NSERC HI-AM


HI-AM 2018 Annual Conference

NSERC-CFI Strategic Network for Holistic Innovation in Additive Manufacturing

Participant Information Package | May 22-23, 2018

University of Waterloo | NSERC CRSNG | INNOVATION.CA Canada Foundation for Innovation | Fondation canadienne pour l'innovation

www.conference.nserc-hi-am.ca

University of Waterloo
Waterloo, ON, Canada

Outline

Welcome Message

On behalf of the Board of Directors of NSERC Strategic Network for Holistic Innovation in Additive Manufacturing (HI-AM), I am very pleased to welcome you to the NSERC HI-AM Conference 2018.

The HI-AM Network was conceived in June 2017 to address a strategically chosen set of challenges confronting the widespread adoption of additive manufacturing (AM) by industry, train the AM experts needed by Canadian market, and forge lasting relationships between academic and industrial contributors to the field of AM. The research performed within the HI-AM Network is directed by 19 faculty members with expertise in materials processing and characterization, process modeling, advanced precision tool-path planning, and control from 7 universities across Canada.

The HI-AM annual Conference provides an opportunity for Network researchers and industrial partners to come together, share their findings, and explore the future research directions. We are honored to have as our keynote speakers Mr. Mohammad Ehteshami of GE Additive, Dr. Mohsen Seifi of ASTM International, Prof. Ian Gibson of Deakin University, and Prof. Timothy Simpson of Pennsylvania State University. The Conference also features 32 presentations on pressing issues such as Material Development for Laser-based AM, Advanced AM Process Modeling, Process Optimization for AM, and Novel Metal-based AM Techniques.

On behalf of the Conference Organizing Committee, I am extending our gratitude to the keynote speakers, presenters, session chairs, and participants. We hope you enjoy and benefit from the first NSERC HI-AM Conference.

Ehsan Toyserkani
NSERC HI-AM Network Director
Conference Chair

About NSERC HI-AM Network

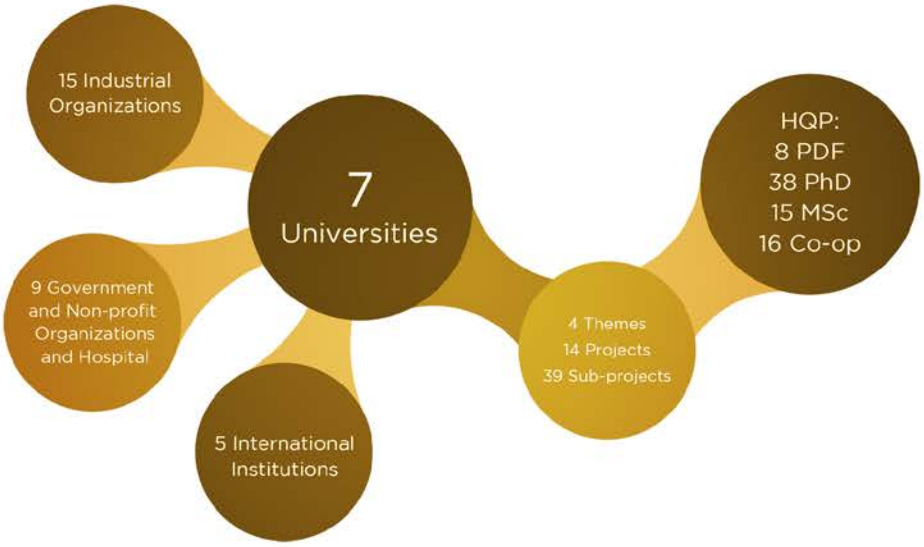
University of Waterloo is proud to host the first strategic Canadian network in additive manufacturing bringing together 7 universities, 18 Industrial partners, various government organizations, and 5 International collaborators. The goal of this network is to leverage Canada's competitive advantage in transition to the intelligent manufacturing.

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a combination of technologies fabricating complex structures in a layer-by-layer fashion. AM provides advantages such as near-infinite design freedom, rapid design-to-market cycle, fast part repairing, and clean manufacturing.

AM is a key element in the new trend to the digitization of manufacturing, known as Industry 4.0. In this transition process, the greatest impacts will come through the AM of metal parts. Despite all the significant advancement of this technology, especially in the last decade, some technical challenges and shortcomings such as lack of intelligence in current AM systems, lack of a clear relationship between the quality flaws and process parameters, the high cost of AM, and low efficiency still need to be addressed for the complete realization of Industry 4.0.

The strategic network for holistic innovation in additive manufacturing (HI-AM) research program will address these challenges to effectively make AM ready for Industry 4.0, while delivering AM to the mainstream manufacturing through 4 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



