NSERC HI-AM Network

NSERC-HI-AM.CA @NSERC_HI_AM @NSERC HI-AM NETWORK 2020–2021

HOLISTIC INNOVATION IN ADDITIVE MANUFACTURING

PROGRESS REPORT 3

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

PROGRESS REPORT 3

2020-2021

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Message from the Chair and Director

Ralph Resnick
Chair of the Board of Directors

Ehsan Toyserkani
Network Director

It is our privilege to present the third progress report of the NSERC Strategic Network for Holistic Innovation in Additive Manufacturing (HI-AM). This report summarizes the research outcomes and network activities that took place between July 2020 and July 2021.

First and foremost, we are very grateful to the members of the Network, including 19 Principal Investigators; 22 Industry, Government, and Non-profit partners; 120 highly qualified personnel; three academic collaborators; and ten international academic partners. Furthermore, we recognize the contributions of the members of the Board of Directors, the Scientific Advisory Committee, and the Commercialization and Outreach Advisory Committee.

In early 2021, the HI-AM Network signed a Memorandum of Understanding with the American Society for Testing and Materials (ASTM) International, outlining a cooperative framework for the development of standards in the area of additive manufacturing. We are grateful to ASTM for their trust in the Network. This MoU demonstrates the high value ASTM places in the quality of research produced by the Network, and their confidence in the contribution our results can make towards standards development. We are very pleased to announce that two HI-AM projects have been registered in ASTM to develop standards on quality assurance and powder compaction density measurement methods. Several projects are also on the radar of ASTM, and discussions with the associated principal investigators are underway.

We are grateful to ASTM for their trust in the Network. This MoU demonstrates the high value they place in the quality of research produced by the Network, and their confidence in the contribution our results can make towards standards development.

The Network has produced substantial results through its 35 active and 4 completed projects across four research themes under the supervision of the Network principal investigators. More than 289 journal and conference papers have been produced through these projects; and six invention disclosures have been filed.

Across research themes and R&D teams, interesting and impactful results are now emerging from the HI-AM Network. Efforts are being made to commercialize these inventions through our industrial partners.

We originally planned to hold the 2021 HI-AM conference at Dalhousie University in Halifax; however, the continuation of the pandemic gave us no choice but to hold a virtual conference once again. The conference took place on June 1st and 2nd, 2021, and featured 115 talks and poster presentations, with more than 600 participants. This conference would not have been possible without the contributions of many individuals and organizations. In particular, we would like to extend our appreciation to the Natural Sciences and Engineering Research Council of Canada (NSERC), University of Waterloo, Dalhousie University, EOS, Exergy Solutions, Javelin Technologies, KSB, Leichtbau BW GmbH, Multi-Scale Additive Manufacturing Lab, Postprocess Technologies, Promation, PULSTEC, SLM Solutions, Suncor Energy, Trumpf, and Xact Metal.

One of the major negative impacts of the pandemic has been the cancellation of our exchange programs in 2020 and 2021. In addition, several outreach programs have been delayed. The network manager is working very hard to allow these events to take place in 2022. Several experimental projects have also been altered, and we will face some progress delays as a result.

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

Ralph Resnick,
Chair of the Board of Directors

Ehsan Toyserkani,
Network Director

Shaping the Future of Additive Manufacturing

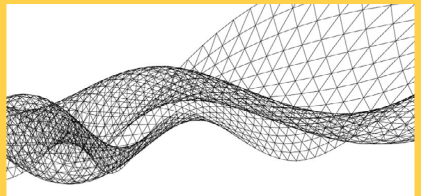
Additive Manufacturing (AM) has the potential to change the entire manufacturing sector by 2030. Despite the recent progress in this field, there are several remaining challenges hindering the widespread industrialization of this technology, from expensive and limited powder feedstock to the need for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

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

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

HI-AM Research Themes

THEME 1: Material Development Tailored with Optimum Process Parameters



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

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

THEME 4: Innovative AM Processes and AM-made Parts

Mission and Vision

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

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

To this end, the following objectives are pursued:

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

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

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

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

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

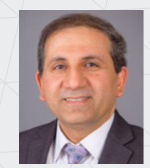
Governance

BOARD OF DIRECTORS*

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

VOTING MEMBERS

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



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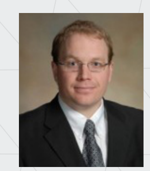

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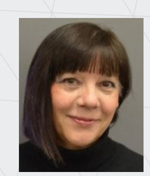

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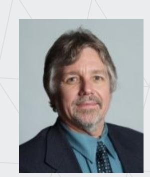

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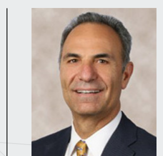

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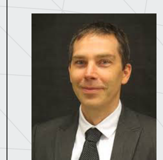

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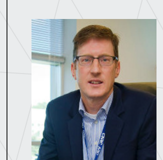

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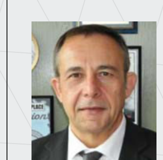
Director, Research and Development



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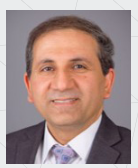
*As of October 2021

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.



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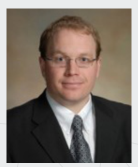

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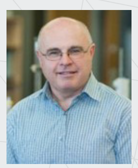

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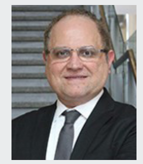
Professor of Chemical and Materials Engineering



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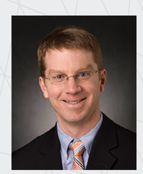

Timothy Simpson
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Paul Morrow Professor of Engineering Design and Manufacturing

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

*As of October 2021

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
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Director of Strategic Initiatives

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Dave Dietz
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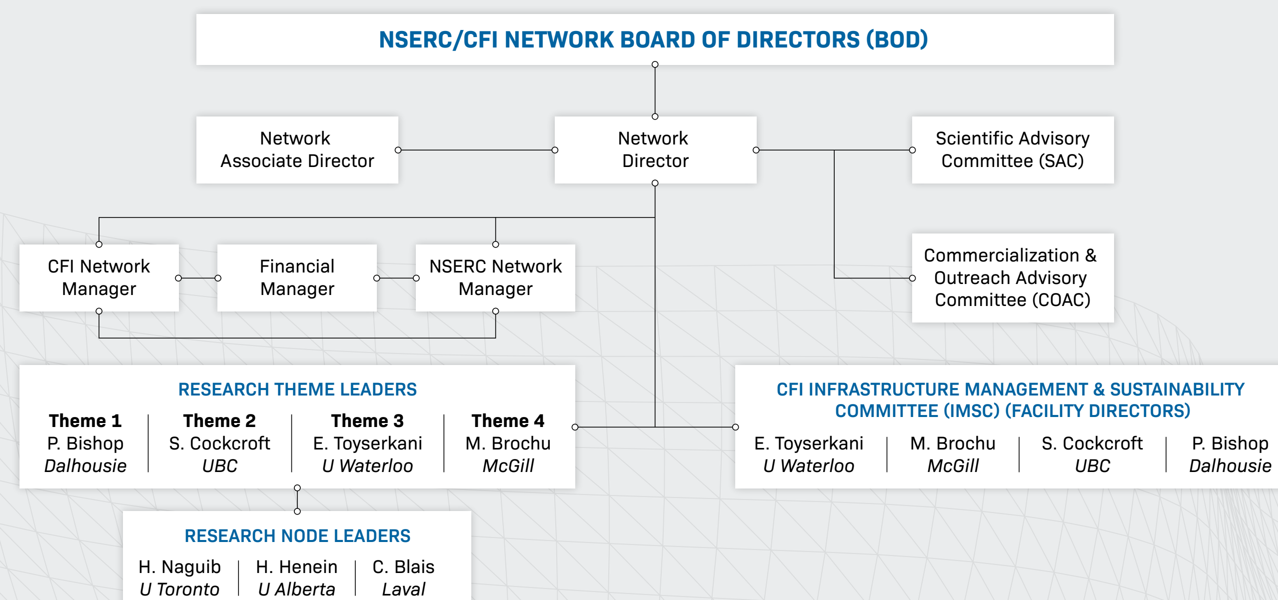
Manager, NSERC HI-AM Network

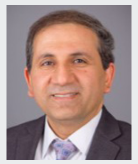
*As of October 2021

GOVERNANCE STRUCTURE



Principal Investigators

THEME/NODE LEADERS



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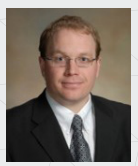

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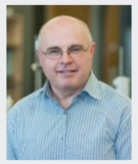

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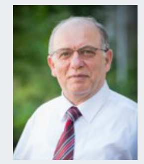

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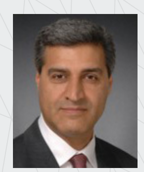

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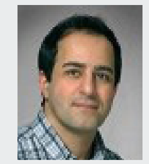

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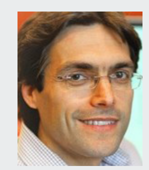

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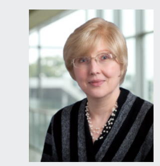
Département de génie mécanique



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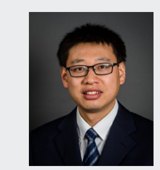

Yu Zou
PhD
University of Toronto
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Dept. of Mechanical & Industrial Engineering

