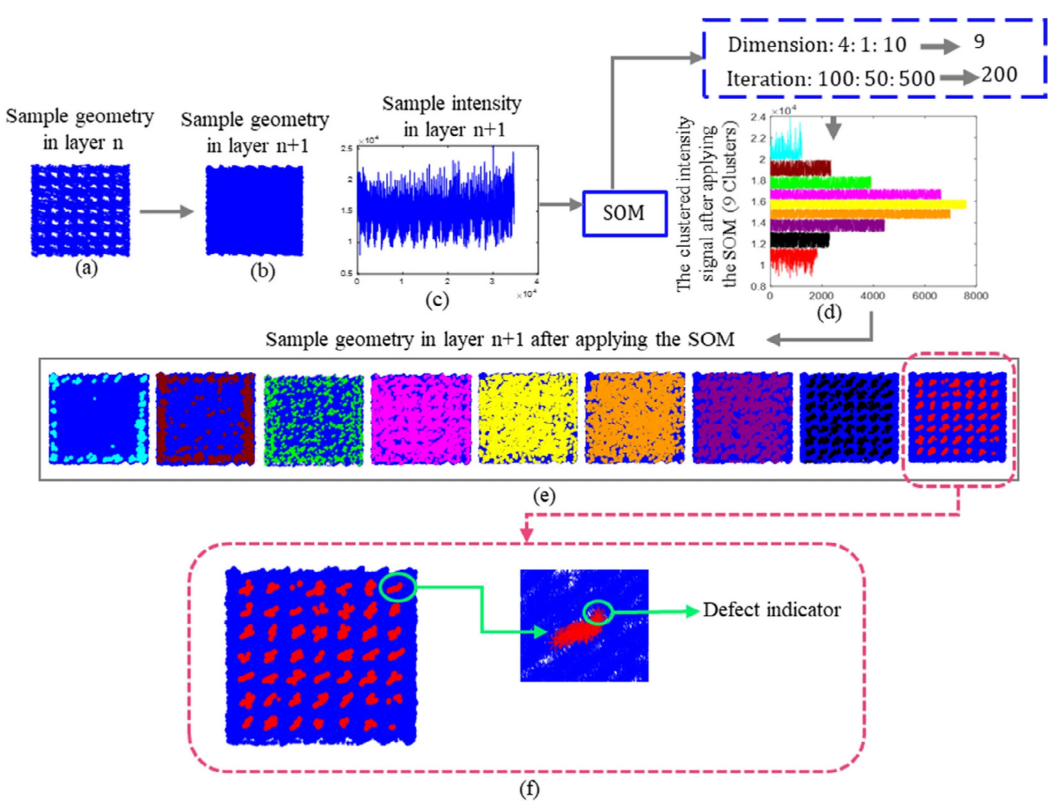

The defect indicator detection procedure using the self-organizing map algorithm. (Subproject 3.2.2 | Taherkhani, Katayoon, et al. "Development of control systems for laser powder bed fusion." The International Journal of Advanced Manufacturing Technology 129.11 (2023): 5493-5514.)

RESEARCHERS

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RESEARCH OUTCOMES

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

DESCRIPTION

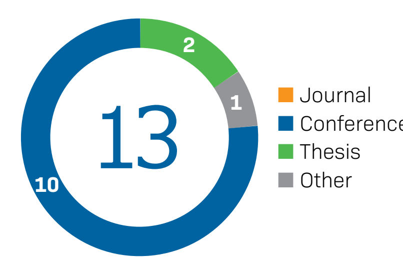
The properties of parts manufactured using powder bed metal AM processes are directly affected by the specifications of the powder layer such as powder morphology, layer thickness, and applied powder compaction force. The compaction force is particularly important as it affects powder packing density. 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.

Subproject 3.3.1: Measurement System Development and Validation of Combined Powder Spread, Compaction and Binder Fluid Dynamics Linked with Sintering Model + Subproject 3.3.2: Closed-loop Control of Compaction Density and Binder Imbibition and Experimental Validation

PROGRESS

In these merged subprojects, the University of Waterloo research team took a comprehensive approach to studying and modeling the binder jetting process. They developed and validated dynamic powder compaction and spread models, as well as high-resolution pore network models and 3D densification and distortion models using sintering theory. Additionally, they devised predictive geometric compensation strategies to control and accommodate for part shrinkage and distortion during sintering, along with binder imbibition and powder-binder interaction models. On the experimental front, the team explored the use of dual-channel jetting of Boron-based and Boron-free binder to achieve a 10-20% density variation in a single part without resorting to latticing techniques.

RESEARCH DISSEMINATION
(to date)



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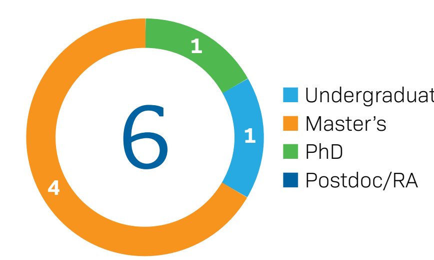

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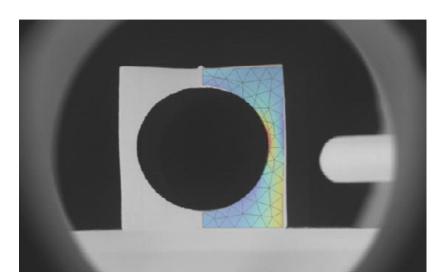

FEM sintering model overlaid with optical dilatometer image. (Subproject 3.3.1/3.3.2 | Boychuk, Roman, et al. "Toward Sintering Predicting Densification and Distortion in Binder-Jet Additive Manufacturing". The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada)

RESEARCHERS

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- Roman Boychuk, University of Waterloo, MASc
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RESEARCH OUTCOMES

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

DESCRIPTION

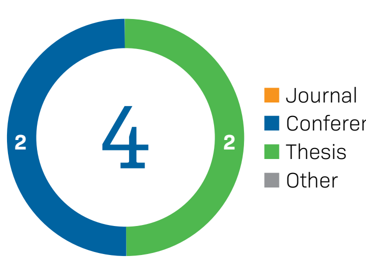
Industry currently uses a limited number of path planning algorithms/protocols (e.g. raster path determination) based on proprietary algorithms that accommodate desired part characteristics. However, for parts with multi-materials and special internal architectures, such as molds and turbojet nozzles, 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.

Subproject 3.4.1: Combined Trajectory Optimization and Thermal Analytical Models

PROGRESS

The objective of this subproject was to determine the most efficient deposition in EB-based AM technologies. Linked with the modeling results from project 2.1, the research team at the University of British Columbia focused on modeling the electron beam deflection system for precise beam position control. Additionally, they worked on predicting cycle time using finite impulse response filter and polynomial trajectory generation techniques. This subproject concluded in 2023.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)

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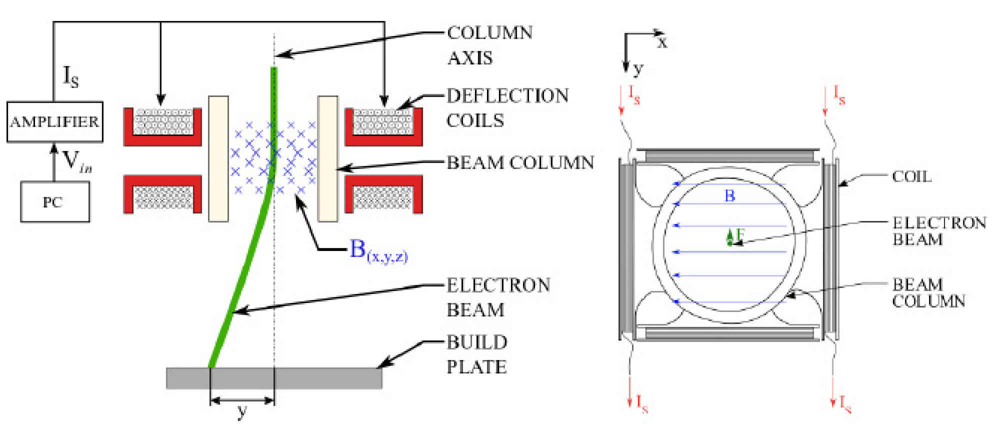

Diagram of electron beam deflection system. (Subproject 3.4.1 | Parks, Scott. Modelling of electron beam deflection system for beam position control in metal additive manufacturing. Diss. University of British Columbia, 2020.)

RESEARCHERS

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- Randy Yuwono, The University of British Columbia, MEng (Collaborator)
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- Sharon Tam, The University of British Columbia, MASc

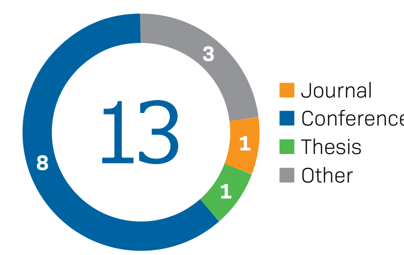
RESEARCH OUTCOMES

Subproject 3.4.2: Adaptive Path Planning Protocols/Controllers and Experimental Validation

PROGRESS

In this subproject, the team at the University of Waterloo has devised and validated rapid modeling and model calibration approaches for LPBF and LDED. They explored diverse methods including statistical models, analytical closed-form models, and machine learning techniques. Integrating in-line strategies for process signature detection, they connected these with characterization and experimental datasets. The researchers have applied for a patent for the active learning algorithm developed within this subproject. Control systems for adaptive path planning will be pursued beyond the Network's scope as a continuation of this work.

RESEARCH DISSEMINATION
(to date)



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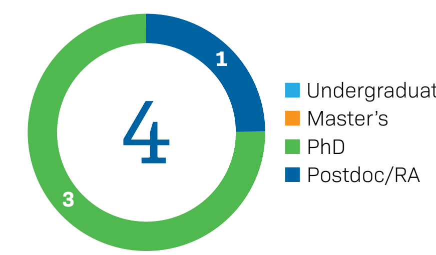
(member and collaborator)



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RESEARCHERS

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- Deniz Sera Ertay, University of Waterloo, PhD (Collaborator)
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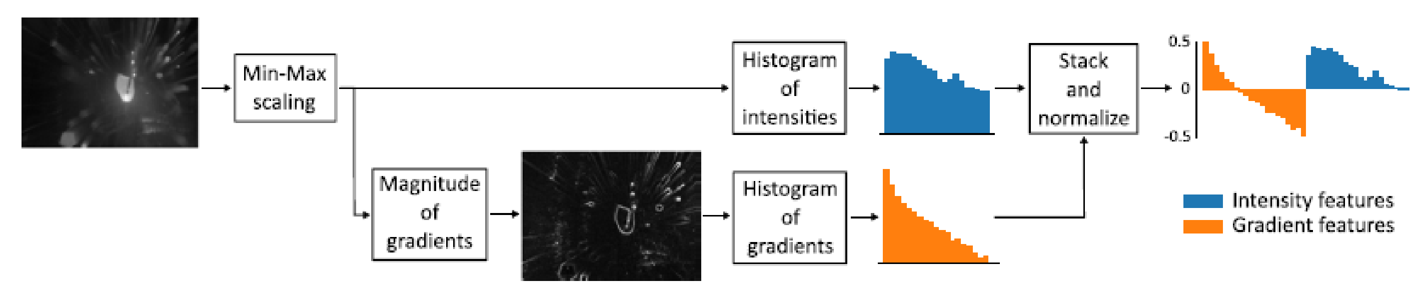
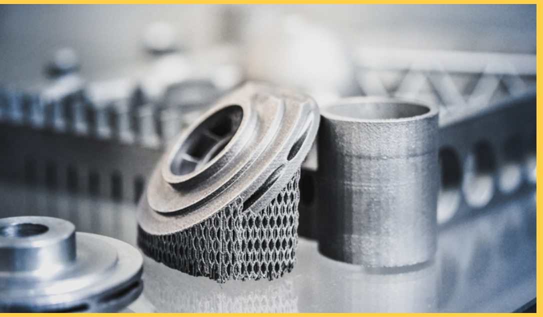
- Andrew Katz, University of Waterloo, RA



Feature extraction from in-situ images in the DED process. (Subproject 3.4.2 | van Houtum, Gijs JJ, and Mihaela L. Vlasea. "Active learning via adaptive weighted uncertainty sampling applied to additive manufacturing." Additive Manufacturing 48 (2021): 102411.)

RESEARCH OUTCOMES

Research Progress



THEME 4

Innovative AM Processes and AM-Made Products

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

An important advantage of using AM processes is the ability to create complex shapes that are impossible to make by conventional manufacturing methods. Examples include, but are not limited to, multi-material molds with conformal channels, functionally graded materials, cellular structures, and optimized orthopedic implants. Another advantage of AM is that its processes can be used to repair high-value parts. Being able to repair parts rather than replacing them is forecasted to 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.

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.

Subproject 4.1.1(i): Magnetically driven vacuum-based powder delivery processing head for LPF-AM

PROGRESS

This subproject initiated prior to the Network's inception and wrapped up in 2018. The findings revealed challenges regarding the feasibility of the proposed magnetically driven powder delivery system. Consequently, with the Board's approval, an alternative project (4.1.1(ii)) was proposed to cover the remainder of the Network's term. The mathematical modeling outcomes regarding the electrodynamic concentration of non-ferrous particles in a DED system have been published.