Network Partners

Academic Institutions

UNIVERSITY OF WATERLOO

UNIVERSITY OF TORONTO

UNIVERSITY OF ALBERTA

UBC

McGill UNIVERSITY

DALHOUSIE UNIVERSITY

UNIVERSITÉ LAVAL

Network Partners

Government Partners

Non-Profit Organizations

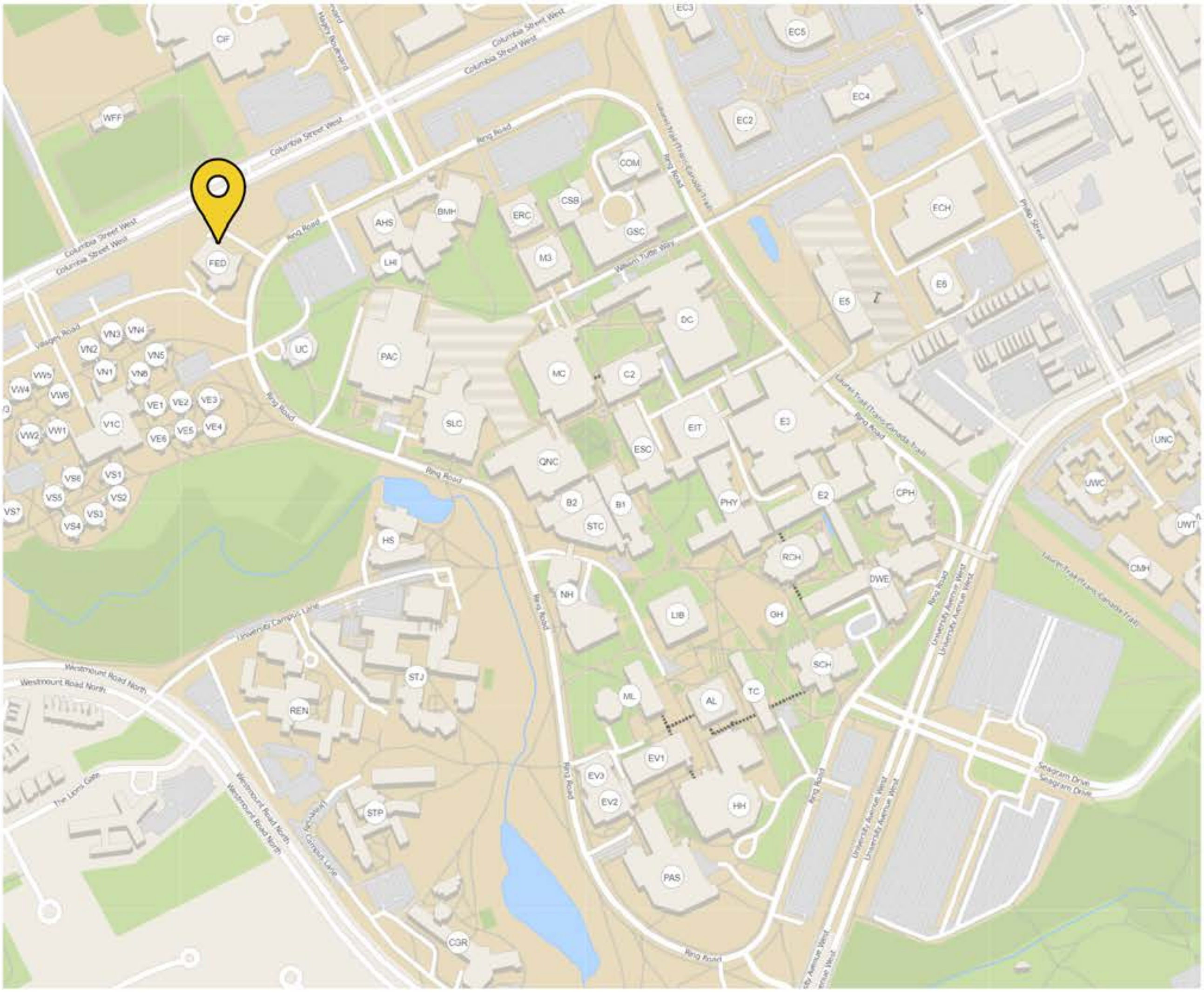
Industrial Partners

Venue

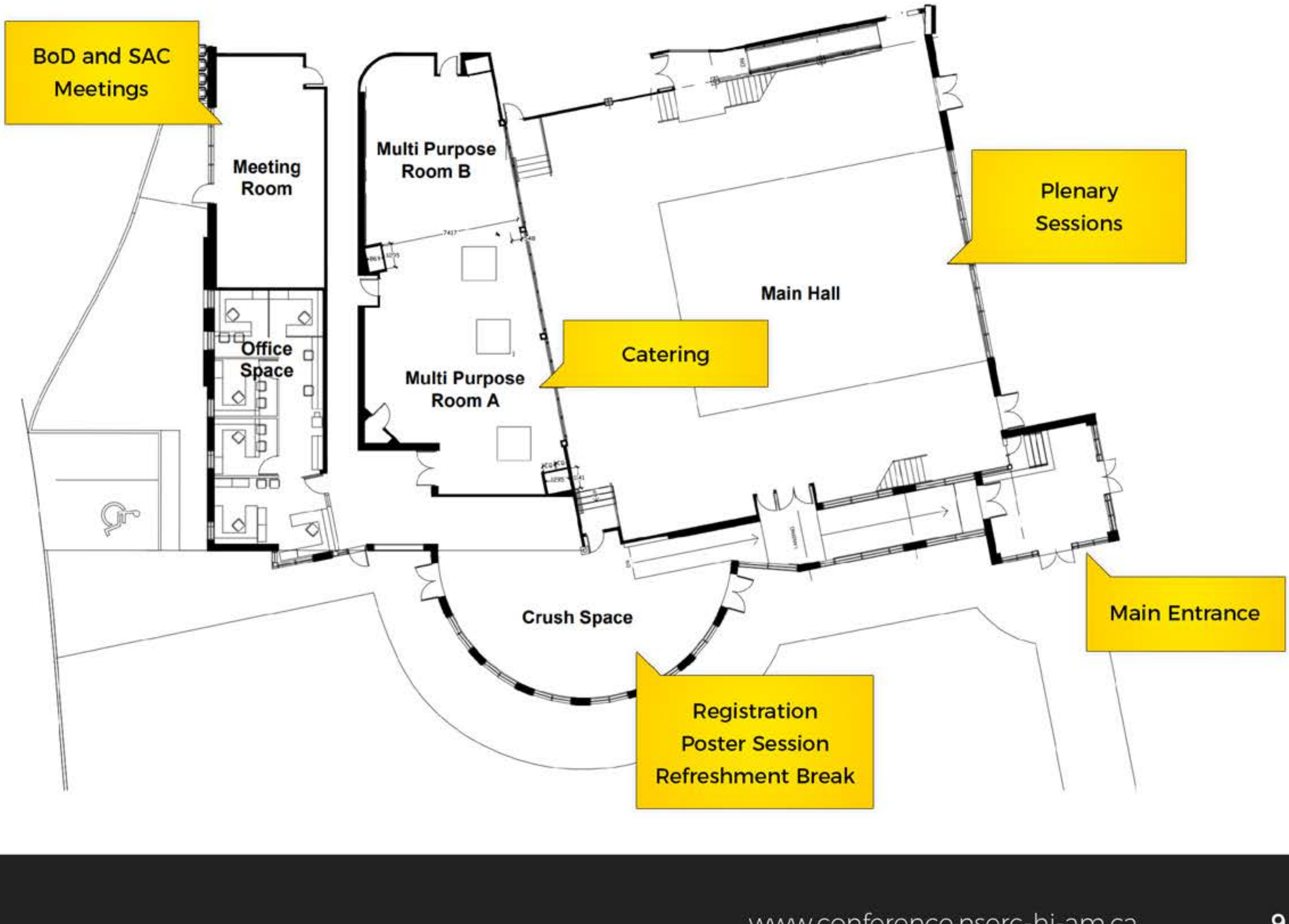
The conference will be held in the Federation Hall (Fed Hall), 200 University Ave We, Waterloo.

Located in University of Waterloo's main campus, Fed Hall is one of the premier event spaces in Waterloo.

The venue is within walking distance of summer residences and University Club.



Venue


BoD and SAC Meetings
Meeting Room
Multi Purpose Room B
Plenary Sessions
Main Hall
Office Space
Catering
Multi Purpose Room A
Main Entrance
Crush Space
Registration
Poster Session
Refreshment Break

Keynote Speakers

Mohammad Ehteshami

Vice President and General Manager

GE Additive, USA

Accelerating the metal additive revolution

Mohammad Ehteshami is currently Vice President at GE Additive – focused on the additive product strategy. In this role, Mohammad provides strategic direction to the technical and product roadmaps for the GE Additive portfolio. Most recently, Mohammad was Vice President & General Manager for GE Additive, helping to launch the business in September 2016. Prior to this Mohammad was Vice President & General Manager of Engineering for GE Aviation. Mohammad has a Bachelor's degree in Mechanical Engineering from Old Dominion University and a Master's degree in Mechanical Engineering from the University of Cincinnati.

Mohsen Seifi

Director of Global Additive Manufacturing Programs

ASTM International, USA

Amplifying Additive Manufacturing Standardization

Dr. Mohsen Seifi joined ASTM International in 2016 as the director of additive manufacturing (AM) programs, in which he facilitates' standardization activities across all ASTM AM related technical committees and building new partnerships as well as development of new AM standards related programs within diverse ASTM portfolios. He has also appointment as an adjunct assistant professor at Case Western Reserve University (CWRU) in Cleveland, OH. He received both his master's and doctoral degrees from CWRU in materials science and engineering with emphasis on metal AM qualification and standardization.

Ian Gibson

Professor of Additive Manufacturing

Deakin University, Australia

Prof. Gibson is the recipient of the International Freeform and Additive Manufacturing Excellence (FAME) Award for over 25 years of contribution to the field of additive manufacturing. Prof. Gibson has joined the school of engineering at Deakin University since 2013 and has been involved in development of multiple design and manufacturing courses with a focus on industrial design, medical devices, and sports technology. He is the co-author of the book *Additive Manufacturing Technologies*, which has been cited over 2700 times.

