Teaching Additive Manufacturing in a Higher Education Setting

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CONTEXT

Short courses in Additive Manufacturing (AM, colloquially known as '3D Printing') often provide only a cursory coverage of engineering principles. The final year subject 'MECH482 Introduction to Additive Manufacturing' was developed with the aim of providing solid academic grounding and practical experiences in this new field of study, for higher education engineering students. The subject delivery incorporated the Project-Based Learning (PjBL) paradigm (Williams and Seepersad, 2012).

PURPOSE

To evaluate the effectiveness of teaching AM to final year higher education engineering students, including the use of PjBL as a method of reinforcing taught content.

APPROACH

The inaugural offering of the subject 'MECH482 Introduction to Additive Manufacturing' comprised lectures, tutorials and labs, complemented by group discussions, video clips, guest speakers and site visits to AM production / research facilities. Lecture and tutorial coverage included: basic concepts and history of AM, Design for AM (DFAM), AM software, STereoLithography (STL) format, AM process chain, Vat Polymerization (VP), Powder Bed Fusion (PBF, polymer Laser Sintering - pLS and metal Laser Sintering - mLS), Extrusion-based (Fused Deposition Modelling - FDM), Material Jetting (MJ), Binder Jetting (BJ), Directed Energy Deposition (DED), and Direct Write (DW) processes, Medical applications and future directions. Throughout the subject theoretical and practical content was progressively incorporated as per the PjBL paradigm. Students were also able to build upon skills learnt in prior subjects such as Computer Aided Design (CAD) and 'soft' skills such as quality assurance, project management and presentation. The subject culminated in a Group Assignment representing a major proportion of the students' overall assessment. Deliverables included a written report, an additively manufactured item and an oral presentation. Additional assessment was via written examination (mid-session quiz and final exam), tutorial questions and AM lab exercises. A purpose-designed AM Laboratory with seven 3D printers was provided by the Faculty for student use.

RESULTS

Key measurable results, taken from Faculty result sets and student Subject Evaluations, included No. of enrolled students: 45; Gender breakup: female: 5 %, male: 95 %; Attendance rate of lectures and tutorials: 80 %; Unscaled composite results: 81 % HD, 19 % D; Overall student satisfaction with subject: 90 %. Subject evaluation feedback indicated that students responded positively to the variety of teaching methods employed. Students commented that they particularly benefited from applying their theoretical knowledge of AM to the building of tangible physical models as per the PjBL paradigm (University of Wollongong, 2014). However student feedback also indicated that the subject difficulty and academic content was set too low for a final-year subject. This was reflected in the high pass rates. Subsequent iterations of this subject have sought to increase the level of academic rigour, content and difficulty to a more acceptable standard commensurate of a final year subject.

CONCLUSIONS

The subject has proven to be a popular choice for final year students with a number of our graduates now being employed in the AM sector. It is hoped that methods of teaching employed in this subject, including PjBL, will further facilitate students' active participation in the "… new paradigm in engineering education of creativity-led, innovative thinking with design acumen." (Littlefair, 2013).

KEYWORDS

Additive Manufacturing, 3D Printing, Project-Based Learning, PjBL.

Introduction

Interest in the emerging field of Additive Manufacturing (AM, colloquially known as '3D Printing') continues to grow rapidly both in Australia (Wohlers, 2011) and globally (Wohlers, 2015). Education providers are now beginning to capitalise on this valuable opportunity for attracting students and equipping them for the new paradigm in manufacturing. However short courses in AM often provide only a cursory coverage of engineering principles and lack the desired combination of solid engineering theory and practical experience essential for this field of study.

Following a comprehensive market investigation of currently available courses in AM, the School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong identified the need for an introductory subject combining both a solid academic grounding and practical experience. Although such subjects were beginning to be taught in overseas universities there appeared to be few suitable subjects available domestically. It was therefore decided to create a new six credit point subject, 'MECH482 Introduction to Additive Manufacturing', and to offer this to engineering students at the University of Wollongong in Spring Session 2014. This subject was planned to be the first of a number of offerings under the broader area of study of AM. The subject was designed to incorporate the Project-Based Learning (PjBL) method described by Williams and Seepersad (2012).

