Engineering Faculty Document No. 46-23
December 5, 2022

To: The Engineering Faculty

From: The Faculty of the School of Materials Engineering

Re: New graduate course – MSE 56800 Additive Manufacturing of Materials

The Faculty of the School of Materials Engineering has approved the following new graduate course as of December 5, 2022 (see attached document of course description). This action is now submitted to the Engineering Faculty with recommendation for approval.

MSE 56800 Additive Manufacturing of Materials, Sem 1 or 2, Class 3, Credit 3. Prerequisites: MSE 33000 or MSE 36700 concurrently or graduate standing.

The course takes an MSE approach to additive manufacturing, integrating deposition processing, powder processing, and solidification processing principles in the full range of AM process configurations and kinematics. The overarching goal is to learn how microstructure development, and thus the resulting material properties, are controlled by the interaction of physical, chemical, thermal and mechanical phenomena in the shaping of materials by additive processing. All the main classes of materials and AM processes are covered. Additional objectives are to quantitatively analyze the capabilities and limitations of AM relative to established commercial shaping processes; and to critically analyze the AM research literature.

> This course was taught under a temporary course number in Spring 2021 and Spring 2022, with enrollment of 55 and 50, respectively.

David Bahr, Head
School of Material Engineering

Proposal for New Graduate Level Course for Academic Review
MSE 56800 – Additive Manufacturing of Materials

Note: The detailed course proposal is intended for academic review by the appropriate area committee of the Graduate Council. It supplements the Form 40G that is intended for administrative review of the Graduate School and Registrar.

TO: Purdue University Graduate Council

FROM: Faculty Member: Kevin Trumble
Department: School of Materials Engineering
Campus: West Lafayette

DATE: December 5, 2022

SUBJECT: Proposal for New Graduate Course

MSE 56800 Additive Manufacturing of Materials
Semester 1 or 2, Lecture 3, Credit 3. Prerequisites(s): MSE 33000 or MSE 36700 concurrently, or graduate standing

1. Course Description

The course takes an MSE approach to additive manufacturing, integrating deposition processing, powder processing, and solidification processing principles in the full range of AM process configurations and kinematics. The overarching goal is to learn how microstructure development, and thus the resulting material properties, are controlled by the interaction of physical, chemical, thermal and mechanical phenomena in the shaping of materials by additive processing. All the main classes of materials and AM processes are covered. Additional objectives are to quantitatively analyze the capabilities and limitations of AM relative to established commercial shaping processes; and to critically analyze the AM research literature.

2. Justification for the Course

2.1 Justification of the need for the course

Additive manufacturing (AM), sometimes generically described as "3D Printing," has emerged as a family of materials processing routes unified by layer-by-layer deposition or building of 3D materials structure (shaping), usually in a line-by-line process within the layers that is computer numerically controlled. The processes have advantages for producing complex, custom and miniature parts without the need for tooling (molds or dies). Intensive world-wide research and development continues to increase their commercial applications. Seven distinct classes of AM processes are now recognized, Vat Polymerization, Material Extrusion, Material Jetting, Binder Jetting, Powder Bed Fusion and Directed Energy Deposition, spanning all the main classes of materials (polymers, ceramics and metals) and their composites. The MSE approach of relating microstructure development in processing to resulting materials properties provides a powerful framework for advancing the engineering and science of this emerging technology. By understanding the capabilities and limitations of the processes in terms of their constituent materials processing elements (e.g., polymerization, melting and solidification, particle consolidation) the course will provide students a solid foundation for leading the further development and application of AM technologies. Research and teaching of AM at Purdue continue to expand and at least some elements are encompassed by nearly every engineering discipline. Computer control systems (IE, ECE, CS), manufacturing processes (ME and IE), custom tissues and prostheses (BME and ME), polymer and particulate processes (CHE and IPPH) and more recently in construction (CE). By taking such a general approach, the course will also serve the broad needs at Purdue. The course was offered under a temporary number in Spring 2021 and Spring 2022, with enrollment of 55 and 50, respectively

2.2 Justification that the course be taught at a graduate level

MSE 56800 will be taught at the graduate level, requiring background beyond the introductory undergraduate materials course. Upper-division undergraduates are required to have the 300-level materials processing lecture and/or lab class. Graduate students should have at least had an introductory materials courses in their background. A general AM processes textbook is well suited to the course. The course will focus on the microstructure development in shaping that leads to the properties that control performance in engineering applications. Thus, some experience with materials properties-structure relationships is necessary. Several examples of advanced topics from the AM research literature are incorporated and students then have an assignment to prepare an up-to-date review on a fundamental or applied AM research topic of their choosing. This gives students a chance to explore more advanced topics in at least one subfield of AM.