Timothy Simpson

Paul Morrow Professor of Engineering Design & Manufacturing

Pennsylvania State University, USA

Replicate, Adapt, Optimize: The Three Stages of Design for Additive Manufacturing

Timothy W. Simpson is the Paul Morrow Professor of Engineering Design & Manufacturing at Penn State. He is the Director of the world's first graduate program in Additive Manufacturing & Design and Co-Director of the Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). He has extensive experience with laser-based powder bed fusion and directed energy deposition for metals, and he specializes in Design for Additive Manufacturing. He contributes a monthly column on additive manufacturing to Modern Machine Shop and has helped educate over 600 industry practitioners in the use of additive manufacturing.

Conference Agenda

Day 1

8:00 AM	Morning Coffee
8:30 AM	Opening: Prof. Feridun Hamdullahpur, President and Vice-chancellor, University of Waterloo
	Network Director Note: Prof. Ehsan Toyserkani
8:50 AM	**Session 1: Introduction to HI-AM R&D Programs in each Node; Chair: Prof. Mihaela Vlasea**
8:50 AM	**Keynote: Mohammad Ehteshami, Vice President and General Manager, GE Additive, USA**
9:20 AM	Overview of AM R&D at the University of Waterloo, Prof. Ehsan Toyserkani
9:30 AM	Overview of AM R&D at McGill, Prof. Mathieu Brochu
9:40 AM	Overview of AM R&D at Dalhousie University, Prof. Paul Bishop
9:50 AM	Overview of AM R&D at the Univesity of British Columbia, Prof. Steve Cockcroft
10:00 AM	Overview of AM R&D at the University of Alberta, Prof. Hani Henein
10:10 AM	Overview of AM R&D at the University of Laval, Prof. Carl Blais
10:20 AM	Overview of AM R&D at the University of Toronto, Prof. Hani Naguib
10:30 AM	Morning Break
10:50 AM	**Session 2: Material Development I; Chair: Prof. Kevin Plucknett**
10:50 AM	**Keynote: Dr. Mohsen Seifi, Director, ASTM International, USA**
11:20 AM	Presentation 1 - Laser Powder Fed Deposition of Ti-Based MMC Coatings [M. Harding, Z. Memarrashidi, I. Donaldson, K. Plucknett, P. Bishop]
11:40 AM	Presentation 2 - Tensile Properties and Microstructural Characterization of entirely built vs. repaired A357 specimens made by Directed Energy Deposition [L. Simoneau, A. Bois-Brochu, C. Blais]
12:00 PM	Presentation 3 - Interstitial gain modeling for effective powder recyclability in Selective Laser Melting (SLM) Additive Manufacturing(AM) for Ti6Al4V alloy [A. Das, G. Azimi, M. Brochu]
12:20 PM	Canada Makes 3D Challenge winner announcement

Day 1 Continued

12:25 PM	Lunch Poster Session
1:50 PM	**Session 3: Design, Topology Optimization, Modeling I; Chair: Prof. Daan Maijer**
1:50 PM	**Keynote: Prof. Ian Gibson, Professor, Deakin University, Australia**
2:20 PM	Presentation 4 - Thermal fluid modeling of melt pool dynamics in the electron beam additive manufacturing of Ti6Al4V [E. Nishimura, S. Cockcroft, D. Maijer]
2:40 PM	Presentation 5 - Prediction of Melting Mode Transition in Powder Bed Laser Fusion [S. Patel, M. Vlasea]
3:00 PM	Presentation 6 - A comprehensive investigation of the volumetric heat sources used in the heat transfer modeling of selective laser melting [Z. Zhang, Y. Huang, R. Adhitan, S. Imani, E. Toyserkani]
3:20 PM	Afternoon Break
3:40 PM	**Session 4: Novel AM Systems and Process Optimization; Chair: Prof. Fiona Zhao**
3:40 PM	Presentation 7 - Identification of Significant Process Parameters Affecting the Surface Roughness of Laser Powder-bed Fusion Hastelloy X Parts [U. Ali, Y. Mahmoodkhani, R. Esmaeilizadeh, A. Kasinathan, A. Keshavarzian, Z. Zhang, S. Imani, O. Ibhadode, E. Marzbanrad, E. Toyserkani, A. Bonakdar]
4:00 PM	Presentation 8 - Design of conformal porous structures for the cooling systems of injection mold [Y . Tang, Y. Zhao]
4:20 PM	Presentation 9 - LPBF Recipe Translation between Continuous and Modulated Laser Systems with different Spot Sizes [A. Rogalsky, I. Rishmawi, E. Toyserkani, M. Vlasea]
4:40 PM	Presentation 10 - Maximizing Green and Sintered Density of Pure Iron Parts using Binder Jetting Additive Manufacturing [I. Rishmawi, M. Salarian, E. Toyserkani, M. Vlasea]
5 PM - 6 PM	Scientific Advisory Committee Meeting

Conference Agenda

Day 2

8:00 AM	Morning Coffee
8:30 AM	**Session 5: Design, Topology Optimization, Modeling II; Chair: Dr. Marjan Molavi-Zarandi**
8:30 AM	**Keynote: Prof. Timothy Simpson, Professor, Pennsylvania State University**
9:00 AM	Presentation 11 - Geometric Deviation Modeling and Tolerancing in Additive manufacturing: A GD&T Perspective [B. Rupal, A. Qureshi]
9:20 AM	Presentation 12 - A review of manufacturability for laser powder bed fusion processes [Y. Zhang, Y. Zhao]
9:40 AM	Presentation 13 - An Analytical Model for Laser Powder-bed Additive Manufacturing [Y. Huang, E. Toyserkani, B. Khamesee]
10:00 AM	Presentation 14 - Elastic and failure response of imperfect three-dimensional metallic lattices: the role of geometric defects induced by Selective Laser Melting [L. Liu, D. Pasini]
10:20 AM	Morning Break
10:40 AM	**Session 6: Material Development II; Chair: Prof. Mathieu Brochu**
10:40 AM	Presentation 15 - Quantification of microstructure to reveal the solidification path of an alloy [A. Bogno, J. Valloton, H. Henein]
11:00 AM	Presentation 16 - An adaptable 3D printing technology for development of binder jetting and direct ink writing graphene oxide dispersion material systems [X. Shen, T. Morrison, H. Naguib]
11:20 AM	Presentation 17 - Additive Manufacturing of Ni-Based Superalloys [S. Atabay, K. Plucknett, M. Brochu]
11:40 AM	Presentation 18 - Development of thermally stable aluminum alloys for laser powder bed additive manufacturing [R. Ley, M. Brochu, I. Donaldson, P. Bishop]
12:00 PM	Closing Remarks: Prof. Pearl Sullivan, Dean of Faculty of Engineering, University of Waterloo; Awards announcement
12:20 PM	Lunch
1:30 PM	Board of Directors Meeting

Parking

Visitor parking is available to participants in lots "M," "J," "S," and "V." Parking lots "M" and "J" are the closest lots to the venue.

