Application of Additive Manufacturing in Design & Manufacturing Engineering Education

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Abstract — This paper details how education and training in both digital manufacturing and materials processing was implemented as part of an undergraduate engineering programme involving 90 students. The programme was provided through additive manufacturing (3D printing), which enabled the students to develop an understanding of part design, fabrication and performance. The 3D printing study was carried out using Fused Deposition Modelling (FDM) and involved the fabrication of a turbocharger turbine part. This was subsequently evaluated using a customized test rig to assess the printed turbine rotation speed, under a fixed air-flow. The dimensions and morphology of the fabricated parts were also evaluated. Students benchmarked the performance of their turbine parts, against the part which was found to exhibit the highest rotation speed. A pre- and post-course survey was conducted to track the learning experience and feedback from the students involved. The results demonstrated that incorporation of digital manufacturing, self-guided and peer learning improved the engagement and learning experience.

Keywords—digital manufacturing, engineering education, design innovation, additive manufacturing

I. INTRODUCTION

This paper details the development of a practical course work for undergraduate engineering students to help them develop skills in design, additive manufacturing (3D printing), part performance, evaluation and materials examination. There is a constant need for engineers to be creative and develop the ability to solve technical problems quickly and effectively through in-depth knowledge of a range of technologies and capabilities[1]. There is also the need for practical work within education to incorporate approaches for the multiple learning styles present among the student groups[2].

Of growing importance for industrial product development is digital manufacturing, which allows for the automated manufacturing of a digital design [3]. It is a more cyclic process than traditional manufacturing, whereby a design is developed, tested, simulated and evolved virtually using computer-aided design (CAD) software [4]. Moreover Generative Design (GD) avails of the ability of additive manufacturing (AM) to create extremely complex geometries over that of traditional manufacturing [5] and Artificial Intelligence (AI) to redesign components within set boundary conditions [6].

When designing an education programme consideration of an individual's learning style is critical. A learning style is defined by Coffield as an individual's unique approach to learning based on strengths, weaknesses, and preferences[7]. Gardener reported that learning styles are logical-mathematical, linguistic, musical, spatial, bodily-kinaesthetic, interpersonal, and intrapersonal [8]. By identifying the learning style of the individual and presenting or teaching educational content in that style, the individual's knowledge, absorption, retention, and self-confidence can improve over the use of teaching practices that present content in one style for the whole class. As shown by Kapur, the theory of "productive failure" has been proven as an effective method for increasing the learning experience [9]. An example of an approach that has been successfully applied to the teaching of MATLAB/Simulink to undergraduate engineering students is the inverted-classroom approach [10]. This involves a number of learning methods, including self-guided learning with the use of videos and quizzes.

Within large class groups it is not easy to apply learning styles that suit each individual or create healthy competition. The aim of this study is in addition to the students developing an understanding of part design, fabrication and performance, is that it facilitates a learning experience that appeals to multiple styles. The education and training in both digital manufacturing and materials processing was implemented as part of a module on Manufacturing Technology. This module includes a broad range of topic areas including materials processing, sustainability, manufacturing systems and Industry 4.0 [11]. The lecture programme is complimented by practical work of which one element is additive manufacturing. This enables the students to gain experience in part design, printing, performance evaluation and materials characterisation.

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For this study a turbocharger turbine blade was selected as the component of interest, due to its ease of manufacture as a polymer demonstrator, as well as the existing adoption of AM by the aerospace industry for metal turbine part fabrication [12]. Turbines were also selected as part of the module course work as individual technology demonstrators i.e. within production process, machining, lean manufacturing etc.

The research questions which were evaluated as part of the practical programme were:

1. Can the use of digital manufacturing in engineering education increase student engagement?
2. Can the use of self-guided learning via digital manufacturing increase insights and understanding of the design and manufacturing process?
3. Can the use of self-guided learning increase the enjoyment and desire to learn?

Survey data is used to monitor the learning experience of the students and show the advantage of the developed method for teaching digital manufacturing.

II. METHODOLOGY

This study involved an undergraduate engineering student class of 90 students. Introductory lectures on topics such as digital manufacturing, additive and subtractive manufacturing, and the design and printing processes were given. Background information along with examples of publications in the technical literature on turbine design were also provided to the students. For this exercise the 90 students were divided into groups of 3, which were given periods between 4 and 7 weeks to design and test turbocharger blades. The students were provided with detailed notes on how to download and operate the Autodesk and Cura software required for AM part fabrication [13], [14]. Based on requests from the students for additional support in part design, a tutorial video was also prepared and made available to the students for download. Critically, they were given minimal tutorials or notes on how to approach the design itself. They were thus required to use their own research and design knowledge.