Assessment will be primarily through two in-class exams and a final exam (written exams constitute 80% of final grade). The exams require intensive problem solving and reasoning from concepts covered in lecture and homework. A research review-update assignment is based on open-ended research and requires the students to synthesize the literature and assess the current state of the art in a particular area. While the final grades for the course are curved, undergraduate students are not assessed separately from the graduate students (mostly seniors) and are expected to perform at the same level.

The course will continue to serve students from across the engineering disciplines. In the first two offerings (2021 and 2022) it attracted over 100 students from 6 different disciplines, including ME, BME, AAE, CHE, and CE, as well as MSE.

2.3 Justification for online delivery

MSE 56800 will continue serving as one of the core MSE courses for students pursuing online Master's degrees in Engineering, including the rapidly growing Professional MS degree programs in multiple disciplines.

3. Learning Outcomes and Methods of Assessment

3.1 Learning Outcomes

All Students will be able to:

A. Identify the generic elements of any additive manufacturing process.
B. Identify and understand the main unit materials process involved and be able to predict how processing parameter will change resulting material structure and properties.
C. Relate additive processing to characteristic microstructure features and defects.
D. Interpret standards and specifications for processing and properties produced by the different additive manufacturing processes.
E. Distinguish quantitatively between the different additive manufacturing processes in terms of their shaping capability compared to traditional bulk shaping processes.

Most Students will be able to:

A. Identify AM processing defects and their origins in particular processing parameters
B. Specify an optimum AM process for a particular material, component and service conditions.
C. Explain properties variability and anisotropy in AM products in terms of processing constraints.
D. Analyze critically the state of research on a particular current topic in additive manufacturing

3.2 Assessment Methods

Assessments will be achieved through three exams (two midterms and a final exam). Each exam will require complex problem solving and reasoning. These exams will be designed to assess students' knowledge of the AM processing and resulting microstructure development in polymers, metals, ceramics and their composites, and their skills in assessing the corresponding properties for specific applications.

Several homework sets will be assigned throughout the term to reinforce the information covered during lecture. The homework will be nominally graded and solutions to the more difficult problems will be covered in detail in class and during review sessions held prior to the exams.

3.3 Final Grading Criteria

Grading is based on the following weighting: two mid-term exams (20% each), a comprehensive final exam (35%), current topics research review (15%), and (5) homework sets (10%). Graduate and undergraduate students will be evaluated together and a single curve will be applied to the final grade assignments if necessary. The final grading scale will be based on overall class performance, with grade divisions no higher than 85% -A, 70% -B, 60% -C, 50% -D.

3.4 Methods of Instruction

The primary method of instruction will be through lectures, discussion and feedback on homework exercises, to help the students achieve the learning outcomes. These include analyses of basic principles of concepts covered during lectures and their application in practice.

3.5 Prerequisites

Completed or concurrently MSE 33000 or MSE 36700, or graduate standing

4. Course Instructor

Kevin Trumble, Professor, MSE, member of the Graduate Faculty:

Prof. Trumble has extensive experience teaching materials engineering at Purdue. He has developed and taught an array of undergraduate and graduate courses, mainly in the materials processing area, including MSE 512 Powder Processing, MSE 536 Solidification Processing, and MSE 548 Deposition Processing. Each of these courses provides part of the materials processing principles that are integrated in the proposed Additive Manufacturing of Materials course.