Purpose

The purpose of this paper is to evaluate the effectiveness of teaching AM to final year higher education engineering students through the subject 'MECH482 Introduction to Additive Manufacturing', including the use of PjBL as a method of reinforcing taught content.

Approach

Subject objectives

The overall objectives of the subject were:

1. To identify the fundamental principles and key phases of the AM process chain
2. To classify and critique the various AM processes
3. To demonstrate a basic scientific understanding of AM techniques by means of tutorial exercises
4. To apply AM design and manufacturing methods by means of a group assignment

Lectures

Lectures focussed on the engineering principles of AM and consisted of 16 x one hour sessions covering the following topics:

- Basic concepts of AM
- History of AM
- AM process chain
- Design for AM (DFAM)
- Software for AM
- STereoLithography (STL) format
- Introduction to OpenSCAD

- Vat Polymerization (VP) processes
- Powder bed fusion (polymer Laser Sintering - pLS, metal Laser Sintering - mLS)
- Extrusion-based processes (including Fused Deposition Modelling - FDM)
- Material Jetting (MJ) processes
- Binder Jetting (BJ) processes
- Directed Energy Deposition (DED) processes
- Direct Write (DW) processes
- Post-processing
- Medical applications
- Future directions and opportunities

All lecture material was developed to align with the prescribed text (Gibson, Rosen and Stucker, 2015). In addition to the taught content three x one hour guest lectures were also organised for the students covering the topics AM in the Creative Arts, DFAM with SolidWorks (Dassault Systèmes 2014), and Development of a Local AM Equipment Industry.

Tutorials

Five x two hour tutorial sessions, covering Objectives 1-3, were incorporated into the subject. The first three of these sessions focussed on end-of-chapter review questions from the prescribed text. The fourth tutorial tasked students with the design of a simple parametrically defined door hinge using OpenSCAD (OpenSCAD.org, 2014), and its manufacture using the School's AM equipment. The final tutorial required students to design and manufacture a simple benchmarking part for the testing of AM resolution, accuracy or surface finish similar fashion to the Problem Based Learning (PBL) example of Williams and Seepersad (2012).

Laboratory

A purpose-designed AM Laboratory was provided for the practical component of the new subject. Co-located with a shared Advanced Manufacturing Workshop, the AM Laboratory consisted of eight UP Plus FDM printers (Beijing Tiertime Technology, 2014) arranged so that a group of two students could comfortably sit at each workstation. In order to manage the AM equipment and consumables a part-time lab assistant was employed. Supervised lab availability was capped at four hours per week, with out-of-hours access by prior arrangement. The layout of the AM Laboratory is shown in Figure 1.

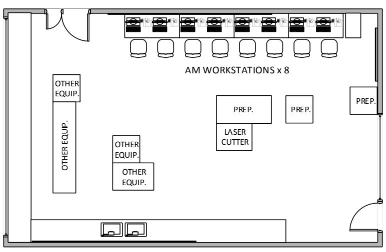

Figure 1: Layout of the AM laboratory

Site visits

To further reinforce the theoretical and practical aspects of AM two site visits were organised. The first was to a nearby University of Wollongong-affiliated AM R&D facility, and the second visit was to a medical device facility which used AM exclusively for the production of hearing aid shells.

Examinations

A mid-session exam assessed Objectives 1-2 and was set in Multiple Choice Question (MCQ) format. The final exam also assessed these objectives but in written answer format.