Network Partners

ACADEMIC AND RESEARCH INSTITUTION PARTNERS*

MEMBERS

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

COLLABORATORS

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

INTERNATIONAL

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

INDUSTRY PARTNERS*

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

GOVERNMENT PARTNERS*

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

NON-PROFIT PARTNERS*

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

*As of October 2021

Network Statistics (To Date)

7 UNIVERSITIES	2 ACADEMIC COLLABORATORS	22 INDUSTRIAL/ GOVERNMENT PARTNERS	35 ACTIVE PROJECTS 4 COMPLETED PROJECTS
22 PRINCIPAL INVESTIGATORS	122 HIGHLY QUALIFIED PERSONNEL*	63 JOURNAL PAPERS**	51 CONFERENCE PAPERS/ PRESENTATIONS
159 HI-AM CONFERENCE PAPERS/ PRESENTATIONS	19 OTHER PUBLICATIONS***	6 INVENTION DISCLOSURE	4 EVENTS

* 34 HQP have been funded from external sources; 71 HQP have been graduated or completed their program
** Published or under review
*** Thesis, Technical report, Patent

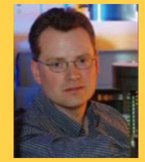
HIGHLY QUALIFIED PERSONNEL (HQP) BY THEME

	Undergraduate	MASc	PhD	PDF/RA
THEME 1	7	13.5	16	10
THEME 2	0	7.5	9	3
THEME 3	3	12	15	3
THEME 4	5	7	6	5
TOTAL	**15**	**40**	**46**	**21**

Research Progress

THEME 1: MATERIAL DEVELOPMENT TAILORED WITH OPTIMUM PROCESS PARAMETERS

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



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

Project 1.1: Development of Next Generation Alloys

DESCRIPTION

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

PROGRESS

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

- Perform non-equilibrium thermodynamic modeling on several binary alloys and print several Al alloys using LPBF, followed by post-build heat treatments and mechanical characterization.
- Conduct laser ablation trials using a range of laser power and scan speeds on as-cast Al-Zr-Y, followed by post-ablation heat treatment and microstructure analyses of as-cast and laser ablated surface layers.
- Study precipitate-coarsening kinetics to determine the AlSi2Sc2 precipitate size as a function of various holding temperatures and times in Al-10Si-0.4Sc after aging. Two microstructure modeling studies are underway to find the eutectic growth velocity and local thermal gradient of as-atomized Al-10Si-0.4Sc alloy and the primary dendritic undercooling.
- Study four alloys produced using impulse atomization to observe the effects of rapid solidification and alloying, both as a single approach and as independent factors, on the microstructure of Al-40Si by comparing the changes in primary Si morphology and distribution across different powder sizes for each alloy and across all alloys for specific powder sizes.
- Prepare ingots of Al-33Cu3Mg05Si using the investment casting approach to determine the heat treatment and tensile properties of the alloy to generate input data required for numerical simulations of stress distribution in the lattice and composite.

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

- Optimize process parameters for DED processing of Ti6242, Beta 21S, and Ti55511 alloys based on microstructure and density responses. Near full density has been realized with optimized deposition parameters.
- Perform fracture surface analysis and tensile tests on parts fabricated using optimized process parameters for all three alloys.
- Start exploring the heat treatment response of optimally built parts using various characterization techniques.

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

- Reduce the oxygen content to below 0.18 wt-% through further modification and thermochemical simulation of novel A8-based and S7-based tool steels.
- Optimize water atomization of S7 to maximize the particle roundness, followed by powder flow and density characterization. Results to date show that the optimized powder has rheological properties identical to those of commercial gas-atomized H13.
- Atomize 17-4PH using Impulse Atomization in He, followed by microstructure analysis, EBSD, and solidification modeling using Thermocalc.
- Investigate the correlation between thermal conditions and denuded region formation for 17-4PH electromagnetic levitation samples.
- Develop and optimize the computer vision model to semantically segment angular and spherical WC from Ni-based WC metal matrix composites built using PTA-AM from optical microscopy images. The model is able to quantify the carbide percentage and mean free path.

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

- Characterize parts made from Rene 41 using LPBF with different angles and thin cross-sections, and study the effect of geometry on solidification microstructure, as well as the effect of elemental segregation on the printability of different cross-sections.
- Fabricate Rene 77 parts using LPBF, followed by heat treatment and comparison of as-built and heat-treated features such as microstructure, tensile properties, and crack susceptibility.
- Study the microstructural evolution during direct aging of an LPBF fabricated part by applying various heat treatments to the as-built samples. Changes in the carbide morphology, γ' size, and volume fraction have been characterized after the samples were subjected to the heat treatment.
- Complete powder characterization, LPBF process optimization, microstructure analysis, mechanical testing, and oxidation resistance studies for five intermetallic materials, including Fe3Al, TiAl (TiAl4822), Ti3Al, and NiAl (stoichiometry).

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

- Optimize, characterize, and study the solidification behavior of TZM alloy fabricated using LPBF.
- Compare the microstructure and mechanical properties of Mo and TZM to understand the effect of process conditions versus alloying elements.
- Conduct a literature review on applications of Mo in the production of heat sinks, and the use of lattice structures in tailoring the coefficient of thermal expansion (CTE).
- Review the literature to identify a suitable Mo-Si-B alloy for LPBF, then design and execute printing and optimization of that alloy based on the knowledge gained through process development for TZM and pure Mo.
- Fabricate Mo constructs with different lattice designs using LPBF, followed by dilatometry and microstructure studies, to examine grain size, structural and morphological characteristics, and solidification behavior of the alloy.
- Investigate the behavior of LPBF-made Mo parts under different thermal conditions via dilatometry.

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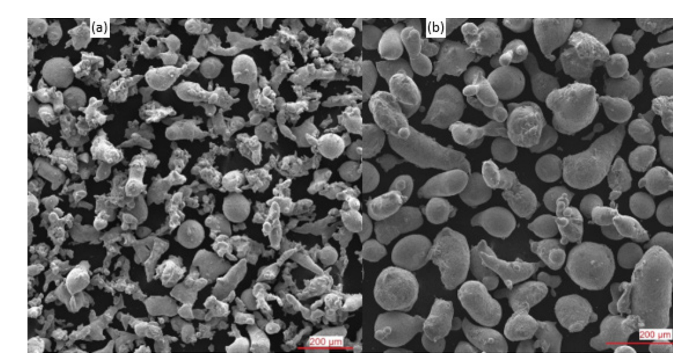


SEM micrographs showing morphologies of water-atomized powders fabricated using (a) conventional atomization configuration, (b) optimized spheroidization. (Sub-project 1.1.3)

Project 1.1: Development of Next Generation Alloys (Continued)

RESEARCHERS

SUB-PROJECT	PRINCIPAL INVESTIGATOR(S)	HIGHLY QUALIFIED PERSONNEL
1.1.1 Development of Thermally Stable Aluminum Alloys for LPB-AM	• Paul Bishop, Dalhousie University • Mathieu Brochu, McGill University • Hani Henein, University of Alberta	• An Fu, McGill University, PhD • Jon Heirly, Dalhousie University, PhD • Quentin Champdoizeau, University of Alberta, MASc • Daniela Diaz, University of Alberta, 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 • 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)
1.1.2 Development of Titanium Alloys for LPB-AM and LPF-AM	• Paul Bishop, Dalhousie University	• Matthew Harding, Dalhousie University, PDF • Greg Sweet, Dalhousie University, PDF • Nick Gosse, Dalhousie University, Co-op, PhD • M.D. Hasan Khondoker, Dalhousie University, PDF (Collaborator) • Addison Rayner, Dalhousie University, PDF
1.1.3 Development of Tool Steels for LPB-AM and LPF-AM	• Carl Blais, Université Laval • Hani Henein, University of Alberta	• Denis Mutel, Université Laval, PhD • William Chaîné, Université Laval, MASc • Anne McDonald, University of Alberta, URA • Dylan Rose, University of Alberta, PhD (Collaborator) • Nasim Navid Moghadam, University of Alberta, PhD • Swalihah Noorani, University of Alberta, URA • Yume Bhutia, University of Alberta, URA (Collaborator)
1.1.4 Development of Nickel Alloys for LPB-AM	• Mathieu Brochu, McGill University • Kevin Plucknett, Dalhousie University	• Sila Atabay, McGill University, PhD • Kevin Lee, McGill University, PhD • Anh Tran, McGill University, Co-op
1.1.5 Development of Refractory Metals for LPB-AM	• Mathieu Brochu, McGill University	• Tejas Ramakrishnan, McGill University, PhD

Project 1.2: AM Processing of Multi-Material Systems

DESCRIPTION

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

PROGRESS

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

- Develop shape memory composites for 4D printing applications using BJ-AM from MXene, with optimized concentration and surface energy with respect to the PVA powder substrate. Successful applications in printing of electrodes in a 2-cell sandwiched micro capacitor and a strain sensor have been demonstrated, testifying to the potential of binder jetting in the development of composites with various functionalities.
- Investigate the effect of isopropyl alcohol (IPA)-assisted PEDOT:PPS coating for transparent actuator applications; preliminary results show great promise in terms of suitability for production of ransparent actuators.
- Optimize the process parameters for direct ink writing (DIW) of MXene-PEDOT: PSS-based ink using a mathematical model based on the constraint of extruding a fixed volume of ink over a fixed distance.
- Parametrize, analyze and model a triangular origami structure, followed by experimental verification of the design through multi-material FDM printing with flexible PLA materials for crease areas and rigid PLA for origami face areas. Compression and impact testing of the origami-inspired samples are ongoing.