5. Course Outline by Week:

1. Introduction, Materials Processing and Additive Manufacturing
2. Generic AM kinematics and cost analysis
3. Polymers, Polymerization and Vat Polymerization
4. Vat Polymerization, Polymer rheology and extrusion
5. Material Extrusion
6. Material Jetting and Exam 1 (covering VP and ME)
7. Surface tension, capillarity and Material Jetting
8. Powders and bulk powder processing
9. Binder Jetting
10. Focused-beam melting and solidification of alloys
11. Powder Bed Fusion and Exam 2 (covering MJ, PP, BJ)
12. Powder Bed Fusion
13. Directed Energy Deposition
14. Directed Energy Deposition and Hybrid processes
15. Comparative AM processes-properties
16. Final Exam

6. Reading List

I. Gibson, D. Rosen, B. Stucker and M. Khorasani, Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing, 3rd Edition, Springer Nature Switzerland AG (2021). ISBN 978-3-030-56126-0 ISBN 978-3-030-56127-7 (eBook); DOI: 10.1007/978-3-030-56127-7. *This book will serve as the main text for the course.*

D. Bourell, H. Kuhn, W. Frazier, and M. Seifi, editors, ASM Handbook, Vol. 24, Additive Manufacturing Processes (2020), DOI: 10.31399/asm.hb.v24.9781627082907. *Selected chapters.*

J. Zhang and Y-G Jung, editors, Additive Manufacturing: Materials, Processes, Quantifications and Applications, Elsevier, Butterworth-Heinemann (2018). DOI: 10.1016/C2016-0-01595-4. *An alternate comprehensive textbook*

CES EduPack, Granta Design. *Interactive software platform for materials properties and processing visualization and design analysis. Requires download of Citrix Receiver.*

Note: All these resources are available electronically through the Purdue libraries

7. Course Syllabus

Purdue University
School of Materials Engineering

MSE 597 Additive Manufacturing of Materials **Spring 2022**

Lecture: TTh 10:30-11:45 WANG 2599 (in-person or distance)
Instructor: Prof. Kevin Trumble, ARMS 2333, 765-494-4114, driscol@purdue.edu
Teaching Assistant: Rahul Franklin, frankl74@purdue.edu

Website: *Brightspace*
Office Hours: By phone, Webex (https://purdue.webex.com/meet/driscol), or in-person; arranged by e-mail preferred. Regular office hours will be set if there is sufficient demand. Rahul will also be available for regular office hours.

Objective: Apply the general materials processing approach to additive manufacturing for all the main classes of engineering materials.

Description: The course will take a materials science and engineering (MSE) approach to Additive Manufacturing (AM), following the structure of the general materials processing course series taught in the School of Materials Engineering (MSE 512 *Powder Processing*, MSE 536 *Solidification Processing* and MSE 548 *Deposition Processing*). The overarching goal is to learn how microstructure development is controlled by the interaction of physical, chemical, thermal and mechanical phenomena in the shaping of materials by additive processing. All major classes of materials and AM processes will be included. Other objectives are to develop the ability to quantitatively analyze the capabilities and limitations of AM processes relative to established commercial processes; and to critically analyze the AM research literature. The course will also provide opportunities for students to explore AM topic area(s) of their own interest.

Brief Outline: Introduction, MSE approach; Manufacturing and materials processing; Unifying aspects of AM; Main AM process classes: vat polymerization, extrusion, printing (jetting), binder jetting, powder bed fusion, directed energy deposition; comparative processing, including AM process design, selection and applications. Supporting fundametnals underpinning the AM processes will include, polymerization; rheology of melts, slurries and pastes; powder characterization and processing; focused-beam energy sources; solidification; etc. A week-by-week topic outline is provided on page 4.

Prerequisites: An introductory course in engineering materials and/or manufacturing processes or permission of instructor.

Textbooks (all available free through the Purdue Library>Databases)
I. Gibson, D. Rosen, B. Stucker and M. Khorasani (**GRSK**), Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing, 3rd Edition, Springer Nature Switzerland AG (2021). ISBN 978-3-030-56126-0 ISBN 978-3-030-56127-7 (eBook); DOI: 10.1007/978-3-030-56127-7. *This book will serve as the main text for the course.*

D. Bourell, H. Kuhn, W. Frazier, and M. Seifi, editors, (**BKFS**), ASM Handbook, Vol. 24, Additive Manufacturing Processes (2020), DOI: 10.31399/asm.hb.v24.9781627082907. *Selected chapters.*