Group assignment

In order to assess Objective 4 the students undertook a group assignment, as per the PjBL paradigm described by Williams and Seppersad (2012). This effectively tied together the theoretical and practical components of the subject. The deliverables for this assignment comprised the following tasks:

1. Identify a product suitable for additive manufacture using AM.
2. Ensure that there are compelling technical and economic reasons for manufacturing this product by AM.
3. Generate and document a formal problem statement, customer needs analysis, specifications list and series of preliminary concept drawings.
4. Compile a decision matrix to identify the preferred concept for further detailed design.
5. Perform a detailed technical analysis (e.g., mechanical performance) and economic analysis (cost of fabrication using different AM processes) on the preferred design. Iteratively refine the design as required.
6. Generate a 3D Computer Aided Design (CAD) model and STL format file of the final design.
7. Manufacture the product using only the equipment in the AM Lab
8. Design, document and implement a testing procedure for assessing the technical performance and usability of the fabricated product. Critically evaluate the test results.

Students were required to document Tasks 1 to 8 in the form of a written report, an additively manufactured item and oral presentation.

Results

Lectures

It was found that by supplementing the lecture presentations with a mix of group exercises, video clips and guest speakers, interest and continuity was maintained in the classroom. The advantage of presenting completely new academic material also came with benefits and drawbacks. Whilst the lecture material tended to generate a significant amount of interest with the students it became quite challenging to locate suitable academic-level teaching resources upon which to base the lectures.

Tutorials

Restricting students to using OpenSCAD for the parametric object tutorial session ensured a level playing field for assessment. It also provided students with a solid appreciation of the power of parametric design. The PBL tutorial session on the design and manufacture a simple benchmarking part was very well received by students. For this tutorial the restriction of choice of CAD software was lifted. Students were free to use any package capable of producing STL output. In this way students could be assessed solely on their DFAM skills and not on their skills in any particular CAD package. There were some issues with the tutorial sessions based on the end-of-chapter review questions, detailed in the Discussion.

Site visits

For many of the students a highlight of the subject was the series of organised site visits to AM facilities. The first of these visits was to a nearby facility involved in the research and development of innovative polymer materials and advanced manufacturing processes. This facility was affiliated with the University of Wollongong. Here students were able to view the operation of AM equipment utilising the various AM processes such as VP, mLS, MJ and FDM. In order to ensure a quality experience two visits were scheduled, with the number of students on each visit being capped at 23 per visit.

The second site visit was to a medical device manufacturing facility specialising In-The-Ear (ITE) hearing aid shells. At this facility students were able to view the complete mass customisation process from inner ear physical impression model generation, through to digital CAD model, STL export, manufacture by VP, final assembly and quality control.

Group assignment

The culmination of the subject was the Group Assignment which tied together much of the theoretical and practical teaching via the PjBL paradigm. An important part of the assignment was the final presentation session where students were assessed whilst pitching their creations in front of peers.