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

- Complete DED process development and heat treatment of H13 alloy, followed by scratch testing to obtain coefficient of friction data and scratch hardness values. Further experiments have been carried out, including microstructural characterization of as-printed samples using SEM, EDS, and XRD; retained austenite measurements using a Proto Manufacturing LXRD system; DSC of wrought H13; and thermal conductivity of wrought H14 using a laser flash analysis approach.
- Characterize copper powder using SEM, ICP, PSD, apparent density, and flow testing.
- Conduct a design of experiments study for DED of FGM based on H13/Cu, followed by DSC, EDS, and EBSD testing of as-printed and heat-treated parts.
- Conduct pack boriding of samples to examine the influence of scratch hardness and boriding on DED of H13.

RESEARCHERS

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

Project 1.3: Cost Reduction Strategies

DESCRIPTION

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

PROGRESS

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

- Study the effect of moisture on powder processing and part contamination in LPB.
- Establish a recyclability threshold of up to 113 cycles for maraging steel 300, and compare the physical, chemical, and microstructure properties of recycled and virgin powders as well as the properties of parts made from each powder.

Sub-project 1.3.2: Plasma Spheroidization of Low Cost Powders

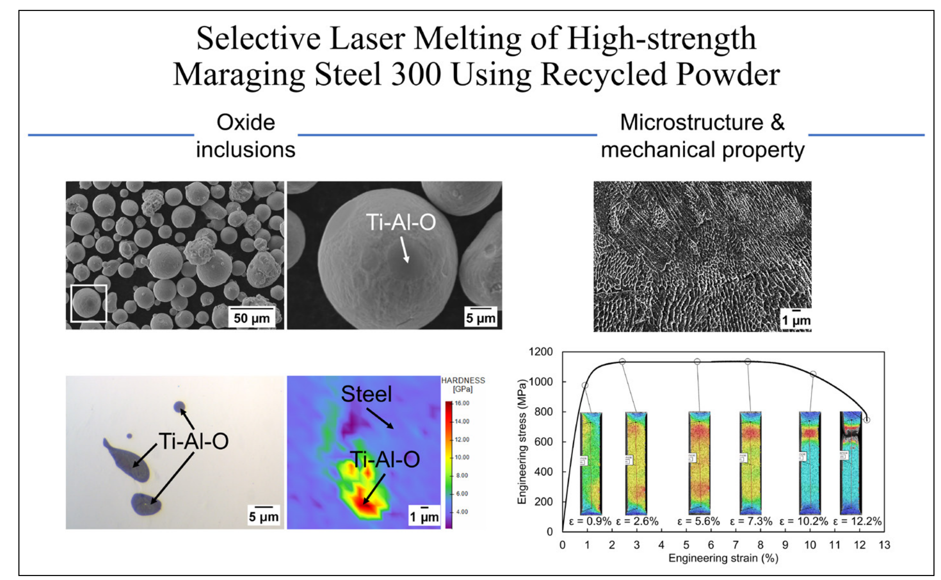
- Characterize different types of Ti powders, including recycled powders from LPBF and DED processes, HDH Ti powders, and sponge Ti powders using PSD, oxygen content, and morphology measurement tests.
- Initiate plasma spheroidization trials of sponge, HDH, and recycled Ti powders, followed by PSD, oxygen content, apparent density, flowability, and morphology characterization.

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

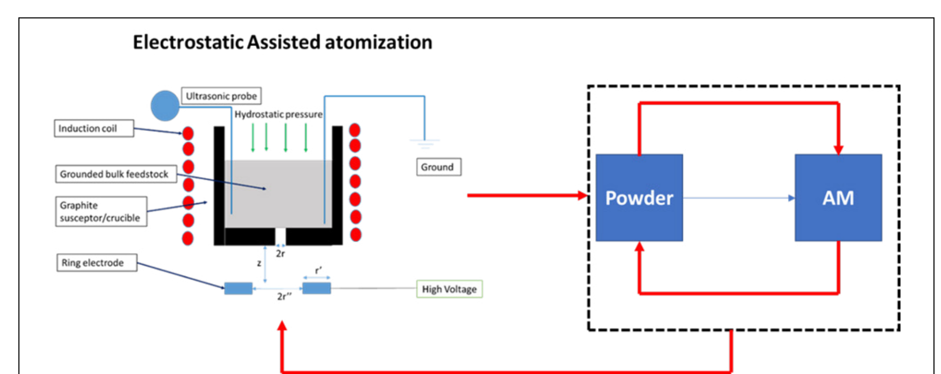
- Refine the electrohydrodynamic atomisation (EHDA) model.
- Carry out several experiments using water, ethylene glycol, and tin as the working fluid with various orifice diameters to determine the appropriate applied frequency for electrostatic atomization, such that the jet operates only in the Rayleigh regime. The experimental results were demonstrated to be within the acceptable error range predicted by multiple theories.
- Print and sinter larger cylindrical compression specimens of D2 tool steel under vacuum using BJAM. Heat treatment studies on sintered parts is underway.
- Complete a detailed study on off-gassing of 5120 steel powder via TG-GCMS. Larger cuboid specimens of 5120 alloy printed using BJAM have been sintered under high vacuum, and 95N2-5H2 atmospheres and optical metallography of sintered samples has been conducted.
- Characterize the microstructure and mechanical properties of as-built and heat-treated samples of DP600 produced by L-DED, and optimize the L-DED process parameters for this alloy. The mechanical properties of L-DED parts have been compared to those of wrought material.
- Compare the density and chemical composition of DP600 parts printed using gas-atomized and water-atomized powders for L-DED processing.
- Conduct a DoE study to optimize the processing parameters for L-DED of 42CrMo4 steel (4140) with density and microstructure as design responses. Experimental studies have been conducted by printing and applying heat treatment of multi-layer clads on a 42CrMo4 substrate, followed by analysis of microstructures, chemistries, and residual stresses.
- Develop a thermo-mechanical-metallurgical (TMM) FEM for L-DED of water-atomized 42CrMo4 steel using Abaqus, incorporating the solid-state transformation strains directly into the mechanical analysis followed by experimental validation of the model.
- Produce water-atomized D2 tool steel and experimental master alloys using the novel technique developed at Laval to obtain near-spherical particles, and simulate the sintering behaviour of binder jet specimens.

RESEARCHERS

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



Selective laser melting of high-strength Maraging Steel 300 using recycled powder (sub-project 1.3.1)



Schematic view of electrostatic assisted atomization. (Sub-project 1.3.3)

Research Progress

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

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

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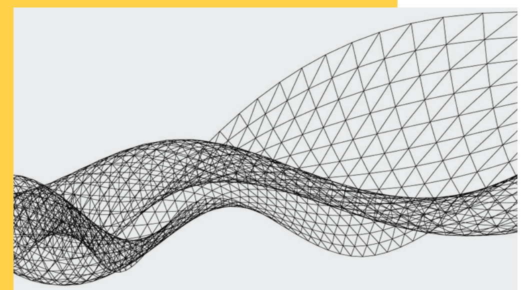


Project 2.1: Multi-scale Modeling of AM

DESCRIPTION

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

PROGRESS

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

- Complete the development of a macro-scale thermal model of the cantilever plate used in the analysis of several support structure geometries. This enables linking the thermal profile within the builds to the extent of deformation observed.
- Modify the baseplate design to support multiple independent testing zones for experimental validation of the inverse heat conduction (IHC) model. The experimental validation has been carried out with and without powder while changing the process parameters to investigate their effect on the resulting temperature data.

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

- Develop the 3D thermal fluid model of melt pool dynamics and powder consolidation in EB-PBF, with a focus on deformation of the free surface associated with evaporative recoil. Model verification and sensitivity analyses are ongoing. Progress towards experimental validation of the model also includes the printing of single tracks of Ti64 on a CP-Ti substrate under various process parameters.
- Conduct a literature review on the microstructure modeling of LPBF of metallic alloys.
- Develop an inverse heat conduction (IHC) model, validated using data obtained from a COMSOL FEM for powderless laser scanning of a substrate, in order to identify the heat flux boundary conditions from LPBF experiments using temperature data obtained in sub-project 2.1.1.

Sub-project 2.1.3: Macro-scale Thermal Field Evolution

- Sub-project 2.1.3 was completed in 2019-2020.

Sub-project 2.1.4: Multi-Scale Modeling of AM:
(a) Macro-scale Stress Field Evolution Simulation,
(b) Meso-scale Stress Field Evolution Simulation,
(c) Residual Stress Characterization

- Develop a multilayer meso-scale model to characterize the development of the strain field around the melt pool as it undergoes solidification. The sensitivity analysis of the model was completed to develop a look-up table providing an estimate of inherent plastic strain for a given set of process parameters.
- Develop a micro-scale thermal/stress model using an alternative geometry with the results of the meso-scale model as a potential input.
- Design, construct, and test an in-situ, battery-powered data acquisition system capable of operating in a vacuum environment with an electron beam present.
- Develop and validate a macro-scale model of the build chamber in an EB-PBF system using cavity radiation to account for radiative heat transport between the powder bed and heat shield walls within the vacuum chamber to examine the effect of cross-sectional geometry on the build chamber temperature.

Sub-project 2.1.5: Microstructural Modeling and Experimental Validation

- Complete the solidification continuous cooling transformation (SCCT) diagram for impulse atomized Al-40Si powder.
- Develop a numerical model of eutectic growth for Al-33wt%Cu.
- In-situ processing of Al-33wt%Cu is progressing with an in-situ video recording system successfully capturing the solidification at various cooling rates. Further tests are planned to study the effect of undercooling on eutectic morphology and spacing.