RESEARCHERS

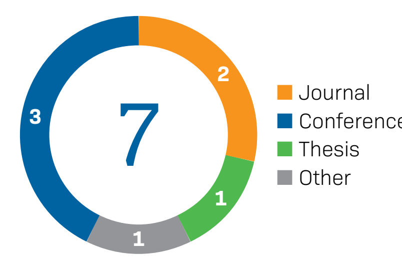
PRINCIPAL INVESTIGATOR(S)

- Ehsan Toyserkani, University of Waterloo
- Behrad Khamesee, University of Waterloo

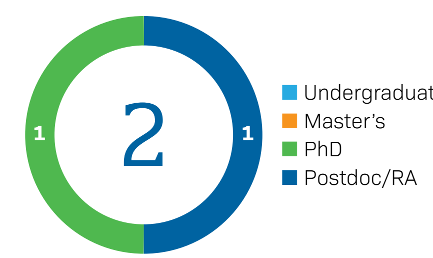
HIGHLY QUALIFIED PERSONNEL

- Yuze Huang, University of Waterloo, PhD, PDF

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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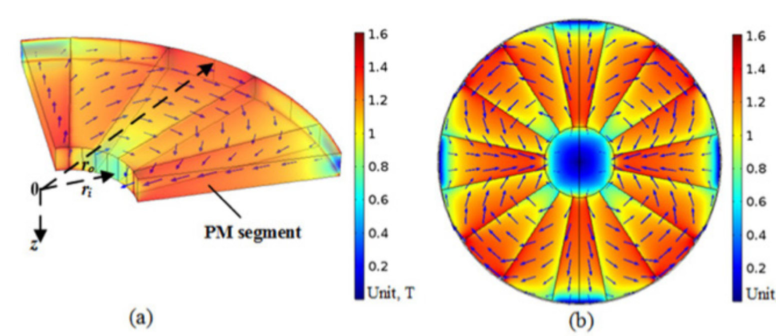


Schematic illustration of the proposed magnetic concentration generator with Halbach PM configuration. (a) 3D view of the quarter segment, and (b) magnetic field intensity norm for the inner region of the Halbach permanent-magnet-based quadrupoles array. (Subproject 4.1.1(i) | Huang, Yuze, Mir Behrad Khamesee, and Ehsan Toyserkani. "Electrodynamic concentration of non-ferrous metallic particles in the moving gas-powder stream: Mathematical modeling and analysis." International Journal of Magnetics and Electromagnetism 5 (2019): 019.)

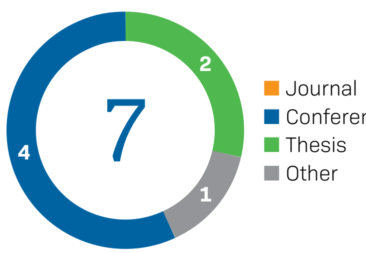
RESEARCH OUTCOMES

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

PROGRESS

In this subproject, the University of Waterloo team explored both in-situ and ex-situ methodologies for integrating optical sensors (Fiber Bragg Grating) within parts manufactured by LPBF. This included an examination of channel geometry, bonding mechanism, and curvature limitations. Additionally, the team focused on embedding optical sensors inside lightweight structures through the creation of lookup tables, which guided feature optimization of cellular structures via topology optimization algorithms while addressing manufacturability issues. This subproject was completed in 2021.

RESEARCH DISSEMINATION
(to date)



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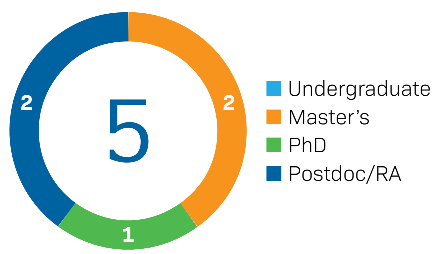

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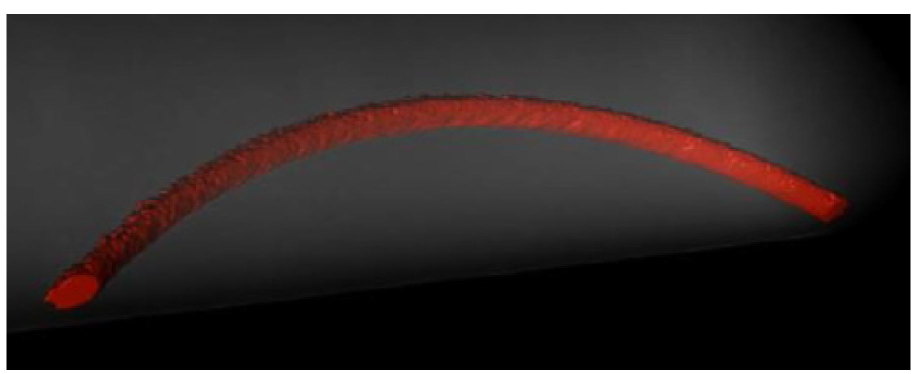
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Ehsan Toyserkani, University of Waterloo

HIGHLY QUALIFIED PERSONNEL

- Kelvin Jisoo Son, University of Waterloo, MASc
- Yuze Huang, University of Waterloo, PhD, PDF
- Ken Nsiempba, University of Waterloo, MASc
- Farid Ahmed, University of Waterloo, PDF (Collaborator)



3D isometric CT scan view of an 800 micron curved channel inside an LPBF-made coupon. (Subproject 4.1.1(ii) | Son, Kelvin. Embedding Optical Sensors in Additively Manufactured Parts for In-Situ Performance Measurement. MS thesis. University of Waterloo, 2021.)

RESEARCH OUTCOMES

Subproject 4.1.2: Levitated Additive Manufacturing

PROGRESS

In conventional DED processes, one side of the build part remains inaccessible due to the requirement for a platform or substrate to support it. In this subproject, the research team at the University of Waterloo showcased the viability of using magnetic levitation technology to enable the part to levitate, getting one step closer to full-position deposition. The research included analytical and numerical modeling of the setup, alongside the design, construction, and experimental validation of a maglev apparatus customized for DED. This subproject concluded in 2022.

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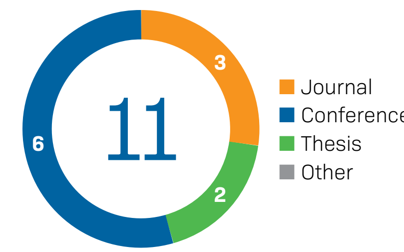

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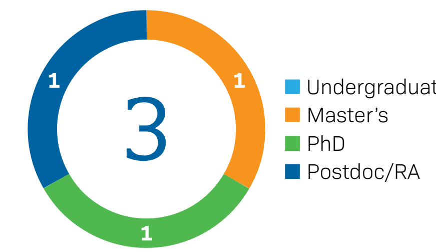

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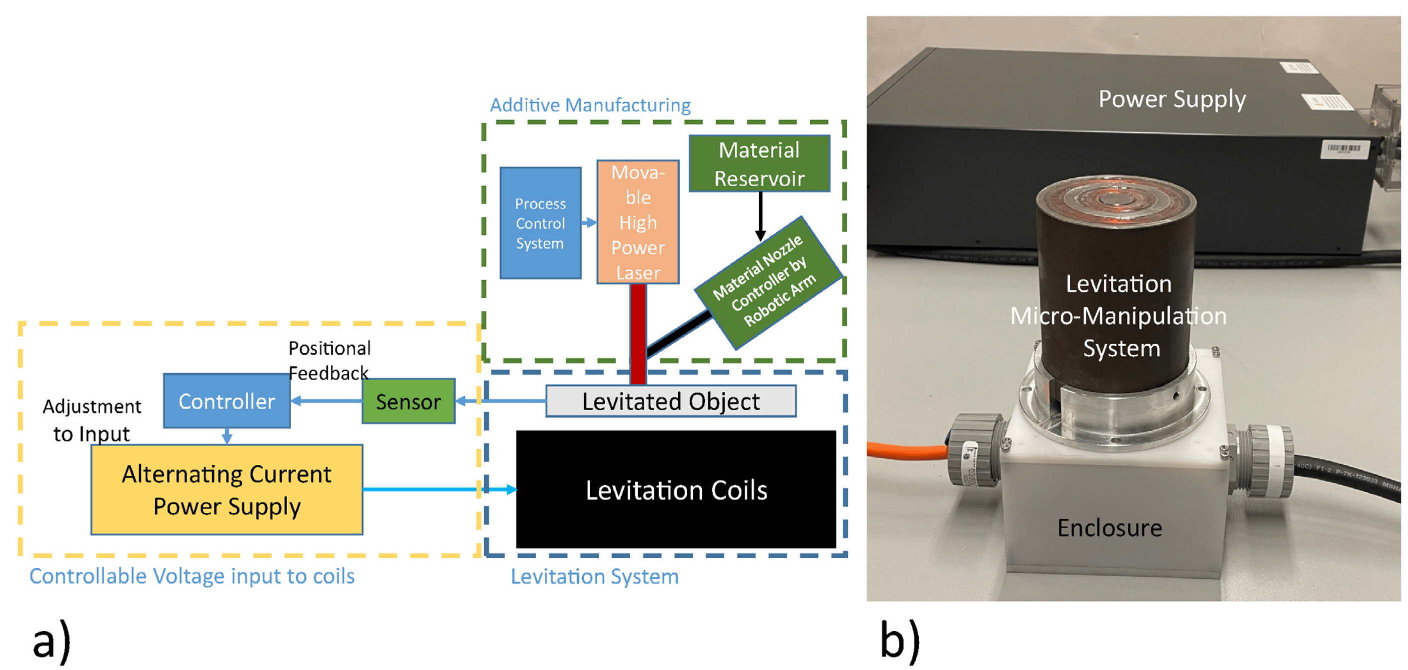
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Ehsan Toyserkani, University of Waterloo
- Behrad Khamesee, University of Waterloo

HIGHLY QUALIFIED PERSONNEL

- Parichit Kumar, University of Waterloo, PhD
- Yuze Huang, University of Waterloo, PDF
- Saksham Malik, University of Waterloo, MASc



Micromanipulator levitation system: (a) schematic of the envisioned system. (b) experimental apparatus. (Subproject 4.1.2 | Kumar, Parichit, et al. "Development of an electromagnetic micromanipulator levitation system for metal additive manufacturing applications." Micromachines 13.4 (2022): 585.)

RESEARCH OUTCOMES

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.

Subproject 4.2.1: Metal AM for Orthopaedic and Implants Technologies

PROGRESS

Building upon the findings of subproject 2.3.2, this subproject utilized the lattice structure designed expertise developed in Theme 2 to manufacture implant structures. These structures aimed to mimic bone tissue properties by employing a blend of random and periodic variations in lattice materials, enhancing bone ingrowth while aligning their mechanical properties with those of the surrounding bone tissue. The methodology adopted by the research team at McGill University involved leveraging topology optimization to fabricate a series of proof-of-concept patient-specific implant geometries, such as an acetabular cup, derived from bone geometry reconstructed from CT data. This subproject was completed in 2021.

RESEARCHERS

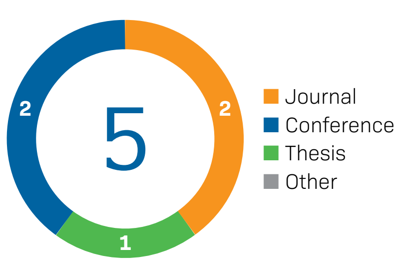
PRINCIPAL INVESTIGATOR(S)

- Damiano Pasini, McGill University

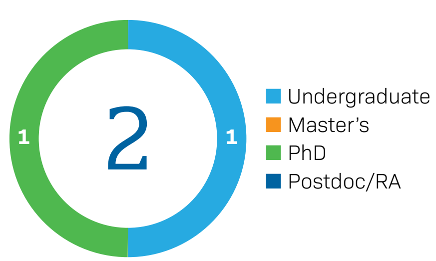
HIGHLY QUALIFIED PERSONNEL

- Ahmed Moussa, McGill University, PhD
- Wendy Li, McGill University, Co-op

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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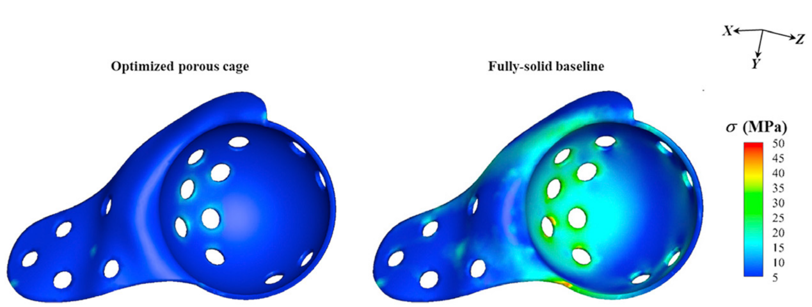


Comparison of the von Mises stress distributions on the optimized porous acetabular implant and the fully-solid baseline. (Subproject 4.2.1 | Moussa, Ahmed, et al. "Topology optimization of 3D-printed structurally porous cage for acetabular reinforcement in total hip arthroplasty." Journal of the mechanical behavior of biomedical materials 105 (2020): 103705.)