Also recommended

J. Zhang and Y-G Jung, editors (**ZJ**), Additive Manufacturing: Materials, Processes, Quantifications and Applications, Elsevier, Butterworth-Heinemann (2018). DOI: 10.1016/C2016-0-01595-4. *An alternate comprehensive textbook.*
CES EduPack, Granta Design. *Interactive software platform for materials properties and processing visualization and design analysis. Requires download of Citrix Receiver.*

Also handy may be any introductory Engineering Materials text (e.g., Callister, Ashby, Flinn and Trojan, Smith, etc.) and any introductory Manufacturing Processes text (e.g. Schey, Kalpakjian, DeGarmo, Groover). *These references will be useful for reviewing related materials and manufacturing fundamentals. Back editions of these books can be obtained for next to nothing from online sellers. Their fundamental content does not go out of date. Although the latest editions may contain some treatment of "additive manufacturing," this is hardly worth spending $200+. These books can also be readily borrowed from libraries.*

Course Format
The course is running in a hybrid in-person/online mode in Spring 2022 through the Engineering Professional Education (EPE) program. Lectures will be recorded with an in-person (on-campus) class in the WANG 2599 studio-classroom and posted to *Brightspace* usually the same day. The the lecture recordings will be available to all student any time.

Lecture Format
The lectures will be presented using partially completed template slides that can be downloaded from the website and used to follow along as Prof. Trumble fills them in on the document camera. This method, developed over many years, accomplishes some of the feel of a chalkboard lecture and avoids "death by powerpoint," i.e., listening to the reading of a deck of slides, which you might just as well read yourself.

Exams
Two midterm exams (February 17 and March 31) and a comprehensive final exam (May 2-7 TBA) will be given. The current plan is to return to in-class exams for on-campus students and in-person, proctored for distance students. As you know, that could change.

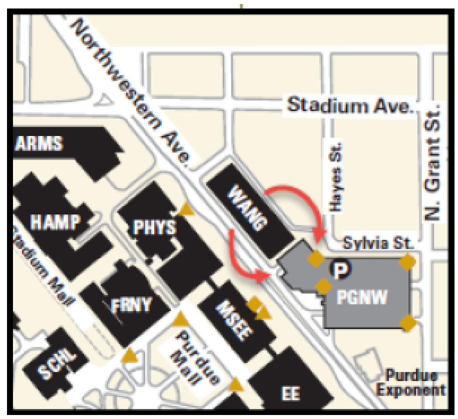
Homework
Homework sets (4-5) will be turned in electronically on *Brightspace* and nominally graded as follows: ✓+(100)/✓(75)/✓–(50). Solutions will be posted and discussed in class.

Presentation Assignment
A communication assignment (due after the second exam) will involve preparing a recorded presentation (voice over Powerpoint) on an AM topic of particular interest to the student.

Pandemic Contingencies
For on-campus students, the current Purdue Covid-19 pandemic protocol (Protect Purdue; see the next page) allows full classroom capacity, but requires masks (and no food or drink, including water). As you know, this could change if the pandemic worsens. The full capacity of WANG 2599 is 75; so even if we return to half-capacity, there will be seats for everyone. Please attend if you can. If in-person meetings become restricted, the lectures will still be available in the recorded format and the exams will be administered online through *Gradescope* or similar platform, using the procedures described on the next page.

Assessments and Grading (percentage of final grade):
Homework problem sets throughout the semester (10%); a virtual (recorded) oral presentation (15%) on an AM topic of particular interest to the student; two midterm exams (20% each); and a comprehensive final exam (35%). Final grades will include "+" and "-" divisions, divided evenly by score within each letter grade range.

Emergency Procedures



Fire, weather, and civil emergency procedures specific to the WANG 2599 will be reviewed in class. Information on emergency preparedness at Purdue is available on the Purdue homepage and at http://www.purdue.edu/emergency_preparedness/.
For a shelter-in-place siren (tornado, hazardous material release, civil disturbance) stay in WANG 2599 and wait for further instructions. In case of a fire alarm, exit WANG via the stairway and assemble in the Northwestern Avenue parking garage.