RESEARCHERS

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

Project 2.2: Accelerated Real-time Simulation Platforms

DESCRIPTION

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

PROGRESS

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

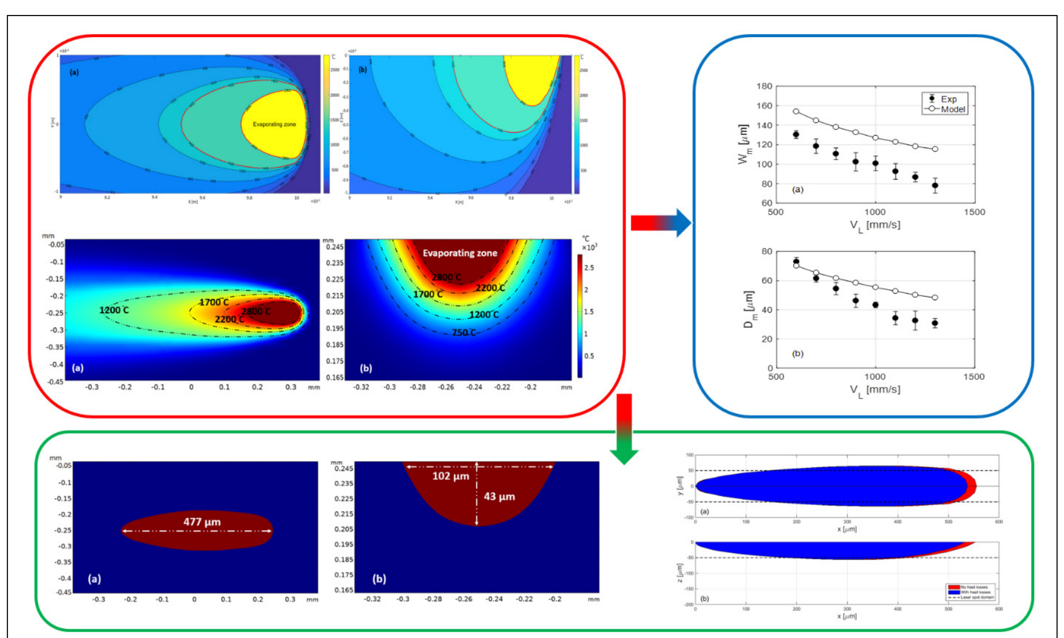
- Sub-project 2.2.1 was completed in 2019-2020.

Sub-project 2.2.2: Fast Process Stress-Field Simulation

- Complete a literature review on the fast predictive thermo-mechanical modeling approaches.
- Develop a 2D thermal model of the LPBF process based on an extended Rosenthal equation, enabling fast prediction of the melt pool dimensions and temperature distribution with reasonable accuracy.
- Develop a 3D finite element model using volumetric heat source (Conical-Gaussian) to verify the thermal model results.

RESEARCHERS

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



Fast process stress-field simulation outcomes. (Sub-project 2.2.2)

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

DESCRIPTION

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

PROGRESS

Sub-project 2.3.1: Pre-processing for Dimensional Control

- Develop a macro-scale finite element model to simulate the deviation of SLM processes and the developed GD&T quantification methods. A complete case study has been conducted on a pin-hole assembly component, leading to the experimental validation of the skin model shapes methodology for geometric tolerance prediction of metal AM parts.
- Continue the simulation phase to relate the input and interim parameters (temperature and stress) to final geometric tolerances.

Sub-project 2.3.2: Lattice Structure Design for AM Processing

- Experimentally validate the numerical model, accounting for defects and geometrical parameters of metallic lattice structures.
- Conduct a literature review on polymeric lattices to extend the methodology to polymer-based lattice structures; then select an appropriate polymer and design a polymeric periodic lattice structure based on the review.
- Develop a machine learning model to link the design, process, and quality of the final products based on a database of 162 labeled designs.
- Develop a system to predict the manufacturability of LPBF and a recommender to provide suggestions to the designer in terms of the process parameters, materials, machines, and placing orientation.

Sub-project 2.3.3: Mismatch Determination During AM of Thin Structures

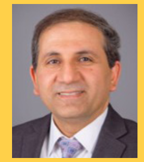
- Simulate the tensile deformation and failure behavior using finite element modeling based on a previously developed CAD 3D model integrated with surface morphology.
- Experimentally characterize the tensile deformation and failure in microstruts using a combination of in-situ imaging and micro-tensile testing.
- Characterize the surface defects and investigate their relation to fatigue crack initiation.
- Obtain superior tensile performance in microstruts using laser machining and electropolishing.
- Conduct a literature review on surface deformation in thin-walled parts.
- Develop a standard fatigue testing method for thin-walled rods / as-built struts.

RESEARCHERS

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

Research Progress

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



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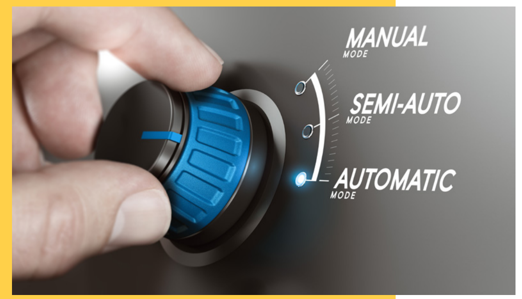
Insufficient process reliability and repeatability, resulting from random and environmental disturbances, are critical impediments for widespread AM adoption. A key solution to compensate for these disturbances is using closed-loop control systems and algorithms to monitor the process, and to tune actuating 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.

PROGRESS

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

- Install the monitoring system in a L-DED system developed by Promation for performance validation and data collection.
- Implement control for geometry and material properties.
- Improve the geometry prediction algorithm to respond to different laser diameters.
- Test the sensor module on processes such as plasma deposition and gas metal arc welding, to visually determine the quality of images and improve the image quality through modification of filters in the visible light range.
- Develop and utilize a machine learning algorithm to predict the geometry of the clad during deposition as well as the cooling rate with a mean absolute percent error of less than 1.6%. The algorithm will be further modified to predict the geometry in multi-layer depositions.

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

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

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

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

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

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

RESEARCHERS

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

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

DESCRIPTION

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

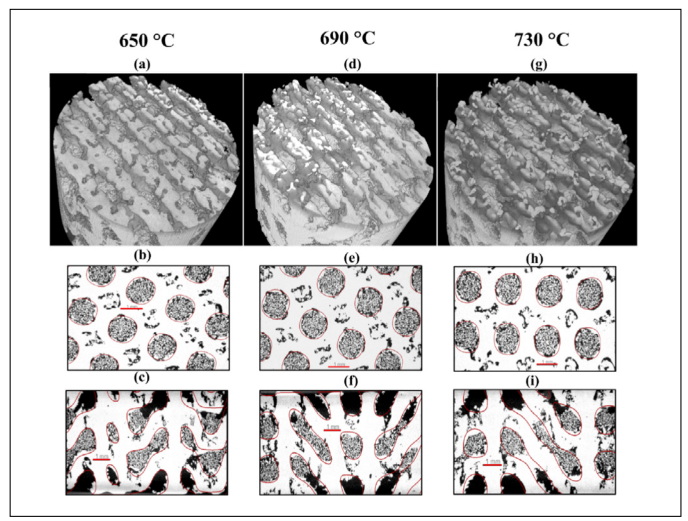
PROGRESS

Sub-project 3.2.1: Knowledge-based Lumped Models

- Develop a hybrid (empirical and physics-based) mathematical model to infer the thermal conductivity of the powder cake in EBM.
- Conduct statistically designed experiments to validate the models in two studies: (1) experimental data acquisition and analysis on the effects of powder re-use on powder characteristics, (2) analysis of tensile properties as a function of spatial effects (distribution on the build plate, orientation), and temporal effects (height along the build). An analysis of surface roughness properties in EBM as a function of spatial and temporal effects is ongoing.
- Investigate the effect of the preheat stage in EBM on the geometric fidelity and de-powdering of complex lattice architectures.

Sub-project 3.2.2: Development of Intelligent Controllers

- Validate the results of absolute limits and self-organized map (SOM) algorithms in the detection of intentional and randomized effects using micro-CT scan results.
- Simulate the monitoring/control process in LabVIEW to obtain real-time data from DAQ system, apply geometry and intensity correction on the data, and apply the SOM algorithm to identify the location of defects, and apply the intermittent controlled based on the defect size to change the laser power.
- Simulate the process in MATLAB and Python to compare their processing times with that obtained with LabVIEW.



2D and 3D XCT visualizations of Diamond 4 TPMS structures manufactured at 650 °C ((a), (b), (c)), 690 °C ((d), (e), (f)), and 730 °C ((g), (h), (i)). (Sub-project 3.2.1)

RESEARCHERS

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

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

DESCRIPTION

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

PROGRESS

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

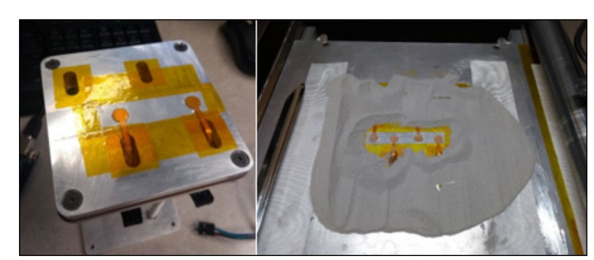
- Develop and calibrate a discrete element powder compaction model. Final experimental validation of the model using vision systems and pressure transducers is ongoing.
- Develop a methodology for extracting pore space and particle space characteristics, and models based on experimental datasets.
- Develop predictive tools for densification based on sinter theory in 1D, 2D, and 3D. A literature review of sintering models relevant to BJAM has been completed; initial experimental and modeling work to study shrinkage, gravity-induced distortion during sintering, and creep is ongoing.