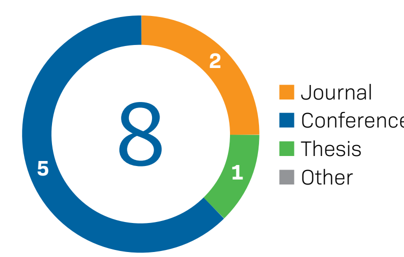
RESEARCH OUTCOMES

Subproject 4.2.2: Development of Smart Molds with Embedded Optical Sensors and Conformal Channels

PROGRESS

In this joint subproject between McGill University and the University of Waterloo, smart injection molds were designed to enhance heat dissipation. The McGill team proposed a novel machine learning method to improve conformal cooling design by tailoring cooling systems to part surfaces and thicknesses. By training a surrogate part temperate prediction model, they optimized cooling topologies, minimizing temperature variance. Following the design phase's completion in 2020, the Waterloo team focused o manufacturing parts with optimized cooling channels and integrated optical sensors, connecting this effort to subproject 4.1.1(ii). Additionally, several collaborator graduate students are developing process parameter sets for materials considered for sensor embedding.

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
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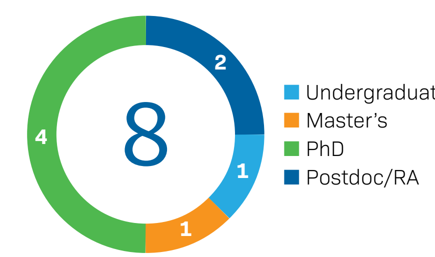

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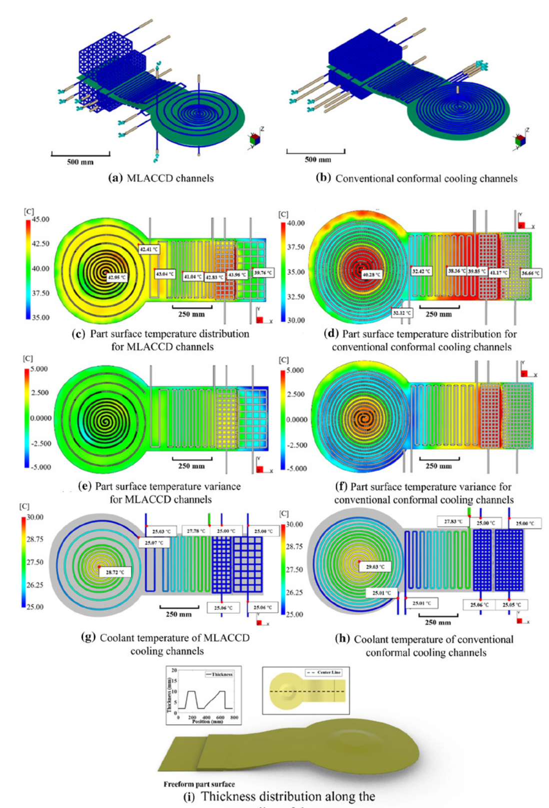
RESEARCHERS

PRINCIPAL INVESTIGATOR(S)

- Yaoyao Fiona Zhao, McGill University
- Ehsan Toyserkani, University of Waterloo

HIGHLY QUALIFIED PERSONNEL

- Tang Yunlong, McGill University, PDF
- Zhenyang Gao, McGill University, MASc
- Danièle Sossou, McGill University, Co-op
- Bahareh Marzbanrad, University of Waterloo, PDF (Collaborator)
- Nadia Azizi, University of Waterloo, PhD (Collaborator)
- Manyou Sun, University of Waterloo, PhD (Collaborator)
- Hamidreza Aghajani, University of Waterloo, PhD (Collaborator)
- Ali Mohammadnejad, University of Waterloo, PhD (Collaborator)



Comparison of conventional conformal cooling channels and machine learning-aided conformal cooling design channels developed in this subproject for a freeform part surface. (Subproject 4.2.2 | Gao, Zhenyang, et al. "Machine learning aided design of conformal cooling channels for injection molding." Journal of Intelligent Manufacturing (2023): 1-19.)

RESEARCH OUTCOMES

TABLE OF CONTENTS

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 Subproject 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.

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

PROGRESS

In this subproject, concluded in 2022, the research team at the University of Alberta worked on modeling solutions supported by experimental results to provide an optimal compositional gradient and process parameter set for abrasion resistance in PTA-DED of FGM parts. The WC-reinforced nickel-based alloys studied in Theme 1 were the focus. The team also developed a machine learning algorithm to automatically separate WC phases in microscopy images, leading to an invention disclosure.

RESEARCHERS

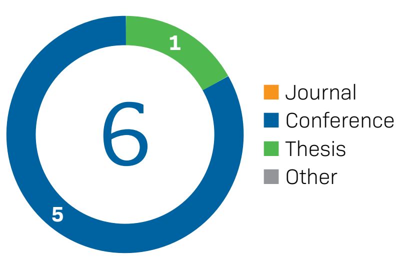
PRINCIPAL INVESTIGATOR(S)

- Hani Henein, University of Alberta

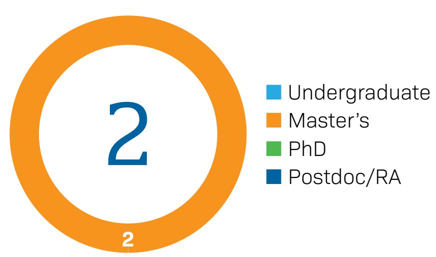
HIGHLY QUALIFIED PERSONNEL

- Zahra Abedy, University of Alberta, MASc
- Geoffrey Bonias, University of Alberta, MASC

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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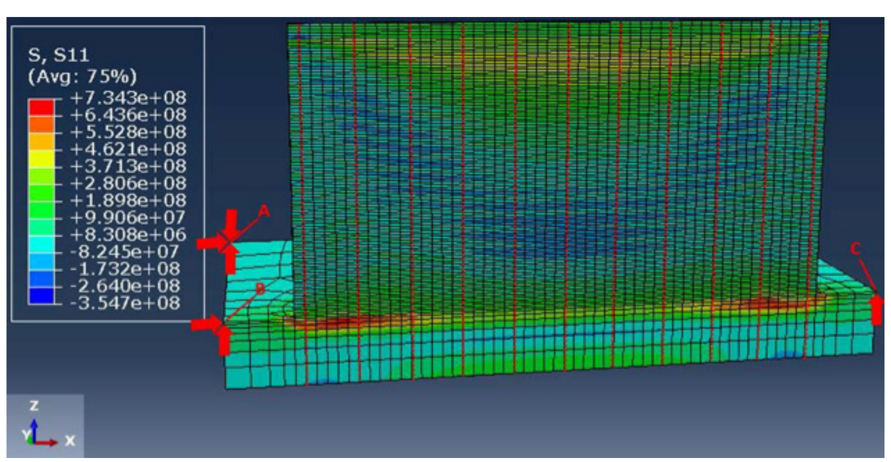


The finite element model developed to predict the residual stresses in FGM parts made via PTA-AM. (Subproject 4.3.1 | Bonias, Geoffrey, Hani Henein, and Tonya B. Wolfe. "Modeling residual stresses of functionally graded deposits using the PTAAM." IOP Conference Series: Materials Science and Engineering. Vol. 1281. No. 1. IOP Publishing, 2023.)

RESEARCH OUTCOMES

Subproject 4.3.2: Direct Manufacturing of FGM Molds Using LPF-AM

PROGRESS

The initial plan was to utilize LDED technology for producing FGM molds composed of tool steel and copper, aimed at minimizing cooling times in injection molding processes. However, unforeseen challenges related to machine availability and compatibility led the research team at Dalhousie University to pivot the project's focus solely towards DED processing of tool steels. Upon the project's completion in 2023, the team developed optimized process parameters for D2 and H13 alloys, devised heat treatment schedules, and conducted thorough microstructural and mechanical characterization, including an extensive analysis of wear properties.

RESEARCHERS

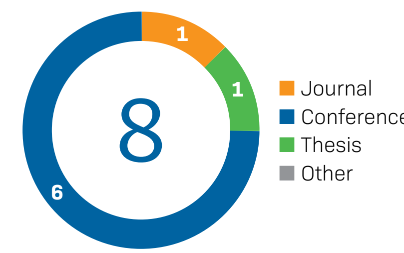
PRINCIPAL INVESTIGATOR(S)

- Kevin Plucknett, Dalhousie University

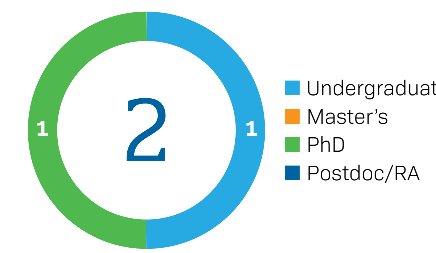
HIGHLY QUALIFIED PERSONNEL

- Samer Tawfik Omar, Dalhousie University, PhD
- Riley Roache, Dalhousie University, Co-op (collaborator)

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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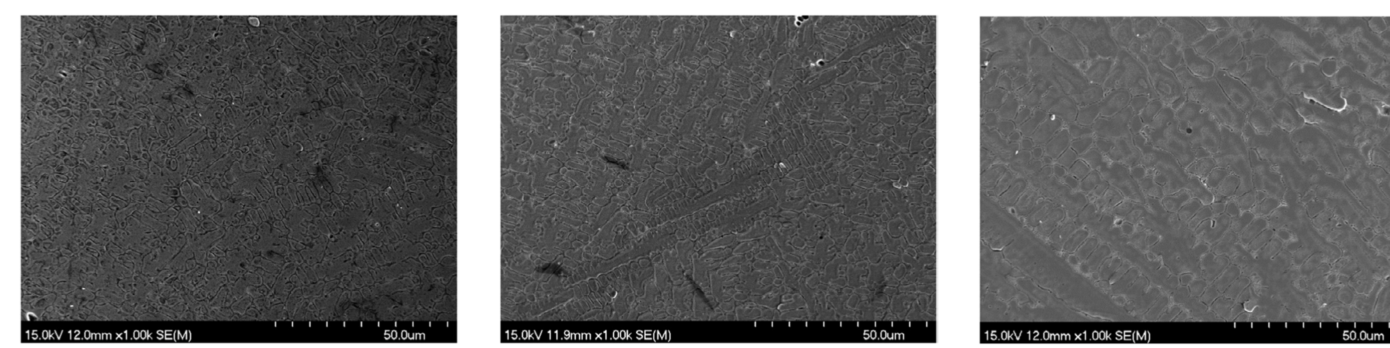


(a) (b) (c)

SEM images of the DED processed samples. (Subproject 4.3.2 | Omar, S. M. T., and K. P. Plucknett. "The influence of DED process parameters and heat-treatment cycle on the microstructure and hardness of AISI D2 tool steel." Journal of Manufacturing Processes 81 (2022): 655-671.)

RESEARCH OUTCOMES

TABLE OF CONTENTS

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.

Subproject 4.4.1: Repair Strategies with LPF-AM

PROGRESS

In this subproject, the research team at Dalhousie University evaluated and compared two repair approaches based on laser DED cladding: micro-composite powder fabrication and "pre-placement" dip-coating. The work, completed in 2023, includes achievements such as the development and optimization of the TiC-Ni3Al coating material system, the innovation of a gelation-based pre-placement method and apparatus as a novel coating technique, and comprehensive characterization of clads, including assessment of wear and corrosion responses.

RESEARCHERS

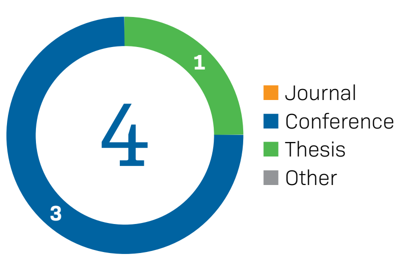
PRINCIPAL INVESTIGATOR(S)

- Kevin Plucknett, Dalhousie University

HIGHLY QUALIFIED PERSONNEL

- Zhila Russel, Dalhousie University, PhD
- Kerilyn Kennedy, Dalhousie University, Co-op
- Eric Moreau, Dalhousie University, PDF

RESEARCH DISSEMINATION (to date)



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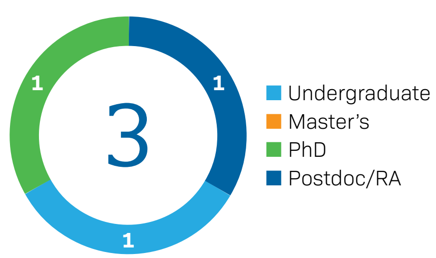

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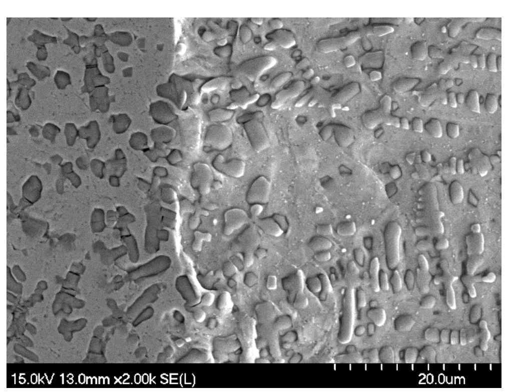


Post scratch micrograph from TiC-Ni3Al (30 vol.%) clad onto D2 steel under 10 N applied normal load. (Subproject 4.4.1)

RESEARCH OUTCOMES

Subproject 4.4.2: Repair Strategies Using EWF-AM

PROGRESS

In this subproject, the research team at McGill University explored the application of electron beam wire DED for repairing high-temperature materials. Their focus has been on mitigating microstructure degradation in the parent material and managing contaminants at the repair/parent interface. To achieve this goal, they developed an FEA model of the process, devised repair strategies tailored to different service conditions, and evaluated both the microstructure and mechanical performance of the repairs and interfaces. The primary outcomes of this work include a more comprehensive understanding of how substrate condition influences the quality of repair structures, alongside the development of a miniature sample test methodology. This subproject concluded in 2022.