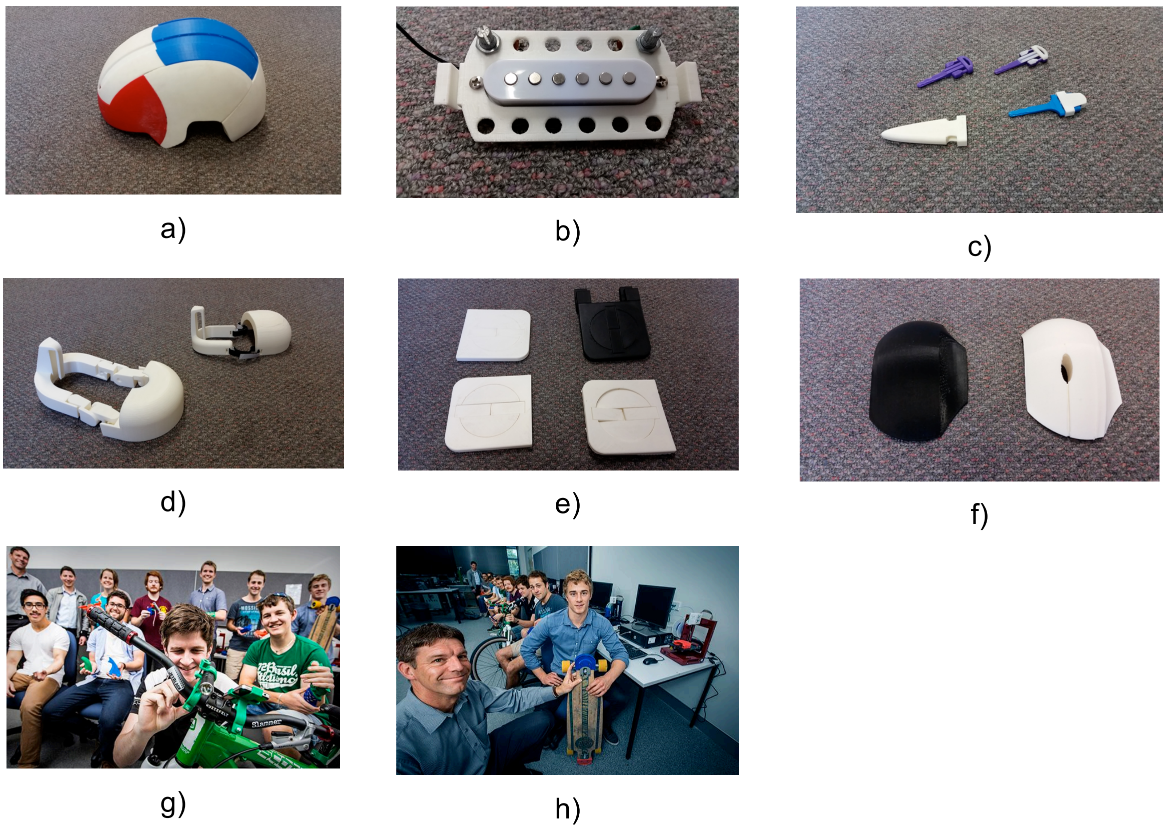

Figure 2: Subset of additively manufactured items from the Group Assignment. a) Customisable bicycle helmet b) Customisable acoustic guitar pickup housing; c) Waterproof 3D printed spare key system; d) Customisable protective overshoes; e) Customisable mousepad / beverage holder for laptop PC; f) Customisable ergonomic computer mouse shell; g) Customisable accessory mount for bicycle; h) Customisable skateboard skid plates

The variety of items selected by groups for their AM assignment was impressive, highlighting the inherent creativity of these engineering students. A subset of items additively manufactured by the students using the AM Lab equipment is given in Figures 2a) to 2h).

Other items designed and manufactured included customisable surfboard fins, retractable earbud headphone case, adjustable filament reel holder, customisable skateboard skid plates, customisable oar gripper for disabled athletes, unmanned Aerial Vehicle (UAV) thrust test rig, customisable industrial pipe cleaning 'pig' and customisable eyeglass frames.

Measurables

Key measurable results, taken from MECH482 result sets and student Subject Evaluations, included:

- No. of enrolled students: 45
- Gender breakup: female: 5 %, male: 95 %
- Attendance rate of lectures and tutorials: 80 %
- Unscaled composite results: 81 % HD, 19 % D
- Overall student satisfaction with subject: 90 %

The Subject Evaluations indicated that students responded positively to the variety of teaching methods employed. Students commented that they particularly benefited from applying their theoretical knowledge of AM to the building of tangible physical models (University of Wollongong, 2014).

However student feedback also indicated that the subject difficulty and academic content was set too low for a final-year subject. This was reflected in the high pass rates. Subsequent iterations of this subject have sought to increase the level of academic rigour, content and difficulty to a more acceptable standard commensurate of a final year subject.

Discussion

Generally speaking it was not difficult to attract sufficient student numbers to the new subject. AM currently elicits a lot of positive media interest and this was reflected in an oversubscription, with numbers capped at 45 as a precaution. This proved to be fortuitous because there were some minor problems with the AM lab equipment but these were duly overcome. Issues such as equipment maintenance and reliability, consumable (filament) supply, accessory tooling, equipment bookings and security were all addressed with the appointment of a lab assistant. This decision was critical to the success of the subject.