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

- Characterize the mechanical properties of parts to investigate the effect of compaction method on the key properties.
- Use a feedback vision-based detector and strain-gauge array to quantify and control the selected powder compaction process for BJAM.

RESEARCHERS

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



(left) New capacitive force sensor array with high sensitivity, as aligned on the build plate – new sensor mount configuration; (right) overview of the new sensor placement in the build bed during data collection design of experiment. (Sub-project 3.3.1/3.3.2)

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

DESCRIPTION

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

PROGRESS

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

- Transfer of research results and knowledge on the design of a novel electron beam magnetic housing to industry.
- Develop two cascaded finite impulse filters (FIR) to deliver smooth position, velocity, and acceleration commands to the AM machine drivers and laser beam. The trajectory planning algorithm is currently being fine-tuned with a focus on improving the performance at corners.
- Develop an L-DED experimental setup based on an in-house built CNC system to test the smooth FIR filter-based trajectory generation.

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

- Develop fast modeling and model-calibration strategies for LPBF and DED by exploring various methods. An active learning (AL) model and data classification system for vision data has already been developed. Work on an experimentally-driven model for adaptive model training and a combined AI and batch selection methodology is underway.
- Test and validate the performance of classifier and segmentation models using the annotated datasets.
- Leverage or embed in-line strategies for process signature detection using VIS high-speed detector and VIS/NIR HDR-based sensors for the wire-fed DED process. Application of similar systems to powder-based DED and LPBF is ongoing.
- Define process stability based on in-process signatures by developing correlations between sensor data, characterization data, and experimental datasets. The use of surface roughness artefacts and melt pool morphology for training the ML models is being investigated.

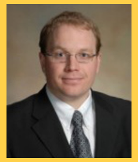
RESEARCHERS

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

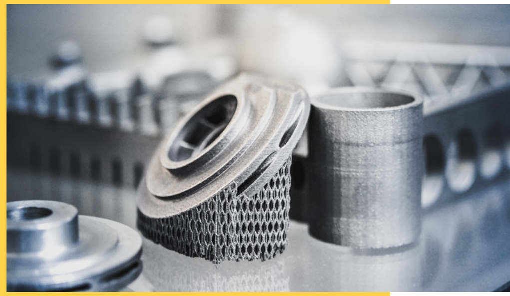
Research Progress

THEME 4: INNOVATIVE AM PROCESSES AND AM-MADE PRODUCTS

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



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



Project 4.1: Innovative AM Processes with Integrated Magnetic Systems

DESCRIPTION

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

PROGRESS

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

- Complete the study of the optimization of coupon parameters for embedding FBG sensors, tensile testing, cyclic testing, and thermal testing.
- Model the failure test to identify the coupon's deformation stage (i.e., linear elastic strain onset, strain hardening, necking, and coupon fracture) by tracking the FBG's peak wavelength as it undergoes the failure test.
- Model the curved channel orientation of the FBG-coupon assembly in COMSOL implementing both MODS and electromagnetism physics.
- Complete the look-up tables for printing of cellular structures based on printability parameters/thresholds, and extract information from topologically optimized structures to adjust the thickness of cells in 2D.

Sub-project 4.1.2: Levitated Additive Manufacturing

- Develop a numerical model of the magnetic levitation setup considering the geometrical constraints of the AM system for estimating the levitation force on the nucleus with different materials and geometry. Initial experimental validation using aluminum alloys have been carried out.

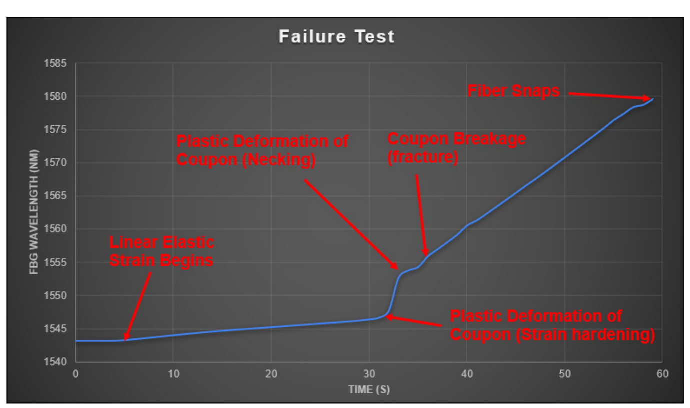
Continued on next page...

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

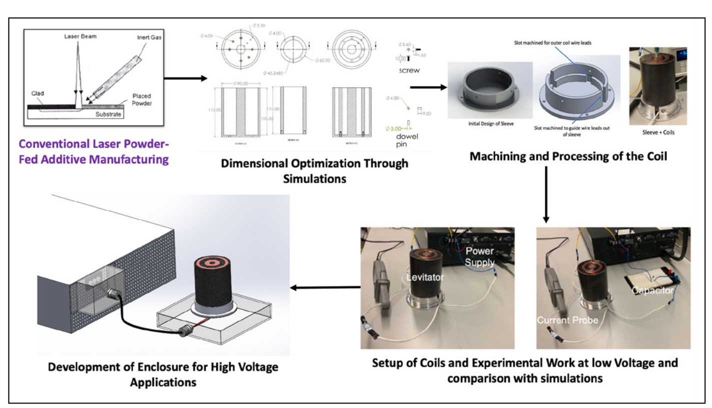
- Use finite element modeling to optimize the geometry of the disc to maximize the levitation force. The model has already been validated by comparing its results to the simulation results from reference papers.
- Develop an enclosure to facilitate the high voltage experiments and to protect the levitation system form powder intrusion from conductive dust.
- Complete and tune the design of an apparatus for magnetic levitation.
- Following the successful setup of the system, experimental validation trials started at low voltage (5-20 V rms) with and without a capacitor, followed by the comparison of the measured magnetic field results to the simulation output. The maximum error observed was 7%.

RESEARCHERS

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



FBG peak reading during failure testing. (Sub-project 4.1.1)



Development of the levitated additive manufacturing setup. (Sub-project 4.1.2)

THEME 4

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

DESCRIPTION

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

PROGRESS

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

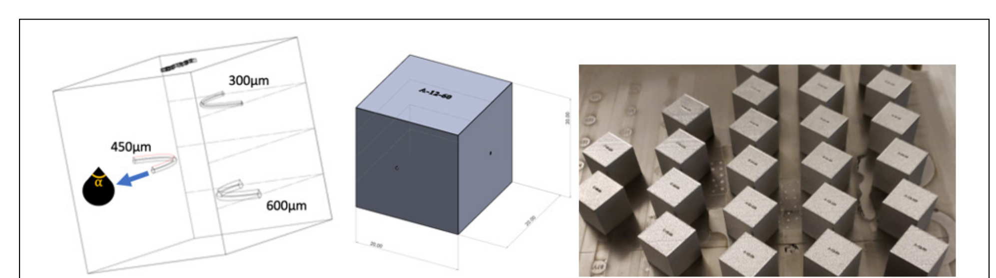
- Design porous implants that can optimally resolve the trade-off between clinical requirements, and account for process-induced defects as well as stress constraints.
- Generate patient-specific implant geometry based on AM limits and bone in-growth properties.
- Manufacture and test proof of concept implants for validation of predicted implant performance metrics.

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

- Complete modeling activities, such as modeling the sensing functions needed for conformal cooling systems and developing a manufacturability analysis model for sensing functionality.
- Design and print parts with curved channels of various diameters and radii to identify the best design based on the printability limits.
- Optimize the process parameters to minimize the surface roughness inside the channels.
- Investigate the effect of the curvature radius on the performance of embedded FBG sensors.

RESEARCHERS

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



Printed cuboids containing curved channels with various dimensions. (Sub-project 4.2.2)

Project 4.3: Development of Innovative FGM Products

DESCRIPTION

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

PROGRESS

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

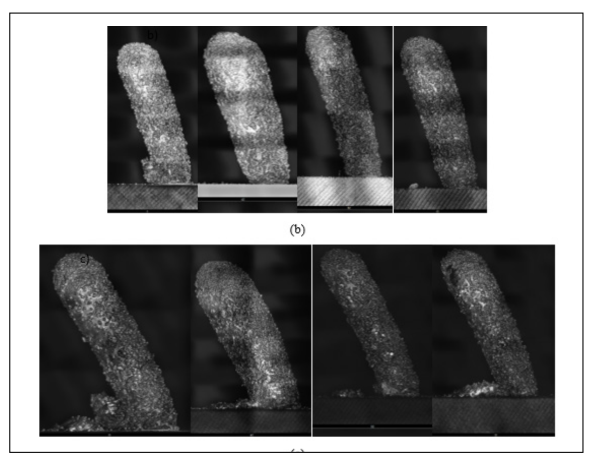
- Develop an auxiliary thermal model of PTA-AM and develop an experimental methodology using an IR camera to validate the model.
- Study the powder heating inside the plasma to provide a precise input for the PTA-AM thermal model.
- Develop a finite element model based on progressive elements activation to accurately predict the stress field in PTA-AM parts with various geometries. A mesh convergence study and experimental validation are ongoing.
- Start printing simple FGM multi-layer walls while awaiting the PTA digital integration (delayed due to COVID-19) to enable the controlled AM of more complex geometries, followed by initial parameter calibration.