RESEARCHERS

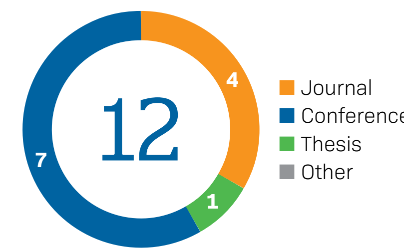
PRINCIPAL INVESTIGATOR(S)

- Mathieu Brochu, McGill University

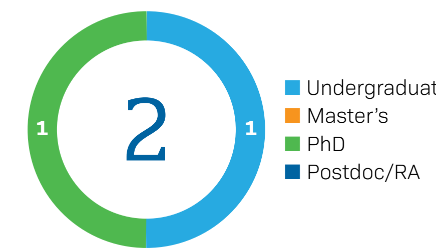
HIGHLY QUALIFIED PERSONNEL

- Fatih Sikan, McGill University, PhD
- Camila Gutierrez, McGill University, Co-op

RESEARCH DISSEMINATION (to date)



HQP PROFILE* (member and collaborator)



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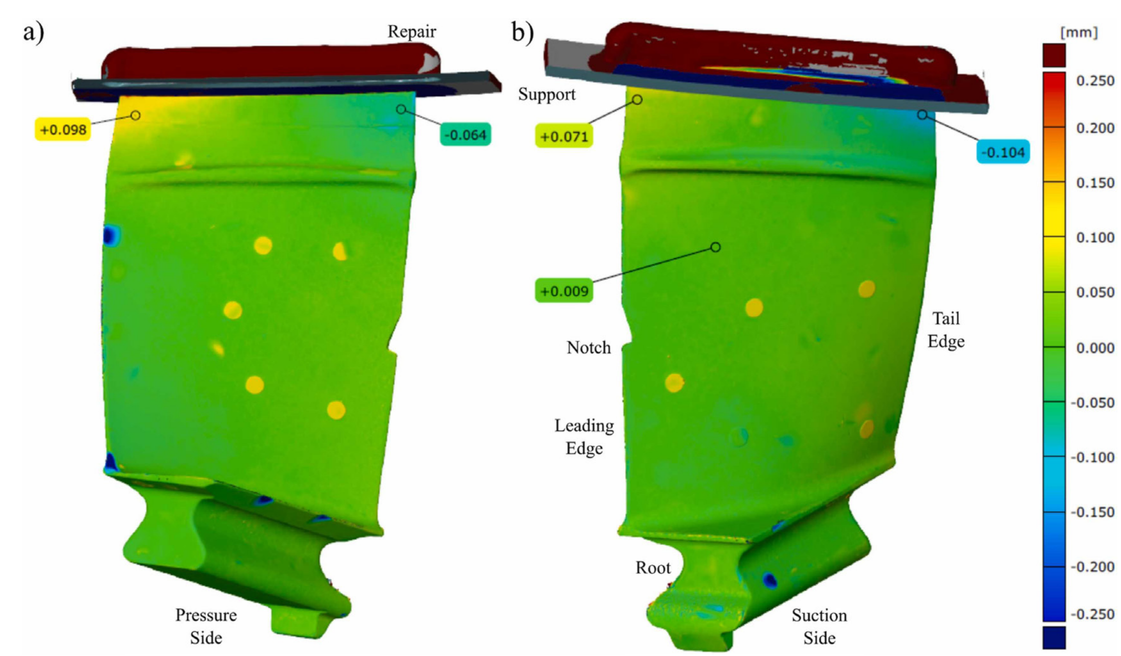


Out-of-plane displacement maps for (a) pressure and (b) suction side of the EB-DED repaired compressor blade. (Subproject 4.4.2 | Sikan, Fatih, et al. "Evaluation of electron beam wire-fed deposition technology for titanium compressor blade repair." Materials Today Communications 35 (2023): 105701.)

RESEARCH OUTCOMES

Subproject 4.4.3: Repair Strategies Using PTA- and FFF-AM

PROGRESS

The University of Alberta's research team spearheaded this subproject, with a primary focus on employing PTA-DED technology for repair purposes. Their innovative approach involved developing an in-situ automated scan-assisted repair process for hybrid AM, now licensed to a Canadian AM company. As an ancillary project, the team has looked into production of polymer-metal and polymer-ceramics composite filaments for fused filament fabrication (FFF) processing. This subproject was completed in 2022.

RESEARCHERS

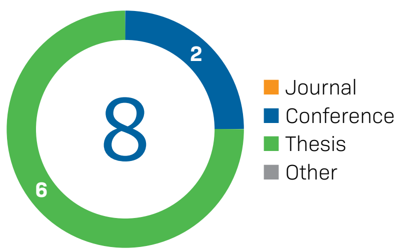
PRINCIPAL INVESTIGATOR(S)

- Hani Henein, University of Alberta

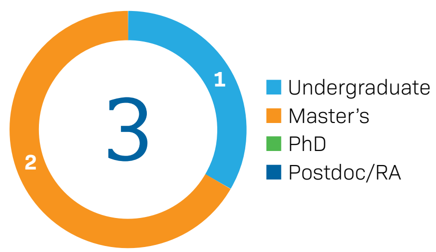
HIGHLY QUALIFIED PERSONNEL

- Nancy Bhardwaj, University of Alberta, MASc (Collaborator)
- Remy Samson, University of Alberta, MASc
- Nathan Wieczorek, University of Alberta, URA

RESEARCH DISSEMINATION
(to date)



HQP PROFILE*
(member and collaborator)



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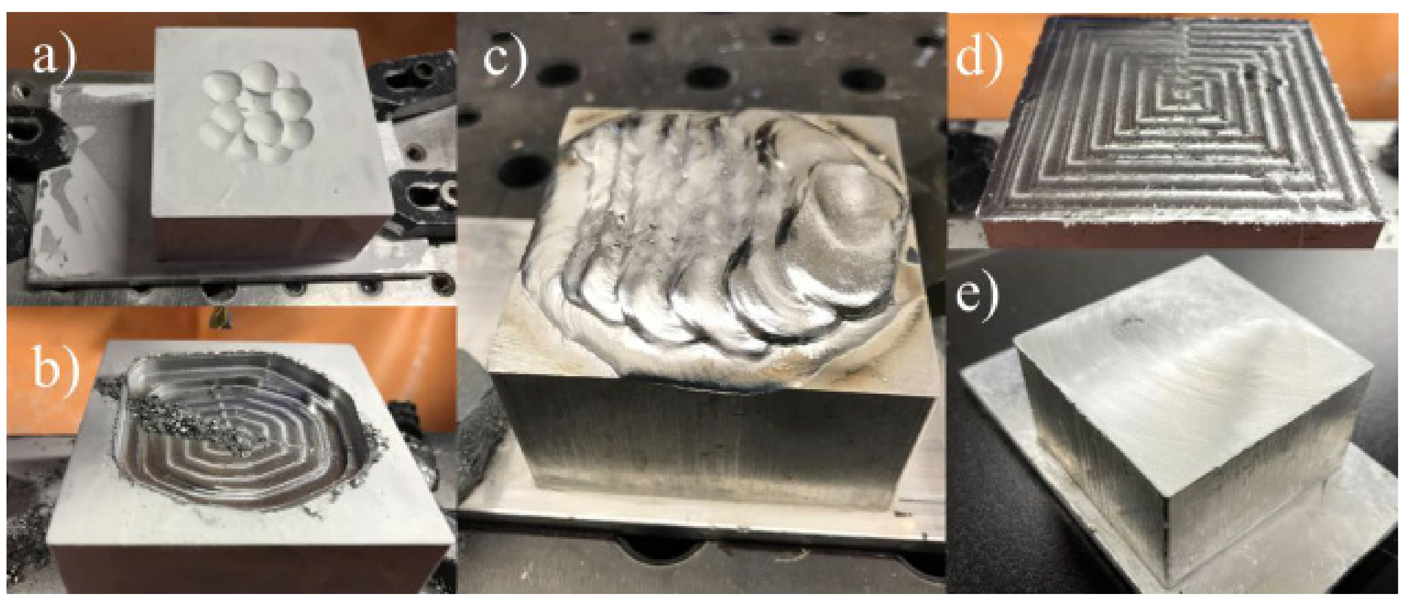

The scan-assisted automated repair process using hybrid manufacturing: (a) initial damaged part, (b) pre-repaired volume, (c) material deposition using PTA-DED, (d) repaired sample after post-machining, and (e) repaired sample after polishing. (Subproject 4.4.3 | Samson, Remy, et al. "Analysis of Repair Interface Automated Hybrid Additive-Subtractive Manufacturing Process". The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada)

RESEARCH OUTCOMES

Finances

The HI-AM Network primarily receives funding from NSERC. The Network received $1 million in its first year, and has received $4.68 million between years 2 and 7. This funding is matched by both industry funds and institutional support from the universities participating in the Network.

YEAR ONE TO SEVEN NSERC FUNDING (2017-2024)

	BUDGET	EXPENSES AND COMMITMENTS*
THEME 1	$1,958,784	$1,891,374
THEME 2	$909,040	$816,333
THEME 3	$640,600	$721,558
THEME 4	$742,973	$ 706,594
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$1,428,603	$1,054,917
TOTAL	**$5,680,000**	**$5,190,776**

YEAR ONE TO SEVEN INDUSTRY/GOVERNMENT PARTNER AND INSTITUTIONS CONTRIBUTIONS (2017-2024)

	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$573,480	$437,097
THEME 2	$301,334	$305,183
THEME 3	$433,336	$322,460
THEME 4	$328,651	$433,227
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$106,932	$188,372
TOTAL	**$1,743,733**	**$1,686,339**

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

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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 2023

Over the past seven 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.

The 2023 HI-AM Conference marked the final event of the NSERC HI-AM Network. A virtual transition event titled HI-AM 2024: Nexus Forum is scheduled for September 2024, allowing Network co-applicants to convene and strategize for future initiatives. The HI-AM Conference is anticipated to return to its regular format beginning with HI-AM 2025, pending the continuation of the consortium under HI-AM 2.0.

The 6th HI-AM Conference, June 27-28, 2023, Dalhousie University, Halifax, NS

HI-AM 2023 *continued*

The 6th HI-AM Conference took place on June 27-28, 2023 in Halifax, NS, and was co-chaired by Professor Paul Bishop from Dalhousie University and Professor Ehsan Toyserkani from the University of Waterloo. The conference was attended by about 150 AM researchers and professionals, showing strong support from the AM community. The conference was opened by Professor Peter Vanberkel, Associate Dean of Research at Dalhousie University's Faculty of Engineering, with opening remarks also provided by the Conference Chairs.

Opening remarks by (left to right): Peter Vanberkel, Associate Dean of Research, Dalhousie University; Paul Bishop, HI-AM 2023 Chair, Dalhousie University; Ehsan Toyserkani, HI-AM 2023 Chair, University of Waterloo.

HI-AM 2023 at a Glance

EDUCATION

- 4 Keynote Talks
- 48 Oral Presentations
- 39 Posters

NETWORKING

- 150 Participants
- 10 Exhibitors
- Tradeshow
- Networking Session
- Social Event

KEYNOTE SPEAKERS

Olaf Diegel
Professor of Additive Manufacturing
University of Auckland,
Creative Design and Additive Manufacturing Lab, New Zealand

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

Tim Horn
Assistant Professor, Mechanical and Aerospace Engineering
North Carolina State University, NC, United States

Denis Cormier
Earl W. Brinkman Professor of Industrial and Systems Engineering
AMPrint Center Director
Rochester Institute of Technology, NY, United States

A total of 91 research works were presented at HI-AM 2023 in both oral and poster formats. Four keynote presentations were delivered by distinguished speakers: Olaf Diegel, Professor of Additive Manufacturing at the University of Auckland, New Zealand; Carolyn Seepersad, J. Mike Walker Professor of Mechanical Engineering at The University of Texas at Austin, United States; Tim Horn, Assistant Professor of Mechanical and Aerospace Engineering at North Carolina State University, United States; and Denis Cormier, Earl W. Brinkman Professor of Industrial and Systems Engineering at Rochester Institute of Technology, United States. Additional activities organized during the conference included a tour of the additive manufacturing labs at Dalhousie University and a happy hour event hosted by Women in 3D Printing.

Women in 3D Printing gathering

Snapshots from the poster sessions at HI-AM 2023

HI-AM 2023 *continued*

The conference received funding from the Natural Sciences and Engineering Research Council of Canada (NSERC) as part of the NSERC HI-AM Program. Additionally, it received support from a variety of partners and exhibitors including Multi-Scale Additive Manufacturing Lab, SLM Solutions, cadmicro, Xact Metal, Indurate Alloys, Tronos, Women in 3D Printing, OU Additive, Metafold, and Renishaw. These organizations significantly enriched the conference experience by showcasing their latest technologies, products, and services at the HI-AM Exhibition. This exhibition offered Network HQP and other attendees the chance to explore firsthand the latest advancements in the field, engage in networking opportunities with industry leaders, experts, and peers, and gain valuable insights into the future direction of the industry.