Lot M:

- Fee: $6 per entry
- Pay station in lot M

Lots J, S, and V:

- Fee: $5 per entry
- Pay station for all three lots is located in lot S

Emergency Phone Numbers

University Police and Parking Services	(519) 888-4911
Venue (Fed Hall)	(519) 888-4700
Delta Hotels by Marriott Waterloo	(519) 514-0404
Homewood Suites by Hilton Waterloo	(519) 514-0088
Waterloo Taxi	(519) 888-7777

Abstracts - Keynote Addresses

Accelerating the metal additive revolution
Mohammad Ehteshami, GE Additive

In this presentation, I plan to walk the audience through the journey of metal Additive as both an enabler and a disruptor simultaneously. We at the GE Aviation in the early years of 2010/2011 were facing a challenge to create the most reliable and most efficient engine for the commercial narrow body planes, namely the A320neo and 737max as well as the C919. Through this challenge we found a solution that actually pointed us to a new technology and industry now known as Additive Manufacturing. I will narrate the successes and failures of this journey plus how it lead us to create a new vertical inside GE by acquiring the Concept Laser, Arcam and GeonX companies in addition to the original Morris technology. I will also highlight the challenges one faces between prototyping and going to a full production as well as what is takes to create an ecosystem that supports the journey and the successful launch of printing engine and components for cost, performance, time to market and vertical integration. I then plan to close the talk by addressing what we have done to enable the academia and the school systems to have access and expose students to the 3-D printing.

Amplifying Additive Manufacturing Standardization
Dr. Mohsen Seifi, ASTM International

As the Additive Manufacturing (AM) industry moves towards series industrial production, the need for standards covering all aspects of the technology becomes ever more prevalent. While some standards and specifications for the various aspects of AM process chain exist and continue to evolve, many such standards still need to be matured or are under consideration/development within standards development organizations (SDOs). A resource to aid in the identification and development and approval of AM standards is a framework that has introduced a comprehensive structure to target various aspects of the AM space, including feedstock materials, design, process/equipment, testing, safety, and finished parts properties. The approach will also enable the development of application-specific standards to address the needs of the various industries. This presentation will discuss the state of the AM standards including gaps, challenges, opportunities and insight based on a recent initiative to establish global center of excellence to support research and development and close the standardization gaps that exist. Potential collaboration opportunities with the stakeholders and technical considerations in support of ongoing/future standards development will also be discussed.

Medical Applications for Additive Manufacturing
Prof. Ian Gibson, Deakin University

This presentation will catalogue my journey through time where I have been looking at medical uses for AM. I believe that we are finally approaching a watershed moment where AM will become commonplace rather than on the periphery of medical treatments. To many it is surprising that it has taken so long to reach this point when we realise that some clinicians have been using the technology for more than 20 years.

Replicate, Adapt, Optimize: The Three Stages of Design for Additive Manufacturing
Prof. Timothy Simpson, Penn State University

A pattern is emerging among companies adopting metal-based additive manufacturing (AM). In the first stage, they use AM to replicate an existing part to understand the technology's costs and capabilities. This starts to give them insight into the process and allows them to move onto the second stage wherein they adapt their designs for AM to reap more of its benefits—leveraging the design and material freedoms that AM affords. Finally, companies will shift to optimizing for AM as they gain confidence in the process while learning how to capitalize on AM to its full potential. These three stages can be effective when designing for AM, but only if expectations are carefully managed at each stage. Automotive, aerospace, and consumer product examples from Penn State's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) are presented to illustrate the benefits and drawbacks of each stage.

Laser Powder Fed Deposition of Ti-Based MMC Coatings

M. Harding[1], Z. Memarrashidi[1], I. Donaldson[2], K. Plucknett[1], P. Bishop[1] | 1- Dalhousie University, 2 - GKN Sinter Metals

Titanium alloys are utilized extensively in the aerospace industry within many scenarios including those that involve tribological loadings (slat tracks, landing gear components, etc.). Unfortunately, titanium is not regarded as a material with high wear resistance ensuring the need for frequent component replacement at significant cost. The application of wear resistant coatings to the titanium substrate is one concept that has been exploited to mitigate this issue. Moving in this direction, the objective of this research was to develop durable coatings that could be applied through laser powder fed deposition (a.k.a. direct energy deposition (DED)). The core material system of interest was a metal matrix composite comprised of Ti64+TiC. Two concepts were considered in feedstock preparation. In one, gas atomized AncorTi-64 powder was mixed with TiC particulate. In the second, the AncorTi-64 powder was mixed with two sources of graphite powder such that the TiC would be grown in-situ during laser ablation. Experimental variables included laser power and scan speed, TiC concentration in the MMC product, and particle size of the graphite additions. All coatings were characterized to assess the resultant microstructure (Optical microscopy, SEM, X-ray diffraction), superficial hardness, and residual stress. It was discovered that the TiC formed in-situ maintained a very distinct morphology that was dependent on the processing parameters employed. Hardness was seen to largely depend on the weight percent of TiC within the coating, and if this TiC was deposited directly, or grown in-situ.

Tensile Properties and Microstructural Characterization of entirely built vs. repaired A356 specimens made by Directed Energy Deposition

L. Simoneau[1], A. Bois-Brochu[2], C. Blais[1] | 1- Université Laval, 2- Quebec Metallurgy Center

Although this family of materials presents interesting mechanical and physical characteristics that are key to the transport industry, the number of studies on aluminum and its alloys built with Additive Manufacturing (AM) is still minor compared to other materials such as Ti-6Al-4V and stainless steels. Directed Energy Deposition (DED) is a sub-category within AM processes that offers unique possibilities thanks to the clever design of its deposition process. Indeed, DED is particularly well suited to add new complex features to existing parts, to vary the chemical composition in function of the XYZ coordinates within a build and to repair surface defects or worn parts. The latter is quite interesting for the manufacturing industry since it enables significant cost savings and is the focus of this study. In this work two different applications were studied: 1) the complete construction of samples made of A356 and 2) the repair of tensile half-specimens made of cast A356 with DED. Samples were characterized in terms of tensile properties, microstructure, crystallographic textures as well as grain size using SEM, EBSD and image analysis.

Interstitial gain modeling for effective powder recyclability in Selective Laser Melting (SLM) Additive Manufacturing(AM) for Ti6Al4V alloy

A. Das[1], G. Azimi[2], M. Brochu[1] | 1- McGill University, 2- University of Toronto

Although Additive Manufacturing (AM) promises low wastage or attractive buy to fly ratios, the widely used Ti6Al4V powders inherently suffer from powder recyclability issues as feedstock powders degrade both in quality and form over ongoing builds in Selective Laser Melting (SLM) AM processes. Previous studies indicate negligible degradation in terms of Particle Size Distribution (PSD) and flowability but a major issue is the rising amounts of interstitial elements like Oxygen and Nitrogen with ongoing builds which gradually render the powder useless by crossing standard specifications. There exists a significant lack of data and know-how on powder recycling so a physicochemical approach is made on understanding how the powders gain these interstitial elements in an SLM AM machine over time during standard operations. A detailed understanding of the changing surface chemistries of the re-used powders over multiple machine runs is studied to facilitate a predictive model of Oxygen and Nitrogen uptake of the powder bed. The model will consider powder characteristics of the bed and the process parameters for the SLM AM machine as input to chart out a gain of these interstitials. Once validated, the model can be calibrated for specific SLM AM systems to provide a logical prediction of the condition of the powders and the disposal limit. This aims to provide manufacturers a controlled powder recycling policy over the existing mal-practice of disposing of the powders after an arbitrary number of re-use.