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

- Complete characterization of wrought D2 tool steel applying a variety of different heat treatment scenarios to establish a baseline measurement for material properties.
- Characterize as-built and heat-treated parts printed via DED by studying scratch hardness and XRD analysis, followed by comparison of the results to those of the wrought and heat treated D2 tool steel.
- Investigate the effect of heat treatment on the mechanical properties of wrought D2 tool steel.
- Print and characterize inclined thin walls to examine the potential of printing internal hollow structures using a DED process. The effect of process parameters on the angle and height errors of the inclined thin walls has been investigated.

RESEARCHERS

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



CLSM images of DED-processed thin inclined walls at (a) 80°, (b) 70°, and (c) 60°. (Sub-project 4.3.2)

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

DESCRIPTION

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

PROGRESS

Sub-project 4.4.1: Repair Strategies with LPF-AM

- Deposit multi-track TiC-Ni3Al coatings on D2 steel substrates by DED laser processing of preplaced feedstock. The coatings have been examined for their microstructural and mechanical characteristics.
- Investigate the effect of processing parameters related to both preplacement and laser cladding on the microstructure, solidification features and basic mechanical performance of the coatings. The processing parameters have been further explored considering the effects of various factors, such as powder preparation, composition of metallic phase, preparation of gel suspension, optimization of the dip coating unit, and laser processing parameters.
- Conduct Potentiodynamic (PD) polarisation corrosion tests for coated and as-received substrates. The experiments have demonstrated a general improvement in the oxidation profile of the coated substrates. Microstructural characterization of post-corrosion surfaces at various processing parameters is ongoing.

Sub-project 4.4.2: Repair Strategies Using EWF-AM

- Optimize and experimentally validate the thermo-mechanical finite element model of the EWF-AM process.
- Utilize the model to accurately predict the grain structure through ex-situ solidification rate and thermal gradient calculations. Microstructural predictions have been validated.
- Study the effect of initial substrate condition on the EWF-AM process to understand the effects of initial residual stresses and different microstructural features on the final distortion and mechanical integrity of the repaired components. Residual stress profile measurements after deposition are underway.

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

- Develop an automated scanning and reconstruction sequence using SDK of the embedded controller of the gantry and the 3D scanner.
- Develop a GUI for the sequence of algorithm and optimize the sequence to reduce the execution time.
- Develop a reverse kinematics strategy for point cloud reconstruction.
- Prepare the gantry system to receive a plasma transfer arc system.
- Carry out NiCr-TiC and NiCr-WC particle packing tests at varying concentrations of carbide as a function of void fraction to optimize filler and composition content for the production of composite filaments.
- Optimize material flow and FFF process parameters, followed by printing and characterization of parts with complex geometry.

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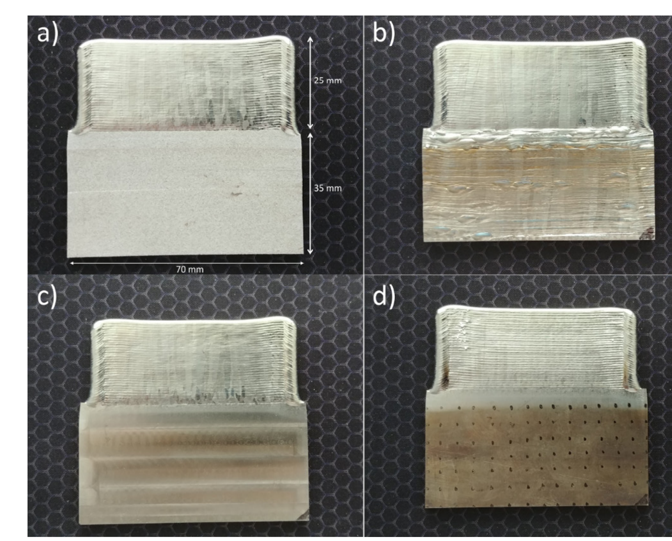
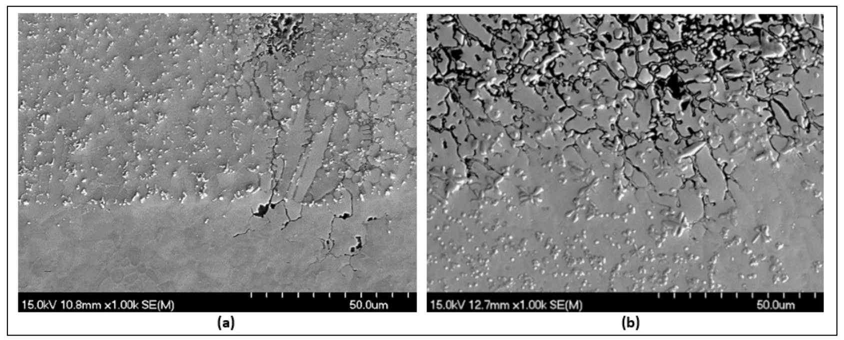


Photographs of EBW deposited (repaired) substrate conditions: a) as-printed (LPBF), b) EBW deposited, c) as-machined wrought, and d) stress-relieved wrought. (Sub-project 4.4.2)

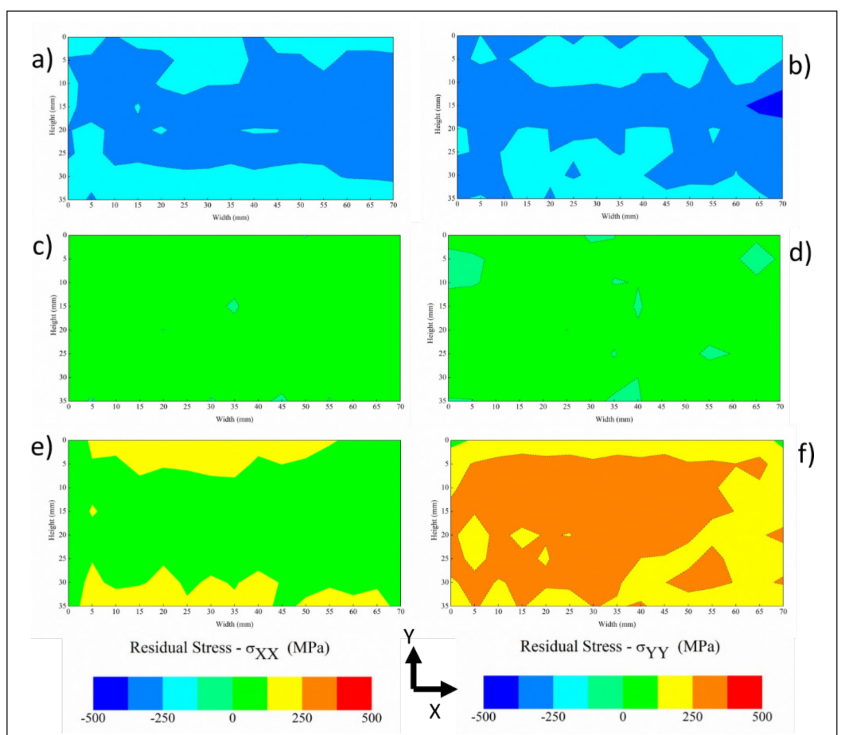
Project 4.4: Advanced LPF-, EWF-, and PTA-AM for Repair and Remanufacturing (Continued)

RESEARCHERS

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



Post-corrosion SEM images obtained from surface of TiC-Ni3Al cermet clad coatings on D2 steel, generated from dip coating suspension of a) 30 and b) 50 vol.% metallic phase, demonstrating formation and progression of oxidation sites slightly above the polarisation potential. (Sub-project 4.4.1)



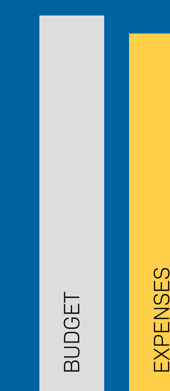
XRD measured residual stress profiles of (a, b) as-machined wrought, (c, d) stress relieved wrought, and (e, f) LPBF printed Ti-6Al-4V substrates. (Sub-project 4.4.2)

Finances

The HI-AM Network receives funding mainly from NSERC. The Network received $1 million in its first year, and has received $1.125 million each year after that. This funding is matched by both industry funds, and institutional support from the universities participating in the Network. The travel restrictions recently put in place because of the pandemic has caused some delay in spending in any travel related expenses, including the 2021 HI-AM Conference, which moved online; and travel related to exchanges and other conferences.