Snapshots from the 2023 exhibition

The evening at Pickford & Black Restaurant encapsulated the conference vibe, giving attendees a memorable opportunity to unwind and network with colleagues. With Halifax Harbor as a backdrop, guests savored Maritimes cuisine in a charming setting. Despite the rain driving most indoors, some ventured out to explore the waterfront patio and nearby wharf.

Snapshots from the conference dinner

The conference closing remarks were given by Professor Hani Henein, HI-AM Network's Node Leader for the University of Alberta. The conference concluded with the announcement of the recipients of student presentation competition awards. The 2023 winners are:

ORAL PRESENTATION COMPETITION:

First Place:

- Amirhosein Mozafarighoraba, Western University
- Joseph Orakwe, University of Waterloo
- Daniel Juhasz, University of Waterloo

Second place:

- Terek Li, University of Toronto
- Anne McDonald, University of Alberta
- Hossein Mohammadtaheri, Concordia University

Third place:

- Hamid Aghajani, University of Waterloo
- Kenzie Timmons, Dalhousie University
- Manyou Sun, University of Waterloo

POSTER PRESENTATION COMPETITION:

First place:

- Justin Plante, Université Laval
- Zahra Kazemi, University of Toronto
- Tomisin Oluwajuyigbe, University of Waterloo

Second place:

- Donatien Campion, École de technologie supérieure Montréal
- Vignesh Krishnan, Dalhousie University
- Muralidharan Kumar, McGill University

Third place:

- Anushree Shah, The University of British Columbia
- Farima Liravi, University of Waterloo
- Peyman Alimehr, University of Waterloo

Recipients of the HI-AM 2023 Student Presentation Awards joined by the HI-AM Node Leaders

Research Outcomes

Project 1.1: Development of Next Generation Alloys

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

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. 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]**
6. 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]**
7. Diaz D, Bogno AA, Dias M, Valloton J, Ivey D, Henein H. Effect of Ce Addition in Hypereutectic Al-Si Alloys During Rapid Solidification. InConference of Metallurgists 2023 Aug 21 (pp. 505-507). Cham: Springer Nature Switzerland. **[Link]**
8. Bogno AA, Valloton J, Rappaz M, Qureshi A, Henein H. Tailored solidification microstructures for innovative use of high-density materials in lightweight products. Journal of Alloys and Metallurgical Systems. 2024 Feb 14:100061. **[Link]**

- At least seven more manuscripts are being prepared for publication or are under review.

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 - Edmonton, 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.
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.

HI-AM CONFERENCE

1. R. Ley, S. Atabay, M. Brochu, I. Donaldson, P. Bishop. Development of Thermally Stable Aluminum Alloys for Laser Powder Bed Additive Manufacturing. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. A. Bogno, A. Sabouraud, H. Henein, A. Qureshi. Hybrid investment casting. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. G. Sweet, J. Hierlihy, I. Donaldson, M. Brochu, P. Bishop. Laser Powder Bed Processing of Aluminum Powders Containing Iron and Nickel Additions. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
4. A. Fu, P. Hudon, P. Bishop, M. Brochu. Application of Fast Cooling Calorimetry in Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
5. A. Sahoo, A. Bogno, H. Henein. The Microstructure, Morphology and Mechanical Properties of Rapidly Solidified Al-10wt%Si-0.4wt%Sc Alloy. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
6. J. Hierlihy, I. Donaldson, M. Brochu, P. Bishop. Development of Al-Zr-Y Alloys for Laser Powder Bed Fusion. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

7. A. Fu, M. Brochu, P. Bishop, P. Hudon. Optimization of Chemical Composition of Al Alloys via Rapid Solidification in Additive Manufacturing. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
8. A. Bogno, M. Tamboli, A. Qureshi, H. Henein. Manufacturing of 3D Lattice Structures by Hybrid Investment Casting. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
9. J. Hierlihy, I. Donaldson, M. Brochu, P. Bishop. Preliminary Investigation of Al-Zr-Y Alloys for Laser Powder Bed Fusion Using Laser Remelting. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
10. A. Fu, M. Brochu. Estimate Solidification Parameters of Al alloys Fabricated by AM based on T0 Curve and Non-equilibrium Solidification. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
11. A. Sahoo, A. Bogno, H. Henein. Rapid Solidification of Al-10Si-0.4Sc Alloy. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
12. D. Diaz, A. Bogno, H. Henein. Alloy Design for Laser Powder-Bed Fusion: Hypereutectic Al-Si Systems. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
13. A. Rayner, P. Bishop. Laser Powder Bed Fusion (LPBF) Processing of UNS C63020 Nickel Aluminum Bronze Powder. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
14. A. Fu, M. Brochu. Influence of Heat Treatment on Microstructure and Mechanical Properties of Al40Si Fabricated by AM. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
15. J. da Silva, H. Henein. Effects of TiB2 in an Al-Cu-Sc Alloy in the Hybrid Investment Casting Process. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
16. J. Comhaire, P. Bishop. Development of AlSi10Mg-AlN Metal Matrix Composites for Laser Powder Bed Fusion AM. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
17. A. Sahoo, H. Henein. Rapid Solidification of Al-10Si-0.4Sc (wt%): Precipitation Behaviour and its Influence on Mechanical Properties. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
18. J. Hierlihy, P. Bishop. Comparison of Laser Powder Bed Fusion Processing and Laser Remelting of an Al-Zr Alloy. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
19. A. Rayner, J. Hierlihy, M. Trask, R. Cooke, P. Bishop. Laser Powder Bed Fusion (LPBF) Processing of a Mixed Nickel Aluminum Bronze Powder. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.
20. J. Comhaire, I. Donaldson, P. Bishop. Development of AlSi10Mg-AlN Metal Matrix Composites for Laser Powder Bed Fusion AM. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.
21. J. Hierlihy, I. Donaldson, P. Bishop. Metallurgical Investigation of Al-Zr(-Y) Alloys for LPBF Using Laser Remelting. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Hierlihy J. Laser Powder Bed Fusion Processing of Aluminum Powders Containing Iron and Nickel. Dalhousie University. 2020. **[Link]**
2. Diaz Jimenez D. Si modification in hypereutectic Al-Si: Combining rapid solidification and alloying. University of Alberta. 2022. **[Link]**
3. Comhaire J. Development of AlSi10Mg-AlN metal matrix composites for laser powder bed fusion additive manufacturing. Dalhousie University. 2023. **[Link]**

- Three additional theses are anticipated to be published.

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

JOURNAL PAPER

1. Rayner AJ, Sweet GA, Craig O, Habibnejad-Korayem M, Bishop P. Investigation of Deposition Parameters for Near-Beta Alloy Ti-55511 Fabricated by Directed Energy Deposition. Journal of Manufacturing and Materials Processing. 2024 Apr 10;8(2):72. **[Link]**

- At least one more manuscript is being prepared for publication or is under review.

HI-AM CONFERENCE

1. M. Harding, N. Goose, M. Brochu, I. Donaldson, K. Plucknett, P. Bishop. Processing of Ti-64 by Laser Powder Fed Additive Manufacturing. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. M. Harding, Z. Memmarashidi, I. Donaldson, K. Plucknett, P. Bishop. Laser Powder Fed Deposition of Ti/MMC Coatings. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
3. N. Gosse, I. Donaldson, M. Harding, P. Bishop. Processing of Ti-64 by Laser Powder Fed Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
4. N. Gosse, G. Sweet, I. Donaldson, P. Bishop. LPF-AM Processing of Beta, Near-Beta and Near-Alpha Titanium Alloys. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
5. N. Gosse, D. Bishop, I. Donaldson. Laser Directed Energy Deposition Processing of Beta, Near-Beta and Near-Alpha Titanium Alloys. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
6. A. Rayner, G. Sweet, P. Bishop. A Parametric Study on the Freeform Fabrication of Near-beta alloy Ti-55511 Printed by Laser Directed Energy Deposition (L-DED) Using a Statistical Design of Experiments (DOE) Approach. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.

THESIS

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

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

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. 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]**
4. Rose D, Wolfe T, Henein H. Microstructural Characterization and Wear Resistance of 60 wt.%, 70 wt.%, and 80 wt.% WC-NiCrBSi Thin Walls Deposited Using Plasma Transferred Arc Additive Manufacturing. JOM. 2024 Jan;76(1):42-56. **[Link]**
5. Rose D, Wolfe T, Henein H. Microstructural Characterization of 70 Wt Pct WC-NiBSi Deposited by PTA-AM. Metallurgical and Materials Transactions A. 2024 Feb;55(2):447-65. **[Link]**

- At least four more manuscripts are being prepared for publication or are 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.
6. A. McDonald, A. Shao, K. Meszaros, A. Qureshi, M. Rappaz, T. Wolfe, H. Henein. Microstructure Map of Rapidly Solidified 17-4PH Stainless Steel. 62nd Annual Conference of Metallurgists (COM 2023), Toronto, ON, Canada, 2023.

HI-AM CONFERENCE

1. D. Mutel, C. Blais. Development of modified A8 and S7 tool steel powders by water atomization for Laser Powder Bed Additive Manufacturing (LPB-AM) and Direct Energy Deposition (DED). The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. D. Rose, T. Wolfe, H. Henein, L. Li. Major Defects in 70wt% WC Ni deposits using plasma transferred arc - additive manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. D. Mutel, C. Blais. Development of Novel Water-atomized Tool Steel Powders for Laser Powder Bed (LPB) and Direct Energy Deposition (DED). The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. W. Chaîné, C. Blais. Development of Novel A8 Tool Steel Powders for AM Produced by Water Atomization. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
5. D. Mutel, C. Blais. Development of Novel Water-atomized Tool Steel Powders to Improve Shock Resistance of AM Parts Made of H13 Tool Steel. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
6. A. McDonald, A. Bogno, H. Henein. Microstructure of Rapidly Solidified 17-4PH Stainless Steel. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
7. D. Rose, H. Henein. Semantic Segmentation of Plasma Transferred Arc Additively Manufactured NiBSi-WC Optical Microscopy Images Using a Convolutional Neural Network. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
8. D. Mutel, C. Blais. Characterization and Analysis of Water Atomized Tool Steel Powders for Powder Bed Laser Fusion by Machine Learning. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
9. D. Rose, H. Henein, Denuded Region Formation in NiBSi-WC Metal Matrix Composites Deposited by Plasma Transferred Arc Additive Manufacturing. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
10. W. Chaîné, C. Blais. AM Using Novel A8 tool Steel Powders Produced by Water Atomization. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
11. A. McDonald, H. Henein. Effect of Cooling Rate on the Microstructure of Rapidly Solidified 17-4PH Stainless Steel. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
12. A. McDonald, A. Shao, K. Meszaros, A. Qureshi, M. Rappaz, T. Wolfe, H. Henein. Microstructure Map of Rapidly Solidified 17-4PH Stainless Steel. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.
13. J. Plante, C. Blais. Artificial Intelligence Applied to the Development of Tool Steels with Low Susceptibility to Cracking for Laser Additive Manufacturing (LAM). The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Mutel D. Développement de poudres d'acier à outils S7 par atomisation à l'eau pour la fabrication additive par fusion laser sur lit de poudre (LPBF). Université Laval. 2023. **[Link]**
2. Chaîné W. Développement de poudres d'acier à outils A8 par atomisation à l'eau pour la fabrication additive. Université Laval. 2024. **[Link]**
3. Rose D. Microstructural Analysis of Ni-WC Metal Matrix Composites Deposited Using Plasma Transferred Arc Additive Manufacturing. University of Alberta. 2023. **[Link]**

- Two additional theses are anticipated to be published.

Subproject 1.1.4: Development of Nickel Alloys for LPB-AM

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]**
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 three more manuscripts are being prepared for publication or are under review.

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.

HI-AM CONFERENCE

1. S. Atabay, K. Plucknett, M. Brochu. Additive Manufacturing of Ni-Based Superalloys. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. S. Atabay, K. Plucknett, M. Brochu. Fabrication of Rene 41 Parts with Laser Powder Bed Fusion. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. S. Atabay, K. Plucknett, M. Brochu. Effect of Heat Treatment on High Temperature Mechanical Properties of Rene 41 Alloy Fabricated by LPBF. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. K. Li, C. Xu, T. Ramakrishnan, X. Wang, M. Brochu. Attempts at Understanding LPBF of Intermetallic Alloys. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
5. S. Atabay, M. Brochu. Laser Powder Bed Fusion (LPBF) of Difficult to Weld Rene 77 Superalloy. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
6. K. Li, X. Wang, T. Ramakrishnan, M. Brochu. Understanding of the Laser Powder Bed Fusion (LPBF) Printability of an Ni_3Al Alloy. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.