Abstracts - Verbal Presentations

Thermal fluid modeling of melt pool dynamics in the electron beam additive manufacturing of Ti6Al4V

E. Nishimura, S. Cockcroft, D. Maijer | University of British Columbia

The behavior of the melt pool in AM affects the temperature history, pore formation and grain size, which in turn, impacts on the mechanical properties of the final built part and residual deformation. Hence, there is a need to development a quantitative link between the process parameters and heat transport at a range of length scales. The evolution of temperature during an EB-based powder-bed process has been investigated at the meso-scale using the Finite Volume based code Flow-3DTM. 2D and 3D thermal-fluid models has been developed to explore the relative importance of the factors affecting the liquid pool profile and the transport of heat within it. The thermal fluid model includes the following phenomena: a free upper surface, a moving surface-based heat flux (Gaussian Distribution), diffusive heat transfer, advective heat transfer, radiation heat loss, evaporation heat loss, recoil pressure due to evaporation, buoyancy forces and Marangoni forces. The results of a parameter sensitivity analysis using the 2D model are presented and indicate that, in addition to the beam parameters, the evaporation heat loss has a significant effect on temperature helping to moderate peak temperatures. Phenomena that have a significant effect on melt pool also include the surface tension and its temperature dependency and the recoil pressure due to evaporation (free surface shape). The results of a preliminary 3D analysis are also presented for comparison.

Prediction of Melting Mode Transition in Powder Bed Laser Fusion

S. Patel, M. Vlasea | University of Waterloo

Volumetric energy density (VED) is a commonly used expression for optimizing process parameters in powder bed laser fusion (PBLF). However, VED has shown to have certain limitations, particularly in predicting melt pool dynamics of PBLF. Melt pool geometry is dependent on the melting mode related to lack of fusion mode, conduction mode, or keyhole mode. These melting modes have a significant effect on the microstructure and mechanical properties in additively manufactured metallic materials. In laser welding, a dimensionless model for predicting melt pool geometry and melting mode has been developed based on numerical modelling and empirical observations. This model presents melt pool geometry as a function of normalized enthalpy. The expression for normalized enthalpy is derived from material parameters in addition to laser parameters thereby making the model material independent. The normalized enthalpy model has been successfully applied to PBLF of materials like 316L stainless steel and Inconel 625. This work studies the applicability of the model to Ti-6Al-4V processed by PBLF. Previous research has studied melt pool geometry on a base plate, which has been shown to have different melting characteristics when compared to a solid part. This work studies Ti-6Al-4V melt pool characteristics based on weld lines printed on built artifacts manufactured during the PBLF process. Additionally, the effect of varying artifact-processing parameters on the melt pool of weld lines is investigated by analyzing the effect of surface roughness and microstructure of artifacts on melt pool geometry.

An Analytical Model for Laser Powder-bed Additive Manufacturing

Y. Huang, E. Toyserkani, B. Khamesee | University of Waterloo

The paper analytically coupling the mass and heat transfer of powder-bed additive manufacturing (LPB-AM), in which the schematic particle distribution was considered and incorporated into the final powder-bed temperature field prediction. The model can perform an efficient prediction of the melt pool dimension, process heating/cooling rate, 3D profiles of simple multi-track structure, and have the potential to be employed for fast process optimization and controller design. The analytical predicted melt pool dimensions were compared with that of a developed numerical model, which agrees well with the numerical results. Sensitivity analysis of the built model shows that the laser power and laser absorptivity have the largest positive effect on the melt pool geometry, whereas the material thermal conductivity has the largest negative effect on the melt pool geometry.

Identification of Significant Process Parameters Affecting the Surface Roughness of Laser Powder-bed Fusion Hastelloy X Parts

Usman Ali[1], Yahya Mahmoodkhani[1], Reza Esmaeilizadeh[1], Adhitan R. Kasinathan[1], Ali Keshavarzkermani[1], Zhidong Zhang[1], Shahriar Imani[1], Osezua Ibhadode[1], Ehsan Marzbanrad[1], Ehsan Toyserkani[1] and Ali Bonakdar[2] | 1- University of Waterloo, 2- Siemens Canada

The relationship between process parameters and properties of the printed parts is one of the main challenges in laser powder-bed fusion (LPBF) additive manufacturing. Unlike conventional manufacturing processes, LPBF involves a large number of input process parameters (~100). It is important to identify the most significant process parameters to achieve the best as-build part quality. This is not possible by using conventional (factorial, fractional factorial) experimental design approaches as they require a huge number of runs. In this paper, Plackett-Burman experimental design is used to identify the most significant parameters that affect the surface roughness of printed LPBF Hastelloy X parts. Results from experimental design show that the skin thickness, geometry and layer thickness are the most significant process parameters affecting the surface roughness of LPBF Hastelloy X parts.

Design of conformal porous structures for the cooling systems of injection mold

Y. Tang, Y. F. Zhao | McGill University

The cooling system of plastic injection mold plays a critical role. It not only affects part quality but also the cycle time of injection molding process. Traditionally, due to the limitations of conventional drilling methods, the cooling system of injection mold usually consists of simple parallel straight channels. It seriously limits the mobility of cooling fluid, which causes the low cooling efficiency for parts with complex free-form surfaces. In this research, an innovative design method for the cooling system of the injection mold is provided by using conformal porous structure. The size and shape of each cell in the porous structure are varied according to the shape of injection molded part. A case study is provided at the end of this paper to further illustrate the efficiency of the proposed method. Comparing to the porous structures designed by the existing method, the proposed method can efficiently reduce the peak temperature as well as decrease the pressure drop of cooling systems.

LPBF Recipe Translation between Continuous and Modulated Laser Systems with different Spot Sizes

Allan Rogalsky, Issa Rishmawi, Mihaela Vlasea | University of Waterloo

Print recipes are generally machine-specific requiring new optimization efforts to move to a different manufacturing system. Reduced parameters such as energy density and interaction time provide scaling rules for spot size. No such guidelines are currently available for the additional degree of freedom associated with point distance in modulated laser systems. In this work a recipe for water atomized pure iron from the continuous laser based EOS M 290 is translated to the Renshaw AM 400 modulated laser system. Using the surface energy density, volumetric energy density and interaction time from the EOS recipe, on the Renishaw we experimentally varied 1) apparent velocity, 2) hatch spacing, and 3) point distance. The experiment design takes the form of a 2^3 factorial. Scaling functions are considered to interpret datasets. Quantitative merit functions include surface roughness part density and pore distribution by computed tomography. The results are discussed both respect to recipe robustness and process speed.

Abstracts - Verbal Presentations

Maximizing Green and Sintered Density of Pure Iron Parts using Binder Jetting Additive Manufacturing

I. Rishmawi, M. Salarian, M. Vlasea | University of Waterloo

Binder jetting additive manufacturing (AM) was deployed to processing of pure iron powder. Surface morphology, particle size distribution, flow properties, and thermal behavior of water atomized pure iron powders were fully characterized using scanning electron microscopy (SEM), particle dynamic image analysis via Camsizer XT, FT4-Powder Rheometer, and Simultaneous Thermal Analysis respectively. A statistical process parameter optimization approach was applied to increase the green part density of manufactured samples. Cylindrical parts were fabricated and the effect of design parameters such as powder spreading/compaction, binder level, and layer thickness on the quality of green and sintered samples was examined using X-ray computed tomography (XCT). The potential application and future research work will be outlined based on the characterization results.