YEAR ONE TO FOUR NSERC FUNDING (2017-2021)

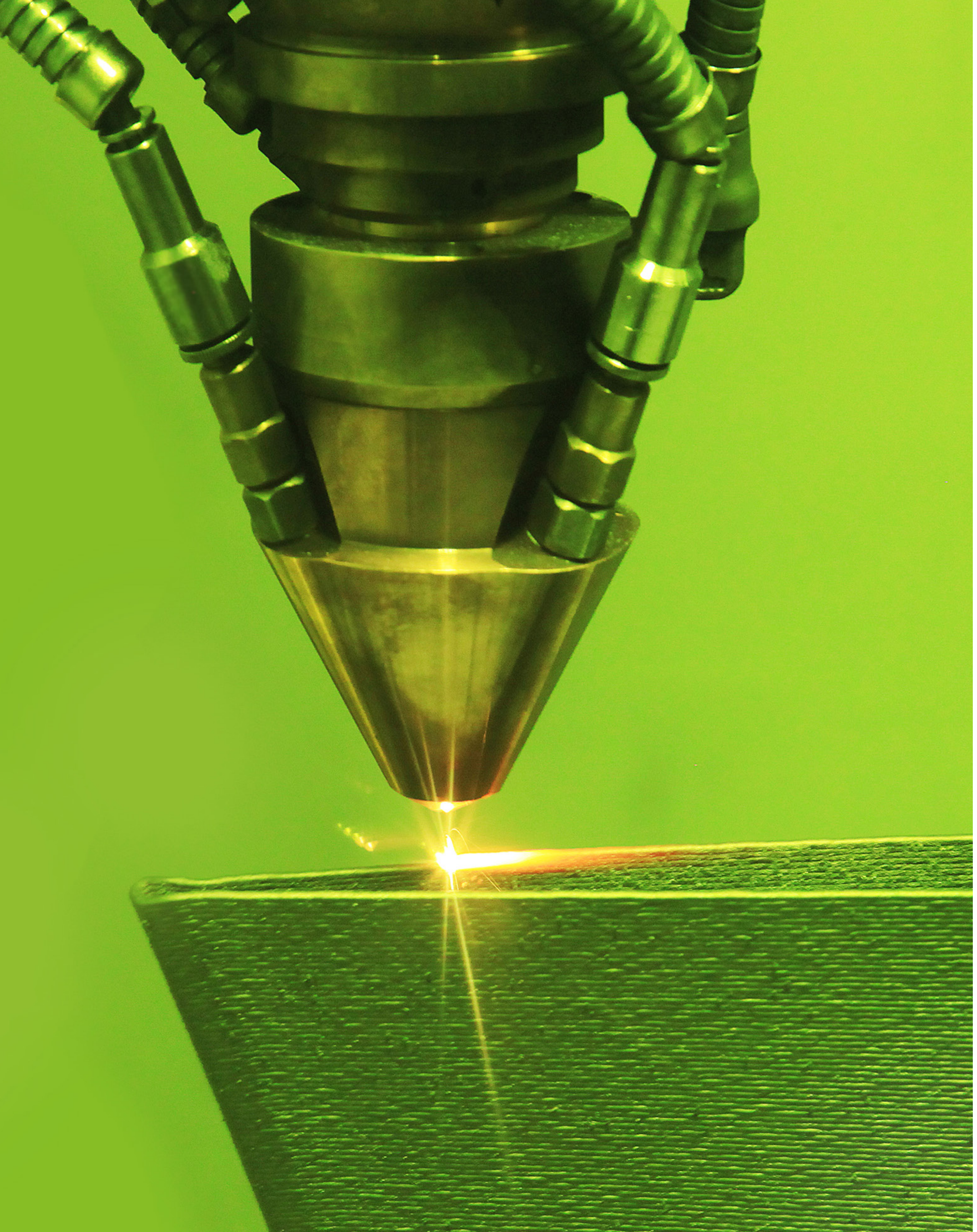
	BUDGET	EXPENSES AND COMMITMENTS*
THEME 1	$1,587,594.71	$1,206,856.16
THEME 2	$775,024.69	$692,572.46
THEME 3	$520,021.98	$530,141.89
THEME 4	$653,315.96	$517,058.70
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$1,019,042.66	$747,493.07
TOTAL	**$4,555,000.00**	**$3,694,122.28**



YEAR ONE TO FOUR INDUSTRY/GOVERNMENT PARTNER AND INSTITUTIONS CONTRIBUTIONS (2017-2021)

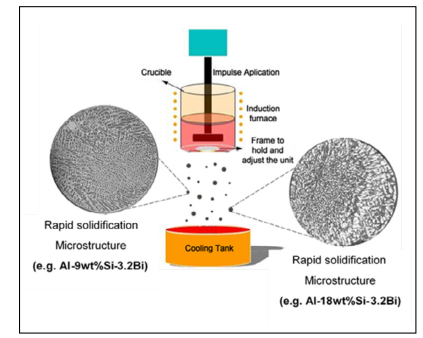
	BUDGET	EXPENSES AND COMMITMENTS
THEME 1	$564,064.00	$248,989.60
THEME 2	$390,334.00	$179,427.37
THEME 3	$376,580.00	$286,000.97
THEME 4	$437,414.00	$291,401.43
ADMINISTRATIVE AND KNOWLEDGE TRANSFER	$78,794.00	$113,086.06
TOTAL	**$1,847,186.00**	**$1,118,905.43**

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

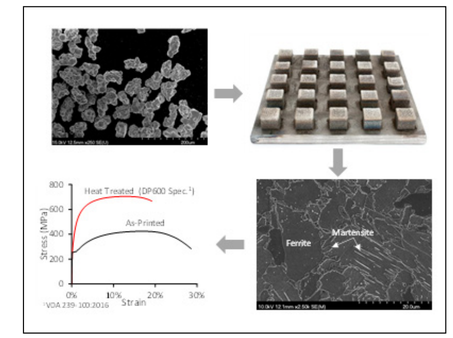


Outreach and Knowledge Transfer

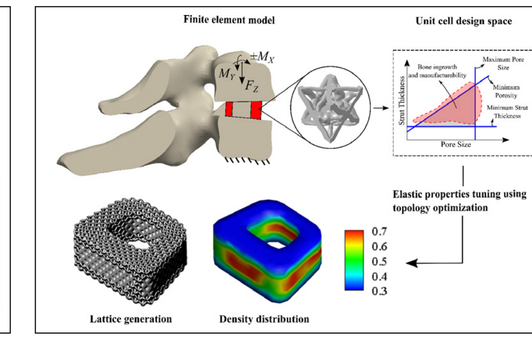
The HI-AM Network fosters communication and information exchange within and beyond the Network in numerous ways, including through Network events, via our online presence, participation in international engineering conferences, training undergraduate and graduate students, and domestic and international student exchanges.



Graphical abstract of the Al-SiBi development. (Sub-project 1.1.1)



L-DED of 4140 for Component Repair Applications. (Sub-project 1.3.3)



A new route to design the next generation of fully-porous load-bearing implants. (Sub-project 4.2.1)

Events with HI-AM Representation*

3DMS 2021, 5th International Congress on 3D Materials Science (virtual)
June 29-July 2, 2021

Powdermet 2021, International Conference on Powder Metallurgy and Particulate Materials – Orlando, FL, USA
June 20-23, 2021

Aeromat 2021 – 32nd Conference and Exposition
May 24-26, 2021

Wear of Materials 2021, 23rd International Conference on Wear of Materials (virtual)
April 26-29, 2021

TMS-DGM Symposium 2021: A Joint US-European Symposium on Linking Basic Science to Advances in Manufacturing of Lightweight Metals
March 15-18, 2021

Materials Science and Technology 2020 (MS&T) (virtual)
November 2-6, 2020

ICALEO 2020
October 19-20, 2020

COM 2020, 59th Conference of Metallurgists, Toronto, ON, Canada (virtual)
October 14-15, 2020

OSA Laser Congress 2020
October 13-16, 2020

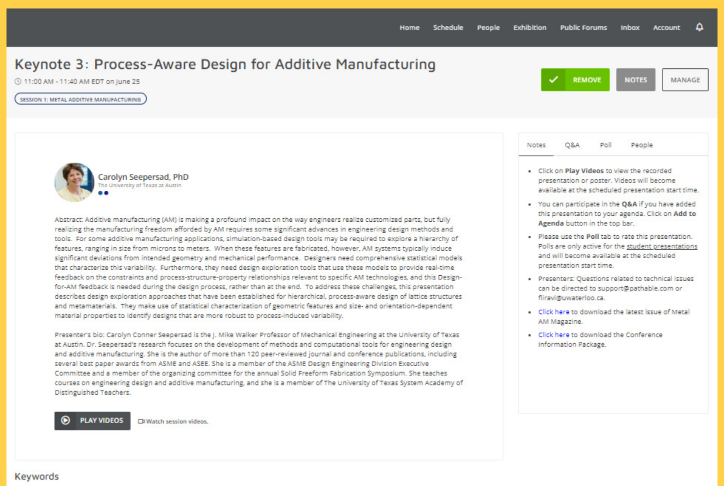
EBAM 2020, 3rd International Conference on Electron Beam Additive Manufacturing, Erlangen, Germany (virtual)
October 5-7, 2020

2020 Materials Science and Technology Technical Meeting and Exhibition (MS&T20), Pittsburgh, PA, USA (virtual)
October 4-8, 2020

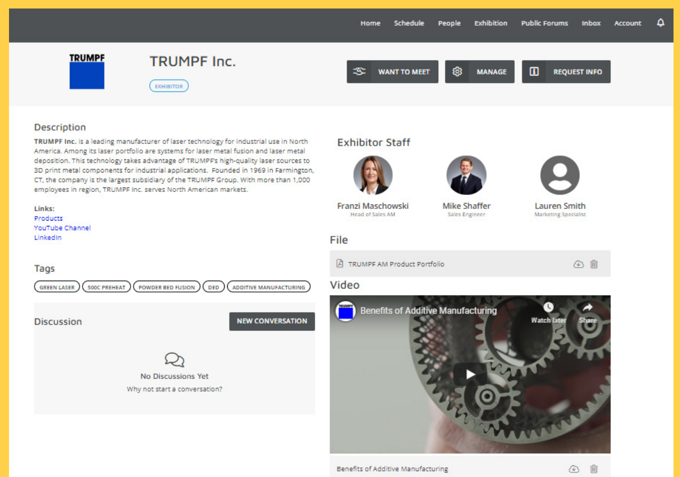
*July 1, 2020 to June 30, 2021

HI-AM Conference 2021

The fourth HI-AM Conference was originally planned to be held at Dalhousie University, Halifax, NS from June 1-2, 2021; instead, because of the ongoing pandemic, it was held online. The online HI-AM 2021, co-chaired by Paul Bishop of Dalhousie University and Ehsan Toyserkani of University of Waterloo, was very well received by the AM community, with 500+ participants from more than 300 organizations, and 1700+ website views. The conference opened with video messages from the co-Chairs, and was followed by pre-recorded presentations and posters that were available on-demand, Q&A sessions, and various networking opportunities. The signing of a memorandum of understanding between the HI-AM Network and ASTM International was also announced during the conference opening.