THESIS

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

Subproject 1.1.5: Development of Refractory Metals for LPB-AM

JOURNAL PAPER

1. Ramakrishnan T, Kumar A, Hudon P, Brochu M. Laser powder bed fusion additive manufacturing of Mo and TZM exoskeleton with Cu infiltration for new heat sinks configuration. Advanced Engineering Materials. 2024 Feb;26(3):2301409. **[Link]**

2. Ramakrishnan T, Espiritu ER, Kwon S, Keshavarz MK, Muniz-Lerma JA, Gauvin R, Brochu M. Laser powder bed fusion additive manufacturing of molybdenum using a nitrogen build atmosphere. International Journal of Refractory Metals and Hard Materials. 2024 Feb 1;119:106555. **[Link]**
3. Ramakrishnan T, Kwon S, Brochu M. Laser powder bed fusion of molybdenum under various ArN2 mixture build atmospheres. International Journal of Refractory Metals and Hard Materials. 2024 Feb 1;119:106556. **[Link]**

HI-AM CONFERENCE

1. T. Ramakrishnan, E. Espiritu, M. Keshavarz, M. Brochu. Characterization and LPBF-AM of commercially pure molybdenum powders. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. T. Ramakrishnan, M. Brochu. Characterization of TZM Alloy Powders and their Laser Powder Bed Fusion Additive Manufacturing Behavior. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. T. Ramakrishnan, M. Brochu. Laser Powder Bed Fusion Additive Manufacturing of Molybdenum Lattice Structures. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. T. Ramakrishnan, M. Brochu. Copper Infusion into LPBF-AM Mo Alloy Lattice Structures for Tailored CTE Heatsinks. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

THESIS

1. Ramakrishnan T. Laser Powder Bed Fusion Additive Manufacturing of Molybdenum and Molybdenum TZM alloy. McGill University. Under Review.

Project 1.2: AM Processing of Multi-Material Systems

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

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]**
8. Li T, Jabari E, McLellan K, Naguib HE. Review of additive manufacturing with 2D MXene: techniques, applications, and future perspectives. Progress in Additive Manufacturing. 2023 Dec;8(6):1587-617. **[Link]**
9. Li T, Saadatnia Z, Chen T, Chen JX, Shi HT, Naguib HE. Facile material extrusion of 3D wearable conductive-polymer micro-super-capacitors. Additive Manufacturing. 2023 Jul 25;74:103714. **[Link]**

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.
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.

HI-AM CONFERENCE

1. T. Morrison, X. Shen, H. Naguib. Graphene-Based Nanocellulose Composites for 3D Printed Electrodes. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. X. Shen, T. Morrison, H. Naguib. An adaptable additive manufacturing technology for development of binder jetting and direct ink writing graphene 3D electronics. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
3. M. Kshad, A. Wickeler, H. Naguib. Additively Manufactured Origami-Inspired Metamaterials. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
4. X. Shen, H. Naguib. Binder Jetting Fabrication of Functionally Graded Materials. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
5. A. Wickeler, H. Naguib. Optimization of Novel Origami Inspired Metamaterials. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
6. T. Morrison, H. Naguib. Graphene Nanocellulose Composites for 3D Printed Electrodes. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
7. A. Wickeler, H. Naguib. Enhanced Impact Energy Absorption of 3D Printed Tessellated Sheets made from Flexible Materials. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
8. T. Li, H. Naguib. Binder Jet Printing of MXene Composite for Energy Storage and Strain Sensing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
9. Y. Sun, Y. Wan, R. Nam, M. Chu, H. Naguib. Localized Actuation Behaviour: Implementation of Functionally Graded Structure in 4D Printed Shape Memory Polymer. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
10. A. Jo, H. Naguib. A Facile Method of Using Inkjet Printing to Fabricate PEDOT: PSS Electrodes onto Nafion Membrane through Ionic Bonding for Origami Inspired Actuators. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
11. K. McLellan, H. Naguib. Development of Hybrid Shape Memory Polymers with Conductive Fillers for Advanced 4D Printing of Therapeutic Devices. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
12. A. Wickeler, H. Naguib. Novel Origami-Inspired Mechanical Metamaterial Development Utilizing Theoretical Modelling Verified Through 3D Printed Sample Testing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
13. K. McLellan, H. Naguib. 4D Precipitation Printing of Shape Memory Polymer Blends for Foamed Strain Sensors. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

14. T. Li, Y. Sun, H. Naguib. Facile 3D Printing of Conductive Polymer. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
15. T. Li, H. Mao, Z. Li, J. Chen, H. Naguib. Data Driven Process Optimization for 3D Printing of Metal via Direct-Ink-Writing. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Morrison TJ. Material Development and Design for 3D Printable Electronic Devices. University of Toronto 2019. **[Link]**
2. Shen X. Towards Integrated 3D Printing as an Industrial Manufacturing Process. University of Toronto 2020. **[Link]**
3. Wickeler A. Origami-Inspired Mechanical Metamaterials. University of Toronto. 2022. **[Link]**
4. McLellan K. Shape Memory Polymer Composites for 4D Printing of Wearable Devices. University of Toronto. 2022. **[Link]**
5. Li T. Synthesis and Characterization of Nanostructured MXene Composite and Aerogel for Energy Devices. University of Toronto. 2021. **[Link]**

- One additional thesis is anticipated to be published.

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

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 three more manuscripts are being prepared for publication or are under review.

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.

HI-AM CONFERENCE

1. O. Craig, K. Plucknett. Material Characterization of AISI H13 Hot Work Tool Steel to Correlate Tempering Conditions to Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. O. Craig, K. Plucknett, A. Bois-Brochu. Geometry and Surface Characterization of Additively Manufactured H13 Hot-Work Tool Steel Using Directed Energy Deposition. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. O. Craig, K. Plucknett. Microstructure Characterization of Directed Energy Deposition of H13 Tool Steel. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. O. Craig, K. Plucknett. Microstructural Characterization of Functionally Graded H13 Tool Steel and Copper using Directed Energy Deposition. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

THESIS

1. Craig O. Material Characterization of Directed Energy Deposition of H13 Tool Steel and Functionally Graded H13-Copper. Dalhousie University. 2022. **[Link]**

Project 1.3: Cost Reduction Strategies

Subproject 1.3.1: Recyclability of Powder Feedstocks for LPB-AM

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]**
4. Lee JE, Sun YC, Lees I, Naguib HE. Additive manufacturing of hybrid piezoelectric/magnetic self-sensing actuator using pellet extrusion and immersion precipitation with statistical modelling optimization. Composites Science and Technology. 2024 Mar 1;247:110393. **[Link]**

- At least one more manuscript is being prepared for publication or is under review.

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.

HI-AM CONFERENCE

1. A. Das, G. Azimi, M. Brochu. Powder recyclability in Laser Powder Bed Fusion (LPBF) Additive Manufacturing (AM). The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. A. Das, J. Lerma, E. Espiritu, A. Nommeots-Nomm, K. Waters, M. Brochu. Contribution of moisture from cellulosic fibre filter in Laser Powder Bed Fusion (LPBF) Additive Manufacturing (AM). The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. H. Sun, G. Azimi, Y. Zou. Microstructure Evolution of Aluminum, Copper, and Aluminum-Copper Alloys Made by Selective Laser Melting. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
4. H. Sun, G. Azimi, Y. Zou. Microstructural Evolution and Mechanical Properties of Aluminum-Copper Alloy and Maraging Steel Made by Selective Laser Melting. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
5. Y. Sun, H. Naguib. Life Cycle, Aging, and Recyclability Study of 3D Printable Mxene. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
6. Y. Sun, B. Ihilov, T. Li, H. Naguib. Functionalization, Oxidation, and Recyclability Study of 3D Printable MXene. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Das A. Moisture Sources in Laser Powder Bed Fusion Additive Manufacturing. McGill University. 2020. **[Link]**
2. Sun HK. Selective Laser Melting of a High-Strength Steel and Joining of Aluminum and Copper. University of Toronto. 2021. **[Link]**

- One additional thesis is anticipated to be published.

Subproject 1.3.2: Plasma Spheroidization of Low Cost Powders

HI-AM CONFERENCE

1. T. Mohammadhassan, C. Blais. An Investigation into the Recyclability of Plasma-Atomized Powders Used in Laser Powder Bed Fusion. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

Subproject 1.3.3: Cost-effective Steel Feedstock for AM

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]**
3. Rayner AJ, Cooke RW, Donaldson IW, Corbin SF, Bishop DP. Binder Jet Printing AISI 5120 Chromium Steel Powder. Metallurgical and Materials Transactions A. 2023 Apr;54(4):1271-85. **[Link]**

- At least two more manuscripts are being prepared for publication or are under review.

CONFERENCE PRESENTATION

1. B. Bharadia , A. Bogno , H. Henein. Electrostatic Atomization: A Containerless Technique. Additive Manufacturing Alberta by Innotech Alberta - Edomnton, AB, 2018.
2. W. Bouchard, S. Gelinas, C. Blais. Effect of boron on the sintering and mechanical properties of parts made from a similar steel powder of AISI 4340 composition developed for binder-jetting. PowderMet 2023, International Conference on Powder Metallurgy and Particulate Materials - Las Vegas, NV, 2023.

HI-AM CONFERENCE

1. B. Bharadia, A. Bogno, H. Henein. Electrostatic Atomization Generating Powders for Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. R. Ley, I. Dolandson, P. Bishop. Binder Jet Printing of Low Cost Tool Steel Powders. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. B. Bharadia, A. Bogno, H. Henein. Electrostatic Atomisation of Metals. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. R. Ley, I. Donaldson, P. Bishop. Binder Jet Printing of Low-Cost Tool Steel Powders. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
5. A. Rayner, R. Cooke, I. Donaldson, P. Bishop. Binder Jet Printing AISI 5120 Chromium Steel Powder. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
6. B. Bharadia, A. Bogno, H. Henein. Electrostatically Assisted Atomisation of Metals. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
7. R. Ley, D. Bishop, I. Donaldson. Binder Jet Printing of Low-Cost Tool Steel Powders. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
8. G. Sweet, M. Amegadzie, I. Donaldson, C. Schade, P. Bishop. Directed Energy Deposition Processing of a Dual Phase Steel. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
9. W. Bouchard, C. Blais. Observing the Effect of Boron on D2 and 4340 for Binder Jetting Application. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
10. W. Bouchard, S. Gelinas, C. Blais. Effect of Boron Additions on the Sintering Response of AISI D2 and AISI 4340 Components Produced by Binder Jetting. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Bharadia B. Electrostatically Assisted Atomization of a Liquid Jet in the Rayleigh Regime. University of Alberta. 2022.
2. Ley R. Binder jet printing of a low cost tool steel powder. Dalhousie University. 2022. **[Link]**

- One additional thesis is anticipated to be published.

Project 2.1: Multi-scale Modeling of AM

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

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]**

HI-AM CONFERENCE

1. A. Khobzi, F. Farhang-mehr, S. Cockcroft, D. Maijer. Numerical Models for the Prediction of Beam/Powder/Melt Pool Interaction in EBAM. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. E. Ogeturk, M. Wells. Monitoring and modeling temperature fluctuations at boundary points in laser powder bed fusion. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. A. Khobzi, S. Sing, W. Yeong, S. Cockcroft, D. Maijer, F. Farhang-Mehr. Geometric Consideration of Support Structures Design for Overhang Features of Dental Implants Fabricated by Selective Laser Melting. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. A. Khobzi, S. Cockcroft, D. Maijer, F. Farhang Mehr. Experimental and Numerical Investigation of Block-Type Support Structure Design Parameters on Thermal Fields within Components Fabricated by Selective Laser Melting. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.

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]**

- One additional thesis is anticipated to be published.

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

HI-AM CONFERENCE

1. E. Nishimura, F. Farhang-mehr, S. Cockcroft, D. Maijer. Thermal Fluid Modeling of Melt Pool Dynamics in the Electron Beam Additive Manufacturing of Ti-6wt%Al- 4wt%V. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. E. Nishimura, F. Farhang-mehr, S. Cockcroft, D. Maijer. Thermal-fluid Modelling of Melt Pool Dynamics in the Electron Beam Additive Manufacturing of Ti-6wt%Al- 4wt%V. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. E. Nishimura, S. Cockcroft, D. Maijer, F. Farhang-Mehr. Thermal Fluid Modelling of Melt Pool Dynamics in the Electron Beam Additive Manufacturing of Ti6Al4V. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. E. Nishimura, S. Cockcroft, D. Maijer, F. Mehr. Thermal Fluid Modelling of Melt Pool Generation in the Powder Bed Electron Beam Additive Manufacturing (PB-EBAM) of Ti6Al4V. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.

5. P. Prakash, M. Wells. Baseplate Design and Inverse Heat Conduction Modeling for Improved Predictive Accuracy of COMSOL Model for Laser Powder Bed Fusion Printing of Metallic Alloy Powders. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
6. P. Prakash, A. Midawi, M. Wells. Microstructure and Microhardness Variation with Build Height in Laser Powder Bed Fusion Fabricated 316L Stainless Steel. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

Subproject 2.1.3: Macro-scale Thermal Field Evolution

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]**

HI-AM CONFERENCE

1. Z. Luo, Y. Zhao. A Fast and Part level Numerical Simulation of Temperature Field in Selective Laser Melting Process. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. Z. Luo, Y. Zhao. Efficient Thermo-mechanical Finite Element Model for Simulating Selective Laser Melting Process in Part Level. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

THESIS

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

Subproject 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

JOURNAL PAPER

1. Pourabdollah P, Farhang Mehr F, Maijer DM, Cockcroft SL. A novel approach for the numerical analysis of in situ distortion in a component made by the directed energy deposition additive manufacturing process. The International Journal of Advanced Manufacturing Technology. 2023 Jan;124(5):1925-38. **[Link]**
2. Rahimi F, Pourabdollah P, Mehr FF, Cockcroft S, Maijer D. A macroscale heat transfer analysis of the build chamber in a commercial electron beam powder bed fusion (EB-PBF) additive manufacturing system during component fabrication. Additive Manufacturing. 2023 Sep 25;78:103831. **[Link]**
3. Pourabdollah P, Farhang Mehr F, Cockcroft S, Maijer D. A new variant of the inherent strain method for the prediction of distortion in powder bed fusion additive manufacturing processes. The International Journal of Advanced Manufacturing Technology. 2024 Feb 26:1-20. **[Link]**

- At least one more manuscript is being prepared for publication or is under review.