Geometric Deviation Modeling and Tolerancing in Additive manufacturing: A GD&T Perspective

B. Rupal, A. Qureshi | University of Alberta

Additive Manufacturing (AM) is becoming a very reliable technology to manufacture custom and complex components. The technology has made an exponential growth in the last decade, with many applications and industrial usage. Still, AM needs to improve in areas like Design for AM, geometric deviation modeling and control, and metrological aspects. Regarding geometric deviation, a lot of models and geometric control methodologies are present in literature. However, most of them are limited to plus/minus dimensioning or just one or two Geometric Dimensioning and Tolerancing (GD&T) characteristics, e.g., flatness, cylindricity, etc. This article focusses on the geometric deviation modeling and tolerancing from the GD&T point of view, since GD&T focusses on component's form and shape along with dimensions. Different methodologies are reviewed which focus on the geometric deviation based AM process modeling, error minimization, accuracy control, form error minimization, etc. These are categorized based on the process stage of the AM: Pre-processing geometric control, in process control and Post processing control. A critical analysis of all the methods based on the GD&T characteristics done and pros-cons brought forward. Finally, a new geometric deviation modeling and control methodology is presented based on analytical modeling of the process and quantifying its effects on GD&T features. A simple case study is presented to validate the new methodology and it's potential. Geometric compensation based on the new methodology and experiential validation is planned at a later stage to quantify and eradicate the geometric error as much as possible.

A review of manufacturability for laser powder bed fusion processes

Y. Zhang, Y. F. Zhao | McGill University

Laser powder bed fusion process is able to produce complex metal geometries. The fast development of laser powder bed fusion process offers new opportunities to the industries. Most research done to date has focused on the modeling of the process. It shows that both object geometries and process parameters play an important role in the result of final fabricates. In this review, what manufacturability is in AM and how it is investigated so far are discussed. All process parameters and design constraints for powder bed fusion process are introduced. Studies done in literature of relationship between process parameters and design constraints and how they affect the manufacturability are summarized.

A comprehensive investigation of the volumetric heat sources used in the heat transfer modeling of selective laser melting

Z. Zhang, Y. Huang, R. Adhitan, S. Imani, E. Toyserkani | University of Waterloo

Selective Laser Melting (SLM) is a rapid manufacturing technique in which geometrically complex parts can be made by selectively melting layers of powder. In order to estimate the dimensions of the melt pool cross-sections during this process, three-dimensional finite element simulations of heat transfer are performed. The models, adopting four different volumetric heat sources, are employed to simulate the processes of laser melting single tracks on a single layer of stainless steel 17-4PH powder. Then prediction results, such as the melt-pool dimensions, the temperature distributions, and the temperature gradients, are summarized and compared, and the simulation results are validated with the experimental results. This work is intended for presenting a relatively comprehensive study about the influences of heat-source models on the heat-transfer-simulation results. Recommendations on choosing a heat source model for selective laser melting are given and explained.

Elastic and failure response of imperfect three-dimensional metallic lattices: the role of geometric defects induced by Selective Laser Melting

L. Liu, D. Pasini | McGill University

We examine three-dimensional metallic lattices with regular octet and rhombicuboctahedron units fabricated with geometric imperfections via Selective Laser Sintering. We use X-ray computed tomography to capture morphology, location, and distribution of process-induced defects with the aim of studying their role in the elastic response, damage initiation, and failure evolution under quasi-static compression. Testing results from in-situ compression tomography show that each lattice exhibits a distinct failure mechanism that is governed not only by cell topology but also by geometric defects induced by additive manufacturing. Extracted from X-ray tomography images, the statistical distributions of three sets of defects, namely strut waviness, strut thickness variation, and strut oversizing, are used to develop numerical models of statistically representative lattices with imperfect geometry. Elastic and failure responses are predicted within 10% agreement from the experimental data. In addition, a computational study is presented to shed light into the relationship between the amplitude of selected defects and the reduction of elastic properties compared to their nominal values. The evolution of failure mechanisms is also explained with respect to strut oversizing, a parameter that can critically cause failure mode transitions that are not visible in defect-free lattice.

Quantification of microstructure to reveal the solidification path of an alloy

A. Bogno, J. Valloton, H. Henein | University of Alberta

The research group at the Advanced Materials and Processing Laboratory, University of Alberta, has developed a methodology to formulate and quantify the solidification paths of alloys. The methodology is based on the quantification of a solidified microstructure for its various phase fractions. This measured data is combined with well-established solidification models to yield undercooling temperatures of individual phases. The thermal history and undercooling of different phases in the solidified alloy are estimated for a wide range of cooling rates (from 0.5 K/min to 104 K/s). A detailed quantitative analysis of eutectic structures also reveals solidification conditions that yield optimum properties. In this presentation, the methodology will be described using examples of Al-Cu, Al-Cu-Sc alloys as well as Al-Si.

Abstracts - Verbal Presentations

An adaptable 3D printing technology for development of binder jetting and direct ink writing graphene oxide dispersion material systems

X. Shen, T. Morrison, H. Naguib | University of Toronto

The study of multi-functional nanoscale materials (graphene, nanotubes, nanowires) has inspired novel applications in manufacture of products with highly desirable mechanical and electrical properties. Developing additive manufacturing techniques for 3D carbon nanomaterial structures could lead to a manufacturing process that facilitates rapid prototyping and promotes ubiquitous usage of nanomaterials in flexible sensors, actuators, and energy devices. Graphene oxide dispersions in water exhibit 4 distinct regions of rheological behavior varying with dispersion concentration: viscoelastic liquid, transition state consisting of viscoelastic liquid and viscoelastic soft solid, viscoelastic soft solid, and viscoelastic gel. The transition state rheology is ideal for inkjet printing, while the viscoelastic gel is ideal for direct ink writing. Binder jetting and direct ink writing are ideal tools for investigating the use of graphene oxide dispersions in additive manufacturing. Shear forces induced by extrusion from thin microscale nozzles in both techniques is also known to facilitate alignment of crystalline carbon nanomaterials, imparting improved mechanical properties and electrical conductivity to the printed structure. A study of the full range of rheological behaviors of graphene oxide dispersions as additive manufacturing materials and their resulting 3D structural properties motivates the design and build of a hybrid binder jetting and direct ink writing 3D printer. Simple models of binder jetting printers and direct ink writing printers are proposed, discussing the overlapping subassemblies that enable the building of a functional hybrid. Performance metrics are presented for the direct ink writing of a cellulose nanofiber (CNF)/ Graphene oxide composite.

Additive Manufacturing of Ni-Based Superalloys

Sila Ece Atabay[1], Kevin Plucknett[2], Mathieu Brochu[1] | 1- McGill University, 2- Dalhousie University

Additive manufacturing (AM) is a promising technology that enables the production of complex parts with a unique freedom in design and short lead times. Variety of metallic materials can be processed through additive manufacturing. However, for application requiring high strength and high temperature resistance Ni-base superalloys are the primary choice of material. While there are variety of Ni-base superalloys that can be produced through AM, most high strength alloys are prone to cracking and considered unweldable. The objective of the project is to better understand the factors affecting these manufacturing difficulties. Traditional studied avenues include process parameters and alloy composition. This presentation will focus on investigating the solidified microstructure for Rene 41 (similar to Udimet 520), material that will be used as reference for this project.

Development of thermally stable aluminum alloys for laser powder bed additive manufacturing

R. Ley[1], M. Brochu[2], I. Donaldson[3], P. Bishop[1] | 1- Dalhousie University, 2- McGill University, 3- GKN Sinter Metals

The long-term objective of this research is to design, develop, and process aluminum alloys for laser powder bed additive manufacturing (LPB-AM) that offer enhanced in-service thermal stability. In doing so, alloys strengthened by a distribution of thermally stable aluminide dispersoids within the microstructure are emphasized. Early stage efforts have addressed systematic additions of iron and nickel. Powders of Al-1Fe, Al-1Ni, and Al-1Fe-1Ni were inert gas atomized for this purpose. Each powder was characterized extensively to assess key attributes (particle size distribution, dynamic angle of repose, microstructure, flow, apparent density, etc.) and then processed via LPB-AM. Each build was then examined to determine finished product density and the general nature of the final microstructure (SEM/EDS, EBSD, XRD).