The group assignment proved to be extremely popular with the students. It was enlightening to see the DFAM process put into practice, the students' 3D printed items being designed, manufactured and tested with a rapid turnaround time. This further highlights the advantages of a PBL and PjBL based approach by moving away from the more traditional lecture-based methodology to an 'active learning' paradigm (Craig, 2014).

The deliverables for this project (written report, additively manufactured item, oral presentation), covering Tasks 1 to 8, required students to work together closely as a coherent team. This in itself was a valuable learning experience for many of the students and reinforced the 'soft' skills so critical to working as an engineer today. In this way students were able to build upon skills learnt in previous subjects such as CAD, solid modelling, quality assurance, project management and presentation.

As with any new subject undertaking a great deal of preparation was necessary before the commencement of lectures. This task was made all the more challenging due to the scarcity of suitable theoretical and assessable material on AM. Fortunately the prescribed text was well suited for incorporation into a lecture series, with its broad range of content on the fundamental principles of AM. It is anticipated that in future years there will be a more expansive range of theoretical AM texts available to educators.

Developing assessable tutorial material of sufficient academic depth was difficult. Whilst the end-of-chapter review questions from the prescribed text provided a good foundation, the lack of a worked solutions manual proved to be a challenge. Internally-produced tutorial material will be developed for future offerings of this subject.

Some elements of the taught material were better received by students than others. For example the theoretical aspects of FDM were clearly understood, presumably because of the plethora of familiar consumer-grade FDM equipment available on the market today. On the other hand the fundamental concepts of VP such as cure depth, working curve and photospeed proved more difficult for students to understand. Future iterations of this subject will attempt to address these shortcomings.

The site visits were a welcome adjunct to the taught and practical components of the subject. Although requiring a significant amount of logistical organisation the benefits far outweighed this effort. Being able to see a fully accredited AM materials research facility, and a commercial medical device production facility utilising AM was a valuable experience for the students. It also proved to be a valuable networking opportunity for the University of Wollongong and its future graduates, and potential collaborations between the organisations were discussed.

One interesting digression from the course during 2014 was the expiry of key AM patents (e.g., Crump’s US patent 5502785 on support removal processes, Hull’s US Patent 5637169 on 3D building with sheets, Deckard’s US Patent 5639070 on selective sintering, Almquist et al’s US Patent 5651934 on SL recoating and Menhennett et al’s US Patent on 3D manufacturing using droplets). In 2015 other key patents such as Hull’s US Patent 5762856 on SL expired, further demonstrating the fluidity of the current AM market and contrasting with other mainstream manufacturing processes which have existed unchanged for many decades. In this way students were able, uniquely, to view the birth and development of a new manufacturing industry in real time.

The subject also proved to be an ideal introductory pathway to the iAccelerate business incubator program (University of Wollongong, 2015), with a number of groups showing a strong interest in enrolling in this entrepreneurial training scheme. This type of program is expected to assist in bridging the so-called academia-to-industry gap highlighted by Wallis (2014) in her recent discourse. Many students also actively participated in a local 3D printing interest group (Wollongong 3D Printing Meetup Group, 2015) as a direct result of their involvement with the Introduction to AM subject. This was an unexpected outcome with the potential to benefit the wider community.

On a more philosophical note the teaching of AM fundamentals to a new generation of engineering students facilitated their active participation in the ‘new paradigm in engineering education’ of ‘creativity-led, innovative thinking with design acumen’ so aptly described by Littlefair (2013). Further illustrating this point, a number of our graduates have now moved on to full-time employment in the AM sector.

Conclusion

The new paradigms of AM and DFAM are expected to become key components of any future industrial culture. Falling directly into the engineering fields of study these paradigms must now be taught at the higher education level. An introductory subject such as that described in this paper has provided valuable insight into the advantages and disadvantages of teaching such teaching. It is hoped that by others will benefit by the lessons learnt from developing and delivering this subject.

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