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]**

2. P. Pourabdollah, F. Farhang Mehr, S. Cockcroft, D. Maijer,. Computationally efficient model to predict the evolution in the thermal field in the EB-PBF and DED processes. MCWASP XVI – Modeling of Casting, Welding, and Advanced Solidification Processes, Banff, AB, Canada, 2023. **[Link]**

HI-AM CONFERENCE

1. A. Chakraborty, F. Farhang-mehr, D. Maijer, S. Cockcroft. Meso-scale thermal, elastic and plastic strain evolution in PB EBAM. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. P. Pourabdollah, F. Farhang-mehr, S. Cockcroft, D. Maijer. Mechanical Modeling of EB Based Wire Feeding Process. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. F. Rahimi, F. Farhang-mehr, S. Cockcroft, D. Maijer. Review on Residual Deformation and Stress Measurement. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
4. P. Pourabdollah, S. Cockcroft, D. Maijer, F. Farhangmehr. Thermo-mechanical Modeling of Laser Powder Bed Fusion of Ti-6Al-4V. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
5. A. Chakraborty, F. Farhang Mehr, D. Maijer, S. Cockcroft. Meso-scale Modelling of Strain Evolution in Powder-Bed Electron Beam Additive Manufacturing. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
6. F. Rahimi, F. Farhang-Mehr, S. Cockcroft, R. Edinger, D. Maijer. Development of An Autonomous In-situ Temperature Measurement System and a Heat Transfer Model of the Build Chamber in Electron Beam Additive Manufacturing. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
7. F. Rahimi, F. Farhang Mehr, S. Cockcroft, J. Ou, D. Maijer. A Simplified Approach to Modelling the Thermal Balance of the Build Chamber in Electron Beam Additive Manufacturing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
8. A. Chakraborty, F. Mehr, S. Cockcroft, D. Maijer. Mesoscale Modelling of the Evolution of Plastic, Elastic, Thermal strain in Powder Bed Electron Beam Additive Manufacturing (PB-EBAM). The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
9. F. Rahimi, S. Cockcroft. A Numerical Case Study on the Thermal Balance of a Pseudo Build Environment in Electron Beam Additive Manufacturing. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
10. P. Pourabdollah, S. Cockcroft, D. Maijer, F. Farhangmehr. Numerical Evaluation of the Effect of the Support Structure Design on the Deformation of Overhang Parts Manufactured by the Electron Beam Powder Bed Fusion (EB-PBF) Process. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
11. P. Pourabdollah, F. Farhang-mehr, S. Cockcroft, D. Maijer. Numerical Analysis and Experimental Validation of Distortion in an Overhang Component Fabricated by the Electron Beam Powder Bed Fusion Process. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Rahimi F. Development of a heat transfer model of a simplified build environment in electron beam additive. University of British Columbia. 2022. **[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. 2022. **[Link]**
3. Pourabdollah P. An exploration of finite element-based methods for predicting the distortion in additive manufactured metallic components. University of British Columbia. 2024. **[Link]**

Subproject 2.1.4 (ii): Property and Design Assessment of a 3D-Printed Metallic Implant

HI-AM CONFERENCE

1. A. Shah, S. Cockcroft, D. Maijer. Property and Design Assessment of a 3D-Printed Metallic Implant. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

- One thesis is anticipated to be published.

Subproject 2.1.5: Microstructural Modeling and Experimental Validation

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]**
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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.
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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.
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4. J. Valloton, A. Bogno, M. Rappaz, H. Henein. Numerical model of A-l33Cu eutectic growth during Impulse Atomization. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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1. Diaz Jimenez D. Si modification in hypereutectic Al-Si: Combining rapid solidification and alloying. University of Alberta. 2022. **[Link]**
2. Sahoo A. Modelling of the Thermal History During Submerged Arc Welding and Wire and Arc Additive Manufacturing. University of Alberta. 2023. **[Link]**

Project 2.2: Accelerated Real-time Simulation Platforms

Subproject 2.2.1: Fast Process Thermal-Field Simulation

JOURNAL PAPER

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1. M. Upadhyay, D. Maijer, S. Cockcroft. Fast-to-run predictive model for thermal fields during Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.

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Subproject 2.2.2: Fast Process Stress-Field Simulation

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2. Imani Shahabad S, Karimi G, Toyserkani E. An extended rosenthal's model for laser powder-bed fusion additive manufacturing: Energy auditing of thermal boundary conditions. Lasers in Manufacturing and Materials Processing. 2021 Sep;8:288-311. **[Link]**

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1. S. Imani Shahabad, Z. Zhang, A. Keshavarzkermani, R. Esmaeilizadeh, A. Bonakdar, E. Toyserkani. The Effect of Laser Scanning Stripe Width on Melt Pool Geometries in Laser Powder-bed Fusion Additive Manufacturing Process. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
2. S. Imani Shahabad, E. Toyserkani. Rapid Prediction of Thermal and Stress Distributions in LPBF Process Using a Finite-difference Modeling Approach. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
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Project 2.3: Pre-processing for Optimization of AM Process Parameters

Subproject 2.3.1: Pre-processing for Dimensional Control

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]**
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1. B. Rupal, A. Qureshi. Geometric Deviation Modeling and Tolerancing in Additive A GD&T Perspective. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
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Subproject 2.3.2: Lattice Structure Design for AM Processing

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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]**
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2. Y. Zhang, Y. Zhao. A Predictive System for Manufacturability Analysis of Laser Powder Bed Fusion Process. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. A. El Elmi, D. Melancon, M. Asgari, L. Lu, D. Pasini. Mechanical and functional performance of porous bone replacement implants. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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5. A. El Elmi, D. Melancon , M. Asgari, D. Pasini. A Framework to Study the Role of Material and Morphology Defects on the Mechanical Performance of Additively Built Lattice Materials. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

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1. Zhang Y. Development of hybrid machine learning models for assessing the manufacturability of designs for additive manufacturing processes. McGill University. 2022. **[Link]**

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Subproject 2.3.3: Mismatch Determination During AM of Thin Structures

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]**
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3. M. Kumar, A. Ghosh, M. Brochu. Review on Mechanical Testing of Meso-and Micro-scale Test Coupons. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. M. Kumar, M. Brochu. Evaluation of Al-Si-Mg Small Scale LPBF Coupons under ELCF. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
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Project 3.1: Innovative In-situ and Ex-situ Monitoring Strategies for AM-made Product Quality Analysis

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

JOURNAL PAPER

1. van Blitterswijk RH, Botelho LA, Farshidianfar MH, Etman P, Khajepour A. Adaptive thermal model for real-time peak temperature and cooling rate prediction in laser material processing. Journal of Manufacturing Processes. 2023 Sep 8;101:1301-17. **[Link]**
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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]**

HI-AM CONFERENCE

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Subproject 3.1.2: Development of Continuous and Layer-intermittent Imaging Capabilities for WAAM

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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, Dehghai 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]**

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2. Y. Kyu Kwak, T. Lehmann, M. Tavakoli, A. Qureshi. Sensor-Based In-situ Process Control of Robotic Wire Arc Additive Manufacturing Integrated with Reinforcement Learning. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
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4. S. Teng, S. Dehghai, H. Henein, A. Qureshi. Active Print Layer Temperature Control through Base Plate heat Extraction Process. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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- Two theses are anticipated to be published.

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

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]**

HI-AM CONFERENCE

1. H. Farag, B. Khamesee, E. Toyserkani. Detection of internal defects and surface cracks in additively manufactured conductive parts by eddy current technique. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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Subproject 3.1.4: Laser Ultrasonic Sensing for LPB- and LPF-AM

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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]**
3. Ansari M, Martinez-Marchese A, Khamooshi M, Keshavarzkermani A, Esmaeilizadeh R, Toyserkani E. Analytical modeling of multi-track powder-fed laser directed energy deposition: on the relationships among process, deposition dimensions, and solidification microstructure in additively manufactured near-β titanium alloy. Journal of Materials Processing Technology. 2022 Aug 1;306:117643. **[Link]**
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HI-AM CONFERENCE

1. A. Martinez, E. Toyserkani. Literature survey of laser ultrasound imaging techniques for defect detection in metal additive manufactured parts. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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3. A. Martinez-Marchese, E. Toyserkani. Detection of a Subsurface Defect in an Additively Manufactured SS 316L Sample Using Laser Ultrasonics. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
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5. A. Martinez-Marchese, E. Toyserkani. Detection of Defects in Additively Manufactured AlSi10Mg and Ti64 Samples Using Laser Ultrasonics and Phase Shift Migration. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
6. A. Martinez-Marchese, M. Ansari, A. Marzo, M. Wang, E. Toyserkani. Implementation of Ultrasound Particle Lensing Technology on a Laser Directed Energy Deposition Machine for Focusing of Ti6Al4V Powder Stream. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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1. Martinez A. Monitoring and Control of Metal Additive Manufacturing Processes Using Ultrasound. University of Waterloo. 2023. **[Link]**

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

Subproject 3.2.1: Knowledge-based Lumped Models

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]**
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1. G. Shanbhag, M. Vlasea. Design of a test artefact to evaluate critical features for Ti-6Al-4V parts manufactured by electron-beam melting (EBM). The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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1. Shanbhag G. Performance Analytics for Electron Beam Powder Bed Fusion of Ti-6Al-4V. University of Waterloo. 2021. **[Link]**
2. Patel S. Melting Modes in Laser Powder Bed Fusion Additive Manufacturing. University of Waterloo. 2021. **[Link]**

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Subproject 3.2.2: Development of Intelligent Controllers

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]**
3. Taherkhani K, Ero O, Liravi F, Toorandaz S, Toyserkani E. On the application of in-situ monitoring systems and machine learning algorithms for developing quality assurance platforms in laser powder bed fusion: A review. Journal of Manufacturing Processes. 2023 Aug 4;99:848-97. **[Link]**
4. Taherkhani K, Cantzler G, Eischer C, Toyserkani E. Development of control systems for laser powder bed fusion. The International Journal of Advanced Manufacturing Technology. 2023 Dec;129(11):5493-514. **[Link]**
5. Ero O, Taherkhani K, Toyserkani E. Optical tomography and machine learning for in-situ defects detection in laser powder bed fusion: A self-organizing map and U-Net based approach. Additive Manufacturing. 2023 Sep 25;78:103894. **[Link]**

- At least two additional manuscripts are being prepared for publication or are under review.

HI-AM CONFERENCE

1. K. Taherkhani, E. Sheydaeian, C. Eischer, M. Otto, E. Toyserkani. In-line melt pool monitoring of laser powder-bed fusion. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. K. Taherkhani, E. Sheydaeian Arani, E. Toyserkani, M. Otto, C. Eischer. Moving Towards the Development of an Artificial-based Defect-detection Model through the Photodiodes Signals Collected from the Melt Pool of Laser Powder-bed Fusion. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. K. Taherkhani, C. Eischer, M. Otto, E. Toyserkani. Development of a Machine Learning Defect-detection Model through the Photodiodes Signals Collected from the Melt Pool of Laser Powder-bed Fusion. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. K. Taherkhani, E. Toyserkani. Development of Intermittent Controllers for Laser Powder-bed Fusion. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
5. K. Taherkhani, E. Toyserkani. ISO/ASTM 52958:2022 Best Practice for In-Situ Flaw Detection and Analysis for the Laser Beam Powder Bed Fusion (LB-PBF) Process. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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1. Taherkhani K. In-Situ Monitoring and Quality Assurance Algorithms for Laser Powder-Bed Fusion. University of Waterloo. 2022. **[Link]**

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1. Taherkhani K, Toyserkani E. Standard Practice for Additive Manufacturing – Powder Bed Fusion Best Practice for In-situ Defect Detection and Analysis (WK76983). ASTM International. Under Review.

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

Subproject 3.3.1: Measurement System Development and Validation of Combined Powder Spread, Compaction and Binder Fluid Dynamics Linked with Sintering Model + Subproject 3.3.2: Closed-loop Control of Compaction Density and Binder Imbibition and Experimental Validation

JOURNAL PAPER

- At least two manuscripts are being prepared for publication or are under review.

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.

HI-AM CONFERENCE

1. G. Shanbhag, M. Vlasea. A review of particle packing models - Current understanding and Future direction. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. A. Groen, M. Vlasea, K. Erkorkmaz. Modelling of Powder Spreading to Optimize Compaction Consistency. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. M. Wang, M. Vlasea. Literature Survey on the Application of Porous Media Knowledge in PBBJ. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
4. A. Groen, M. Vlasea, K. Erkorkmaz. Exploring Force Feedback During Powder Spreading for Binder Jetting Additive Manufacturing. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

5. R. Boychuk, M. Vlasea. The Use of Sintering Models in Binder-Jet Additive Manufacturing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
6. R. Boychuk, M. Vlasea. Sintering Densification and Distortion Prediction Using the Skorohod Olevsky Viscous Sintering Model. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
7. D. Juhasz, M. Vlasea. Property Enhancement of Binder Jet 3D Printed SS316L Parts using Cu Nanoparticles-enriched Binder. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
8. R. Boychuk, M. Vlasea, K. Ghavam. Toward Sintering Predicting Densification and Distortion in Binder-Jet Additive Manufacturing. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.
9. D. Juhasz, M. Yang, A. Rogalsky, M. Keshavarz, M. Vlasea, M. Laher, A. Molavi-Kakhk. Leveraging Design for Additive Manufacturing to Remedy Low Internal Porosity in Metal Powder Binder Jetting. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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1. Wang M. Part Performance Measurement, Analysis and Optimization for Binder Jetting Additive Manufacturing. University of Waterloo. 2020. **[Link]**
2. Boychuk R. Towards Predicting Densification and Deformation in the Sintering of Binder-Jet Additively Manufactured Part. University of Waterloo. 2023. **[Link]**

- Two additional theses are anticipated to be published.