In the event of a major campus emergency, course requirements, deadlines and grading percentages are subject to changes that may be necessitated by a revised semester calendar or other circumstances. These changes would be posted on the course website on *Brightspace*. In case of an extended disruption in which classes on campus are suspended the course will continue in the online only mode via *Brightspace*.

Covid-19 Protocols

See the Protect Purdue central website for Covid-19 updates: https://protect.purdue.edu/. It is critically important that students on campus monitor for Covid-19-related symptoms. Contact the Protect Purdue Health Center by calling 765-496-INFO (4636) or toll-free at 833-571-1043. If you feel at all sick, it is very important not to come to class and to get tested and see a doctor if necessary. One advantage we have with this course format is that the lecture recordings will be available to all students at any time. So, if you do get quarantined, you can keep up with the lectures remotely. If you anticipate an extended absence from the course for any reason (e.g., severe illness) please inform Prof. Trumble as soon as possible, to discuss how you can make up any missed work.

Remote Examinations

In the event that increased pandemic restrictions at Purdue preclude in-person exams, the exams will be administered online through *Gradescope* via *Brightspace* using the following procedure:

A pdf exam file identical to an in-class exam paper (~6 pages) will be downloaded and worked (written out) by the student, either electronically on a tablet or printed and worked on paper and then scanned or photographed, and uploaded as a single electronic file to *Gradescope*.* An extra 20 minutes will be allowed for downloading and uploading exams. The midterm exams, which would normally be given in a 50-minute class period, will thus have a 70-minute limit, the final exam a 140-minute limit. Students are on their honor to work the exam by themselves and without any internet resources.

Mental Health Resources

If you or someone you know is feeling overwhelmed, depressed, and/or in need of support, services are available. For help, such individuals should contact Counseling and Psychological Services (CAPS) at 765-494-6995 and http://www.purdue.edu/caps/ during and after hours, on weekends and holidays, or by going to the CAPS office on the second floor of the Purdue University Student Health Center (PUSH) during business hours. Students should also feel welcome to discuss any concerns they have with Prof. Trumble.

Students with Disabilities
If you anticipate or experience physical or academic barriers based on disability, you are welcome to discuss options with Prof. Trumble. You are also encouraged to contact the Disability Resource Center at: drc@purdue.edu or by phone: 765-494-1247; https://www.purdue.edu/drc/.

Diversity and Inclusion
Purdue University is committed to maintaining a community which recognizes and values the inherent worth and dignity of every person; fosters tolerance, sensitivity, understanding, and mutual respect among its members; and encourages each individual to strive to reach his or her own potential. Purdue's nondiscrimination policy can be found at the following website: http://www.purdue.edu/purdue/ea_eou_statement.html. If you see, hear or experience discrimination in any form you are always welcome to discuss it with Prof. Trumble. The College of Engineering also has a website that provides extensive resources for diversity at: https://engineering.purdue.edu/Engr/AboutUs/Diversity/DiversityResources.

Academic Dishonesty Policy
Purdue University Regulations, Part 5, Section III-B-2-a describes the formal policies governing academic dishonesty. A guide providing specific examples, tips, and consequences is available at http://www.purdue.edu/odos/osrr/academic-integrity/index.html. You are encouraged to study together and discuss coursework, but any work you turn in for grading is expected to be your own original work. Notes presented in the lectures are subject to copyright. Students in the course are granted permission to copy and exchange these notes with other students in the course, but they cannot be sold, bartered or posted on any website.

Week-by-Week Topic Outline (approximate)
1. Introduction, Materials processing and Additive Manufacturing
2. Generic AM kinematics and cost analysis
3. Polymers, Polymerization and Vat Polymerization
4. Vat Polymerization, polymer rheology and extrusion
5. Material Extrusion
6. Material Jetting and Exam 1 (INTRO, VP and ME)
7. Surface tension, capillarity and Material Jetting
8. Powders and bulk powder processing
9. Binder Jetting
10. SPRING BREAK
11. Focused-beam melting and solidification of alloys
12. Powder Bed Fusion and Exam 2 (MJ, PP, BJ)
13. Powder Bed Fusion
14. Directed Energy Deposition
15. Directed Energy Deposition and Hybrid processes
16. Comparative AM processes-properties
17. Final Exam (1/3 comprehensive, 2/3 since E2)