Cellulose Nanofibre and Graphene Oxide Composites for 3D Printed Electrodes

T. Morrison, X. Shen, H. Naguib | University of Toronto

The natural porosity of binder-jetted materials could be advantageous for energy storage applications where porous structures enable fast ion transport within electrodes. This study aims to produce novel, mesoporous, electrically conductive materials compatible with multiple 3D printing technologies, including powder-bed binder jetting, to print supercapacitor electrodes. In this work, cellulose nanofibres (CNF) are utilized as a renewable, abundant substrate material that offers the benefits of high specific surface area, connectivity and excellent mechanical properties. Graphene oxide (GO) is coated to CNF and chemically reduced to create an electrically conductive network. Reduction can proceed directly in the CNF/GO dispersion to easily produce a viscous fluid suitable for direct ink writing and other slurry-based 3D printing techniques. Alternatively, dried CNF/GO powder can be reduced during powder-bed binder jetting by incorporating a reducing agent into the binder. The acidic reducing agent will degrade the cellulose while simultaneously reducing the GO layers, producing unique porous microstructures.

Processing of Ti-64 by Laser Powder Fed Additive Manufacturing

M. Harding[1], M. Brochu[2], I. Donaldson[3], K. Plucknett[1], P. Bishop[1] | 1- Dalhousie University, 2- McGill University, 3- GKN Sinter Metals

The long-term objective of this research is to design, develop, and process novel titanium alloys specifically for laser powder fed additive manufacturing (LPF-AM). To be successful, the outcomes must offer advantages in processing behaviour, dimensional accuracy, and mechanical/physical properties over the titanium alloy most commonly utilized in this technology; namely, Ti-64. Early stage activities in this project have therefore sought to establish a baseline of these attributes using a commercial Ti-64 powder against which all future developments can be compared. A test build geometry was designed for this purpose and distributed to four vendors of LPF-AM systems along with samples of Ancor Ti-64 powder that were all sourced from the the same commercial lot. The microstructures of each build were evaluated using optical metallography, scanning electron microscopy, and x-ray diffraction. Tensile properties were measured on machined test specimens according to ASTM E8M. Freeform build quality was assessed through dimensional measurements and surface characterization via optical profilometry.

Particle decoration: An effective powder modification method toward developing new material for additive manufacturing

E. Marzbanrad, Y. Mahmoodkhani, U. Ali, E. Toyserkani | University of Waterloo

Additive manufacturing techniques are rapidly developing in hardware and software area. However, availability of the materials for rapid fabrication technologies for making functional parts is playing a retarding role in the fast-growing trend of the additive manufacturing. Among more than 5500 commercial alloys, few of them such as steel, AlSi10Mg, TiAl6V4, CoCr and some Ni-based alloys are commercially available for Additive manufacturing. Hence, there is a high demand for research in the area of material for additive manufacturing. Most of the industrial additive manufacturing techniques are consuming material in the form of powder. It is well known that the particle's shape, size distribution, and rheology of powder influence manufacturing defects and the properties of the manufactured parts. Hence, modifications such as adding alloying elements, inclusions or making composite require producing powder with acceptable particle size and distribution range, which might be achievable through conventional powder manufacturing techniques. However, this approach seems to be costly and inefficient for research purpose. Therefore, research into alternative methods for aforementioned powder modification is indispensable. The main objective of this research is to evaluate the effectiveness of nanoparticle decoration as a method for modifying chemical composition of AM powders. For this study, Inconel 625 was selected as main powder and yttrium stabilized zirconia (YSZ) was added to it for producing a metal matrix composite. The effect of decoration the properties of the printed part were investigated and the results was employed to demonstrate the advantages and challenges of nanoparticle decoration on the additive manufacturing process.

Abstracts - Poster Presentations

A systematic investigation of the impact of AM processing parameters on meltpool and heat affected zone size and shape

W. Sparling[1], P. Carriere[2], C. Sinclair[1], S. Cockcroft[1] | 1- University of British Columbia, 2- McGill University

Beginning with electron-beam remelting of Ti-6Al-4V plate, the impact of speed (17-68 mm/s), power (300-1200 W), and preheat temperature (30-715 °C) are investigated experimentally and through modelling. The size and shape of the meltpool and HAZ are examined across these parameters. A simple FE heat transfer model is used and compared with experimental results to examine its applicability within the context of AM. It is found to be reasonably accurate at slower speeds, but under predicts depth at higher speed. This discrepancy is attributed to the model's inability to predict fluid flow. Initial experiments produced at McGill are repeated and expanded upon using an electron beam system at UBC. Martensitic transformations are observed across all samples, leading to the formation of a unique microstructure in samples with higher cooling rates. An estimate of the heating rate and the cooling rate required to produce this microstructure is made based on experimental observation and values derived from the FE results.

A review of particle packing models - Current understanding and Future direction

G. Shanbhag, M. Vlasea | University of Waterloo

Substantial efforts are being placed on predicting green part density based on simplified discrete element models (DEM) considering various forces between particles. However, the first step towards DEM is developing an understanding of sphere and powder packing. Many researchers have studied packing both experimentally and by computer simulation. There are a range of packing models defined in literature; however, they are not directly optimized for additive manufacturing (AM) processes. To provide a better understanding of the packing of spherical particles, the goal of this study is to provide a review of what is currently known about mono-disperse and bi-disperse packings of spheres and how it applies to AM. The focus would be on geometrical parameters such as packing density, coordination number, radial distribution, etc. to develop the basic concepts and relationships applicable to powder bed processes. The results from these packing models (such as Drop and Roll, Eden Growth, Monte Carlo etc.) will be used towards developing a theoretical framework for prediction of packing arrangements and investigating various powder parameters such as packing density, particle size distribution, etc. for AM. These models will be validated experimentally to revamp the algorithms accordingly.

Modelling and Control of Dispensing-Based Additive Manufacturing for the Production of Bone Scaffolds

V. Jacob-John, H. Arkaz, Y. Altintas, R. Wang | University of British Columbia

Bone scaffold is a solid part that can be implanted in the area of a large bone defect in order to provide a support for the bone to grow. Additive manufacturing is an exciting way of producing these bone scaffolds, allowing for custom shapes, and control over porosity and other parameters. Dispensing-Based Additive Manufacturing, is a process where a material in liquid solution is dispensed from a syringe layer by layer in shape to become a solid 3D desired shape. Alginate, a natural material derived from brown seaweed, can be used to create a hydrogel that will work as a bone scaffold. Alginate becomes solid through gelation when soluble sodium alginate is exposed to calcium ions in solution. Here we introduced a new technique of cross-linking alginate in additive manufacturing by adding a Photoacid Generator (PAG) and suspended solid calcium carbonate nanoparticles ($CaCO3$) to the sodium alginate solution to be dispensed. When exposed to UV light, the Photoacid generator can release hydrogen ions and result in the release of free calcium ions to allow controlled gelation. The UV light induced gelation, the dispensing of solution from a syringe and motion of the machine moving the syringe can all be modelled in terms of various input parameters. Later, a process controller can be added to control these inputs to the subprocesses to improve the quality of the finally manufactured hydrogel.