Sample presentation page



Sample exhibition page

A total of 115 poster and oral presentations were delivered at the conference, including 5 keynote presentations. The keynote talks were delivered by Simon Hoeges, Director Technology & Manufacturing Engineering, GKN Additive, Germany; Anthony Rollett, US Steel Professor of Metallurgical Engineering & Materials Science, Carnegie Mellon University, United States; Christopher Williams, Professor of Mechanical Engineering, Virginia Tech, United States; Michael Schmidt, Head of Institute of Photonic Technologies, Friedrich-Alexander University, Germany; and Michael Sealy, Professor of Mechanical & Materials Engineering, University of Nebraska-Lincoln, United States.

The conference was also supported by sponsors and exhibitors from industry and academia: EOS, Exergy Solutions, Javelin Technologies, KSB, Leichtbau BW GmbH, Multi-Scale Additive Manufacturing Lab, Postprocess Technologies, Promation, PULSTEC, SLM Solutions, Suncor Energy, Trumpf, and Xact Metal each had their own virtual exhibition booth.

The conference closing remarks were given by HI-AM Network's Theme 4 Leader, Mathieu Brochu, who will be the Chair of 2022 HI-AM Conference hosted by McGill University. The conference concluded with the announcement of the recipients of student presentation competition awards.

THE 2021 WINNERS:

PRESENTATION COMPETITION:

First Place:
- Jon Hierlihy, Dalhousie University
- Katayoon Taherkhani, University of Waterloo

Second place:
- Farzaneh Kaji, University of Waterloo
- Catherine Desrosiers, École Polytechnique Montréal
- Farhad Rahimi, The University of British Columbia
- Shahriar Imani Shahabad, University of Waterloo

Third place:
- Ambrish Singh, Indian Institute of Technology Guwahati
- Abhi Ghosh, McGill University
- Emmanuel Reyes, Universidad Michoacana de San Nicolas de Hidalgo (UMSNH)

POSTER COMPETITION:

First place:
- Tejas Ramakrishnan, McGill University
- Kyra McLellan, University of Toronto
- Alexander Martinez & Mazyar Ansari, University of Waterloo

Second place:
- Reza Esmaeilizadeh, University of Waterloo
- Owen Craig, Dalhousie University
- Sagar Patel, University of Waterloo

Third place:
- Nicholas Gosse, Dalhousie University
- Parichit Kumar, University of Waterloo
- Maxwell Moyle, The University of New South Wales
- Alejandra Bejarano Rincón, Center for Engineering and Industrial Development (CIDESI)

2021 HI-AM Conference at a Glance

AT A GLANCE
- 500+ participants
- 300+ organizations
- 1700+ website views
- 13 exhibitors

EDUCATION
- 5 Keynote Talks
- 61 oral presentations
- 49 posters

NETWORKING
- 2000+ conversations
- 3 Career Advice sessions
- 18 exhibitor presentations
- Live tradeshow

KEYNOTE SPEAKERS

Simon Hoeges
Director Technology & Manufacturing Engineering
GKN Additive, Germany

Anthony Rollett
US Steel Professor of Metallurgical Engineering & Materials Science
Carnegie Mellon University, United States

Christopher Williams
Professor, Mechanical Engineering
Virginia Tech, United States

Micheal Schmidt
Head of Institute of Photonic Technologies
Friedrich-Alexander University, Germany

Michael Sealy
Professor, Mechanical & Materials Engineering
University of Nebraska-Lincoln, United States

Memorandum of Understanding with ASTM International

The HI-AM Network and ASTM International agreed to advance cooperation by signing a memorandum of understanding (MoU) on additive manufacturing (AM) standards development. This MoU establishes a set of terms between the HI-AM and ASTM to facilitate collaborative activities that are mutually beneficial, promote information exchange on topics of interest, and encourage HI-AM researchers and experts to participate in the ASTM standard development process.

The MoU was signed on January 22, 2021 and announced during the 4th HI-AM Conference on June 1, 2021 by Brian Meincke, ASTM International Vice President of Global Business Development and Innovation Strategy, and Ralph Resnick, HI-AM Chairman of the Board and former America Makes President and CEO. To watch the announcement, **click here**.

"One of our core values has been identifying partnerships with organizations that can support acceleration of standards development," said Meincke. "We are excited to work closely with the HI-AM Network and hope this partnership will advance and facilitate innovative global additive manufacturing standardizations."

In the few months that have passed since the establishment of the MoU, the results of several HI-AM projects in topics as diverse as powder recycling, AM process control and metrology, and repair strategies have been identified as having the potential to be incorporated into ASTM standards. Furthermore, two standard work items have already been registered as a result of this MoU:

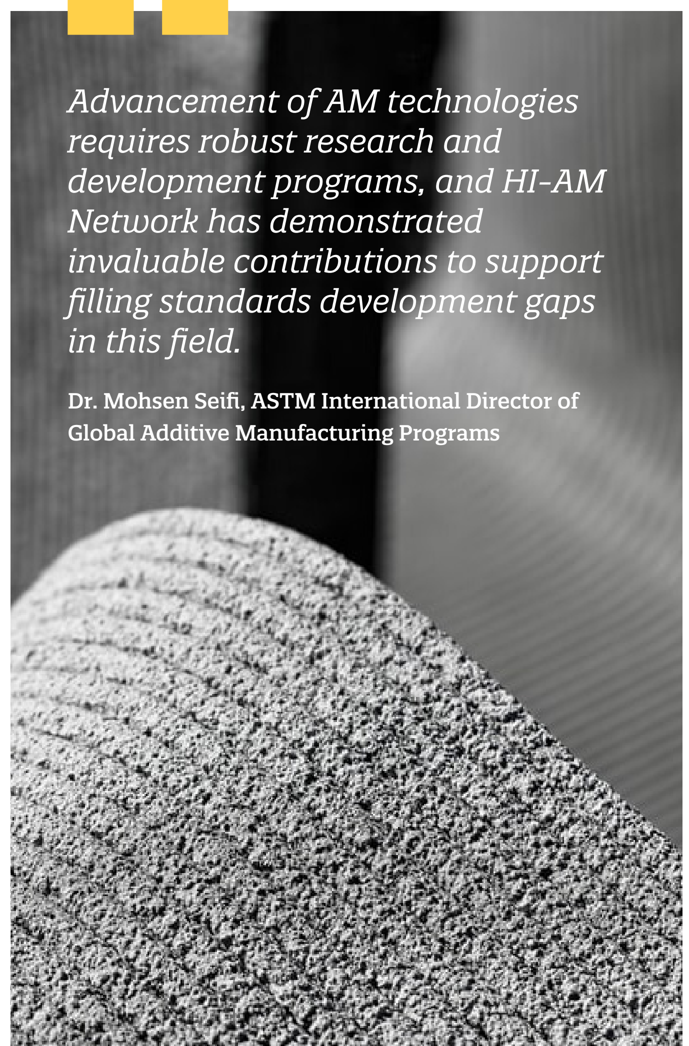
- **ASTM WK76983 –** New Practice for Additive Manufacturing — Powder Bed Fusion — Best Practice for In-situ Defect Detection and Analysis
- **ASTM WK77008 –** New Guide for Additive Manufacturing — Laser Powder Bed Fusion — Guide for Benchmarking of Powder Bed Density

Technical discussions are being held between ASTM and various HI-AM groups to establish more standard development projects.

"This is just the start of what both organizations hope will be a productive partnership," said Ralph Resnick, the Chairman of HI-AM Board of Directors. "We are very excited to contribute to AM standardization led by ASTM and hope this partnership will advance and facilitate this monumental task".

ASTM International contributes to the development of AM standards through the work of the additive manufacturing technologies committee (F42) with support of the Additive Manufacturing Center of Excellence (AM CoE).

"Advancement of AM technologies requires robust research and development programs, and HI-AM Network has demonstrated invaluable contributions to support filling standards development gaps in this field," said Dr. Mohsen Seifi, ASTM International Director of Global Additive Manufacturing Programs. "We are thrilled to partner with world-class universities in the HI-AM Network to focus on key industry challenges and have already registered two standard work items as a result of this collaboration."



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Dr. Mohsen Seifi, ASTM International Director of Global Additive Manufacturing Programs

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UNIVERSITY OF WATERLOO | Department of Mechanical and Mechatronics Engineering

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