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1. Groen A, Vlasea M, Erkorkmaz K. Modelling of Powder Spreading to Optimize Compaction Consistency. Technical Report. American Society for Precision Engineering. 2019.

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

Subproject 3.4.1: Combined Trajectory Optimization and Thermal Analytical Models

HI-AM CONFERENCE

1. S. Parks, Z. Kilic, Y. Altintas. Modelling of Electron-beam Deflection System. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. S. Tam, Y. Altintas. FIR Filter Trajectory Generation for Additive Manufacturing Processes. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

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1. Parks S. Modelling of electron beam deflection system for beam position control in metal additive manufacturing. University of British Columbia. 2020. **[Link]**
2. Tam S. Prediction of Cycle Time Using Finite Impulse Response Filter and Polynomial Trajectory Generation Techniques. University of British Columbia. 2023. **[Link]**

Subproject 3.4.2: Adaptive Path Planning Protocols/Controllers and Experimental Validation

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]**

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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.

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1. G. van Houtum, M. Vlasea. High Dynamic Range Imaging for Laser Powder Fed AM. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. G. van Houtum, M. Vlasea. Machine Learning Applications in Laser Powder Bed Fusion Processes. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. D. Sera Ertay, S. Kamyab, M. Vlasea, Z. Azimifar, T. Ma, A. Rogalsky, P. Fieguth. Prediction of Defects Based on Beam Path and Melt Pool Morphology Using Machine Learning for Laser Powder Bed Fusion. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. G. van Houtum, M. Vlasea. Performance Evaluation of State-of-the-art Machine Learning Methods in DED. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
5. J. Patel, M. Vlasea. Challenges in Physics-driven Machine Learning in Laser Powder Bed Fusion. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
6. G. van Houtum, M. Vlasea. The Effect of Domain Shift on Machine Learning Performance in Additive Manufacturing. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.
7. J. Patel, S. Patel, M. Vlasea. Correlative Analytics of Downskin Surface Roughness Outcomes Using Systematic Data Science Workflows. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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1. Ertay DS. Modeling, performance evaluation, and post-process planning for directed energy deposition. University of Waterloo. 2021. **[Link]**

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1. van Houtum GJ, Vlasea M. Development and integration of feature detection algorithms for metal based AM processes. University of Waterloo. Technical Reports published in Feb, Mar, Apr, May, and June 2020.
2. Patel J, Patel S, van Houtum GJ, Azimifar Z, Vlasea M. AMNOW Metals Challenge - Analysis of Digital Thread Additive Manufacturing and Post-Processing Data – Phase 1. Technical Report. America Makes and NCDMM. 2022.
3. Patel J, Patel S, van Houtum GJ, Azimifar Z, Vlasea M. AMNOW Metals Challenge - Digital Thread Analysis for Build Improvements – Phase 2. Technical Report. America Makes and NCDMM. 2022.
4. van Hutoum G, Vlasea M. AWUS Active Learning Software Technology. Provisional Patent # K8002539USP.

Project 4.1: Innovative AM Processes with Integrated Magnetic Systems

Subproject 4.1.1(i): Magnetically driven vacuum-based powder delivery processing head for LPF-AM

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.

HI-AM CONFERENCE

1. Y. Huang, E. Toyserkani, B. Khamesee. An Analytical Model for Laser Powder-bed Additive Manufacturing. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
1. Y. Huang, H. Asgari, M. Ansari, B. Khamesee, E. Toyserkani. Integration of Physically-based and Statistically-driven Models for Multi-objective Optimization of Laser Powder-Bed Fusion. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.

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1. Huang Y. Comprehensive Analytical Modeling of Laser Powder-Bed/Fed Additive Manufacturing Processes and an Associated Magnetic Focusing Module. University of Waterloo. 2019. **[Link]**

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

CONFERENCE PRESENTATION:

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

HI-AM CONFERENCE

1. K. Nsiempba, E. Toyserkani. Predicting defects of 3D printed (L-PBF) lattice structures. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. K. Son, F. Ahmed, E. Toyserkani. Embedding Optical Sensors in Additively Manufactured Parts for Enhanced Functionality. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. K. Nsiempba, O. Ibhadode, E. Toyserkani. A Surface Roughness Constraint for Topology Optimization. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

THESIS

1. Nsiempba KM. Coupled Experimentally-Driven Constraint Functions and Topology Optimization utilized in Design for Additive Manufacturing. University of Waterloo. 2020. **[Link]**
2. Son K. Embedding Optical Sensors in Additively Manufactured Parts for In-Situ Performance Measurement. University of Waterloo. 2021. **[Link]**

OTHER

1. Son K, Ahmed F, Toyserkani E. Feasibility of Embedding Fiber Bragg Grating in Additively Manufactured Metallic Parts. Technical Report. University of Waterloo. 2020.

Subproject 4.1.2: Levitated Additive Manufacturing

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]**

HI-AM CONFERENCE

1. P. Kumar, B. Khamesee, E. Toyserkani. Magnetic Levitation for Additive Manufacturing. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. P. Kumar, E. Toyserkani, B. Khamesee. Design, Optimization, and Validation of a Magnetic Levitation System for Additive Manufacturing. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. S. Malik, P. Kumar, E. Toyserkani, B. Khamesee. An Analytical Approach in the Design of a Complex Electromagnetic Levitation System for Additive Manufacturing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. P. Kumar, S. Malik, E. Toyserkani, B. Khamesee. Design and Analysis of a Magnetic Levitation Systems for Additive Manufacturing Applications. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
5. P. Kumar, B. Khamesee. Magnetic Levitation for Additive Manufacturing: An Alternate Technique. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
6. S. Malik, B. Khamesee. Electromagnetic Levitation for Additive Manufacturing Applications. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

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1. Malik S. Hardware Design and Implementation of an Electromagnetic Levitation System in an Additive Manufacturing Environment. University of Waterloo. 2022. **[Link]**
2. Kumar P. Development of a Magnetic Levitation System for Additive Manufacturing Processes. University of Waterloo. 2022. **[Link]**

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

Subproject 4.2.1: Metal AM for Orthopaedic and Implants Technologies

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]**

HI-AM CONFERENCE

1. A. Moussa, A. El Elmi, D. Melancon, D. Pasini. Mechanics of Additively Built Porous Biomaterials. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.

2. A. Moussa, D. Melancon, A. El Elmi, D. Pasini. Topology Optimization of Imperfect Lattice Materials Built with Process-induced Defects via Powder Bed Fusion. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.

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

Subproject 4.2.2: Development of Smart Molds with Embedded Optical Sensors and Conformal Channels

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 three more manuscripts are being prepared for publication or are under review.

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1. Y. Tang, Y. Zhao. Design of conformal porous structures for the cooling systems of an injection mold. The First HI-AM Conference (HI-AM 2018). May 2018. Waterloo, ON, Canada.
2. Z. Gao, G. Dong, Y. Tang, Y. Zhao. Design and Optimization of Conformal Cooling Channels Assisted by Supervised Machine Learning Process. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
3. Z. Gao, Y. Zhao. Machine Learning Aided Design of Conformal Porous Structure. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. B. Marzbanrad, E. Toyserkani. Embedding Fiber Bragg Gratings in Curved Channels of Additively Manufactured Parts for Temperature and Strain Sensing. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
5. B. Marzbanrad, E. Toyserkani. Manufacturing Smart Part by Embedding Fiber Bragg Gratings Sensors. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Gao Z. Machine Learning Aided Design of Conformal Cooling Channels for Injection Molding. McGill University. 2020. **[Link]**

Project 4.3: Development of Innovative FGM Products

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

JOURNAL PAPER

- At least three manuscripts are being prepared for publication or are under review.

CONFERENCE PRESENTATION

1. G. Bonias, H. Henein, T. Wolfe. Modeling residual stresses of functionally graded deposits using the PTAAM. MCWASP XVI, Published in IOP Conf. Series: Materials Science and Engineering, 2023.

HI-AM CONFERENCE

1. G. Bonias, H. Henein. Additive Manufacturing of FGM Parts Using PTA. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
2. G. Bonias, H. Henein, T. Wolfe. Thermal Modeling of the AM of Functionally Graded Parts Using the PTA for Residual Stresses Prediction and Material Gradation Selection. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
3. G. Bonias, H. Henein. Thermal and Residual Stress Modeling of Functionally Graded Deposits Using the PTAAM. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
4. G. Bonias, H. Henein, T. Wolfe. Thermal and Residual Stress Modeling of Functionally Graded Coatings Deposited by PTA-AM. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

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1. Bonias G. Thermal and residual stress modeling of functionally graded deposits using the PTAAM. University of Alberta. 2022. **[Link]**

Subproject 4.3.2: Direct Manufacturing of FGM Molds Using LPF-AM

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 two more manuscripts are being prepared for publication or are under review.

CONFERENCE PRESENTATION

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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.

HI-AM CONFERENCE:

1. S. Omar, K. Plucknett. Effects of Process Parameters on Material Characteristics During Direct Energy Deposition of AISI D2 Tool Steel. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
2. S. Omar, K. Plucknett. Influence of Heat Treatment on Microstructure and Hardness of Directed Energy Deposition (DED) Processed AISI D2 Tool Steel. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
3. S. Omar, K. Plucknett. Influence of Layer Thickness upon Material Characteristics of AISI D2 Steel Manufactured Using Directed Energy Deposition. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.
4. S. Omar, K. Plucknett. Wear Properties of Wrought and Directly Deposited AISI D2 Tool Steel. The Sixth HI-AM Conference (HI-AM 2023). June 2023. Halifax, NS, Canada.

THESIS

1. Omar SM. Additive Manufacturing of AISI D2 Tool Steel Using Directed Energy Deposition. Dalhousie University. 2023. **[Link]**

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

Subproject 4.4.1: Repair Strategies with LPF-AM

JOURNAL PAPER

- At least three manuscripts are being prepared for publication or are under review.

HI-AM CONFERENCE

1. Z. Russell, K. Plucknett. Laser cladding of high performance Titanium cermets from sol gel structure. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. Z. Russell, K. Plucknett, G. Mazzanti. Laser DED Cladding of Dip-Coated TiC-Ni3Al Cermets on D2 Tool Steel. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. Z. Russel, K. Plucknett. Scratch Resistance and Damage Mechanisms in TiC-Ni3Al Cermet Coatings Fabricated by Pre-placement Laser Directed Energy Deposition. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

THESIS

1. Russell Z. Development and comparison of HVOF and laser DED methods for depositing TiC-Ni3Al based coatings. Dalhousie University. 2023. **[Link]**

Subproject 4.4.2: Repair Strategies Using EWF-AM

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]**

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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.

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1. F. Sikan, P. Wanjara, J. Gholipour, M. Brochu. Evaluation of additive manufacturing for repair and remanufacturing purposes. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
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3. F. Sikan, P. Wanjara, J. Gholipour Baradari, M. Brochu. Evaluation of Laser Powder Bed Fusion Process for Repair Purposes. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
4. F. Sikan, M. Brochu. Effect of Substrate Condition and Initial Residual Stresses on Electron Beam Wire Fed Additive Repair. The Fifth HI-AM Conference (HI-AM 2022). June 2022. Montreal, QC, Canada.

THESIS

1. Sikan F. Electron Beam Wire-fed Deposition of Titanium Alloys for Repair Applications. McGill University. 2022. **[Link]**

Subproject 4.4.3: Repair Strategies Using PTA- and FFF-AM

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.

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1. N. Bhardwaj, H. Henein, T. Wolfe, J. Chen, N. Laderoute, M. Danysh. Fused Filament Fabrication (FFF) with Metal Matrix Composite Powders. The Second HI-AM Conference (HI-AM 2019). June 2019. Vancouver, BC, Canada.
2. N. Bhardwaj, H. Henein, T. Wolfe. Fused Filament Fabrication of Metal Matrix Composites (MMC). The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
3. R. Samson, T. Lehmann, H. Henein, A. Qureshi. In-situ Volume Reconstruction for Additive Manufacturing Repairs: A Review. The Third HI-AM Conference (HI-AM 2020). June 2020. Virtual.
4. R. Samson, A. Qureshi, H. Henein. In-situ Automated Scan-assisted Repair by Additive Manufacturing. The Fourth HI-AM Conference (HI-AM 2021). June 2021. Virtual.
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1. Bhardwaj N. Fused Filament Fabrication of Metal-Ceramic High-Density Polyethylene Composites. University of Alberta. 2022. **[Link]**
2. Samson R. In-situ automated scan-assisted repair using additive manufacturing. University of Alberta. 2022.

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