Magnetic Levitation with Potential Application in Additive Manufacturing

X. Zhang, B. Khamesee | University of Waterloo

Magnetic levitation uses magnetic field to remotely manipulate an object. There is no mechanical connection between the manipulated object and its actuator. In this research, we propose to realize the three-degree-of-freedom manipulation of a magnetized object using electromagnets array installed around the workspace of the levitated object. The object could be either permanent magnetic material or ferromagnetic material depending on the application. The system provides 10μm accuracy translation control on the levitated object using high precision laser-beam sensors. A Haptic device is introduced to the levitation system to realize the remote manipulation of the object by an operator. In addition, a patent force sensing mechanism is implemented to detect the force when the levitated object is in contact with another object. To improve the stability and robustness of the levitation, an adaptive control algorithm is implemented to secure an uncertain contact. The magnetic levitation system has potential application in additive manufacturing of ferromagnetic parts. Conventionally, multi-joint robotic arms and subtracts are used for multi-degree-of-freedom printing of complex parts. This requires large manipulation spaces and very complex control algorithms. However, the parts being printed can be levitated remotely by magnetic field with up to six-degree-of-freedom using high-speed digital camera. Adding extra material during the printing process can be achieved by either orientation control of the part or by using multi powder nuzzles from several directions. In addition, adaptive control of the levitated part for unknown disturbance and weight variation.

Defect Space Analysis for Invar36 in Powder Bed Laser Fusion Process

D. Ertay, M. Vlasea | University of Waterloo

Powder bed laser fusion (PBLF) is one of the main metal additive manufacturing processes, where the part is manufactured by spreading a layer of metal powder on to the built plate and fused by a laser beam in a layer-by-layer manner. As the nature of the PBLF process is to create parts from metal powder particles, it is traditionally challenging to narrow in a process recipe that will achieve full density parts. The density of the part plays a significant role in mechanical properties of the part (e.g. fatigue resistance, yield strength, ductility), hence it is aimed to manufacture parts with high density. Vast number of studies have shown that the density of the part could be improved by optimizing the process parameters (e.g. laser power, scanning speed, layer thickness, scan strategy), by choosing the powder characteristics (e.g. powder particle size, powder shape and powder distribution) accordingly and also by improving the ambient conditions (e.g. gas flow, ambient temperature and oxygen level). The scan strategy chosen for each layer and the interactions of scan paths at discontinuities such as borders or internal features, create regions with high probability of pore occurrence. In this work, the complex relation between the defects and the toolpath at border discontinuities is investigated for a print recipe which gives 99.99% solid fraction in the core of the part. Samples manufactured by different scan strategies are scanned by X-ray Computed Tomography (CT). The pore space was analysed to extract the pore frequency, size, shape and location with respect to the scan path, border and contour strategies, and gas flow direction at each layer for a modulated laser beam PBLF process. A tool to predict the probability of pore occurrence is presented.

Relationship between defects population and tensile properties of Inconel 625 alloy

H. Asgari, M. Salarian, M. Vlasea | University of Waterloo

X-ray computed tomography (XCT) is a non-destructive method for imaging internal and external 3D features of a solid object. In this study, Inconel 625 tensile samples were manufactured by Selective Laser Melting (SLM) at a constant scan speed but different laser power. Micro-scale CT examination was performed on the samples before and after tensile tests to evaluate the size, morphology, and distribution of the pores along the gauge length. In addition, fracture surfaces of the tensile tested samples were examined using Scanning Electron Microscopy (SEM) to clarify the origin of failure and pore formation. Detailed information obtained from XCT method contributed to establish a relationship between defects population and tensile properties of the samples.

Abstracts - Poster Presentations

Process Mapping and Optimization of Invar36 for Powder Bed Laser Fusion

H. Ma, M. Vlasea | University of Waterloo

Invar36, also known as FeNi36, is a material that is known for its characteristically low coefficient of thermal expansion and it is used in applications requiring high dimensional stability. The material processing of Invar36 using traditional machining methods is difficult due to its work hardening characteristics. Moreover, Invar36 is also known to produce soft and 'gummy' chips, which can deleteriously affect cutting operations. Through the utilization of the powder bed laser fusion additive manufacturing (AM) process, the reliance on traditional methods for machining complex parts can be minimized. Therefore, it is the goal of this study to investigate and optimize the manufacturing process of Invar36 through AM. A laser-based powder-bed fusion process will be used for part production, and a design of experiment (DoE) approach will enable the analysis of the significance of processing parameters on part quality such as dimensional accuracy and porous defects, thermo-physical and tensile properties of produced parts. To provide a basis of understanding for the study, samples of Invar36 powder have been characterized according to particle size, flow characteristics, and elemental composition.

A review of the selective laser melting of AlSi10Mg and investigation of fabricating an aluminum pump housing through additive manufacturing

L. Brock, M. Vlasea | University of Waterloo

The purpose of this work is to investigate the suitability of using additive manufacturing processes to fabricate an aluminum pump housing with complex geometry. The methods of selective laser melting and direct or indirect binder jetting will be considered. The current work provides a review of the selective laser melting of AlSi10Mg, including the ideal processing parameters in terms of the volumetric energy density, the types of artifacts that were built, and the outcomes based on the characterization of the surface quality, porosity, hardness, mechanical strength, fatigue, or corrosion behaviour. In parallel, an existing aluminum pump housing manufactured by casting is investigated in order to determine benchmark values for the mechanical properties and the minimum size requirements for part geometries such as internal channels and thin walls. Test artifacts representative of the pump housing and its required specifications are selected for later manufacture and study in order to determine the best fabrication method and optimized processing parameters.

Non-Destructive Testing of Metallic Parts Made by Laser Powder-Bed Fusion Additive Manufacturing using X-ray Nano-Computed Tomography (Nano-CT)

M. Salarian, E. Toyserkani | University of Waterloo

High-resolution X-ray Computed Tomography (XCT) widely expands the spectrum of detectable internal features with minimal preparation and exceptional resolution. A comparison between nano-scale (500 nm) and micro-scale (3 μm) XCT examinations of an aluminum part manufactured with laser powder-bed fusion additive manufacturing (LPB-AM), known as selective laser melting (SLM), was performed to determine the extent of microstructure details (size and distribution of defects/pores) lost with micro-CT resolution. This will provide insightful information into the further studying of LPB-AM parts and help to predict material strengths/durability.

Magnetic Levitation with Potential Application in Additive Manufacturing

X. Zhang, B. Khamesee | University of Waterloo

Magnetic levitation uses magnetic field to remotely manipulate an object. There is no mechanical connection between the manipulated object and its actuator. In this research, we propose to realize the three-degree-of-freedom manipulation of a magnetized object using electromagnets array installed around the workspace of the levitated object. The object could be either permanent magnetic material or ferromagnetic material depending on the application. The system provides 10μm accuracy translation control on the levitated object using high precision laser-beam sensors. A Haptic device is introduced to the levitation system to realize the remote manipulation of the object by an operator. In addition, a patent force sensing mechanism is implemented to detect the force when the levitated object is in contact with another object. To improve the stability and robustness of the levitation, an adaptive control algorithm is implemented to secure an uncertain contact. The magnetic levitation system has potential application in additive manufacturing of ferromagnetic parts. Conventionally, multi-joint robotic arms and subtracts are used for multi-degree-of-freedom printing of complex parts. This requires large manipulation spaces and very complex control algorithms. However, the parts being printed can be levitated remotely by magnetic field with up to six-degree-of-freedom using high-speed digital camera. Adding extra material during the printing process can be achieved by either orientation control of the part or by using multi powder nuzzles from several directions. In addition, adaptive control of the levitated part for unknown disturbance and weight variation.

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