As the practical element of the course was carried out over a 4-week period, there was considerable potential for competition between the groups as well as for peer learning. This helped to facilitate multiple learning styles and environments. From a manufacturing viewpoint there is the initial challenge of understanding why and where to use certain processes.

The turbine blade design brings in a number of elements for 3D printing performance consideration, such as surface finish, balance, precision and weight. No prescribed methodologies or solutions were provided to the students on the turbine design as a result the anticipated performance is thus unknown. This element allows room for the students to engage and explore the topic themselves. Allowing the students to use 3D printing for prototyping gives direct insights into the manufacturing processes whilst allowing students to understand the limitless possibilities of the technique.

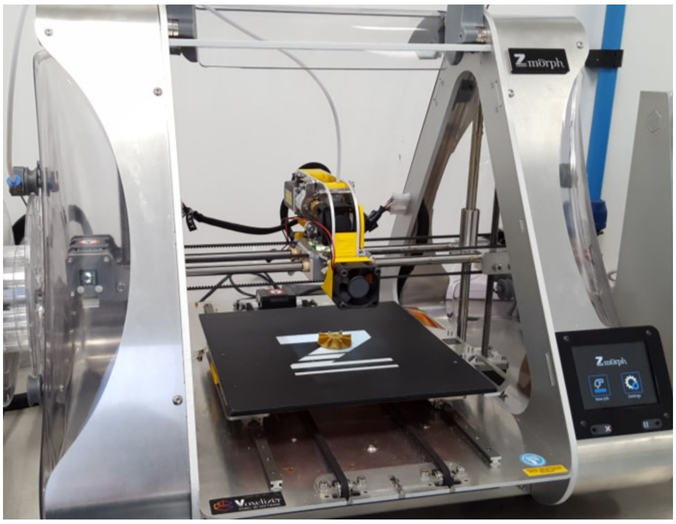

Fig. 1. Zmorph CNC equipment used for 3D printing of the turbine blades.

The activity was designed to be carried out using a relatively low cost printing system with minimal setup costs. A *Zmorph* Fused Deposition Modelling (FDM) 3D printer, shown in fig 1, was one of two used in this study. The polymer filament used was Polylactic Acid (PLA). The part design was facilitated using *Ulitmaker's Cura* open-source slicing software as well as Autodesk's suite of design, manufacturing, and simulation software and educational tutorials and content [14]. *Autodesk Inventory Professional* was used as the main design platform [15]. This software is free for educational proposes and a good platform for students to learn about digital manufacturing on due to the interconnected nature of the software suite. A number of tutorials and other information is also available online for free at the Autodesk Design Academy to assist the students in relation to their self-learning [16]. Within the turbine design there are four major components for consideration by the students as seen in fig 2. These are:

- Turbine Housing
- Mounting Unit
- Turbine
- Turbine shaft

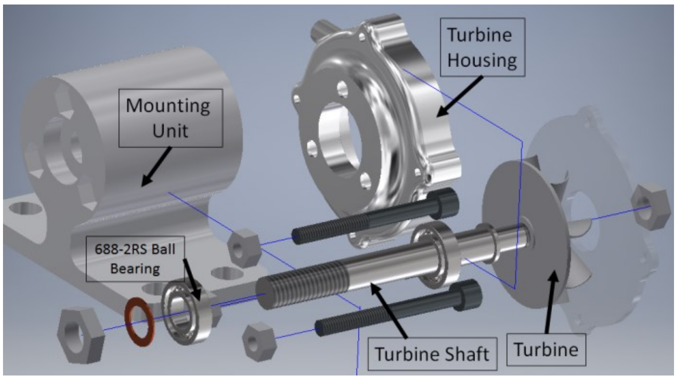

Fig. 2. Exploded view of turbine rig assebly showing major componets.

Within this simple design there are lessons and challenges to be considered in relation to manufacturing, turbine performance, fluid dynamics, assembly, turbulence and operational vibration. The base rig design makes it easy to change the turbine and print it with a high level of flatness for the base of the turbine. This is not typically the construction of a turbo charger turbine, due to the requirements for the design of the housing determined by optimisation of the airflow partners. There is also potential to give the added challenge of developing a compressor to attach to the output shaft of the turbine to create a true turbo charger with multiple simulation scenarios available throughout the design including CFD, FEA, and thermal analysis. This allows the facilitator of the course to choose which topics to focus on and how to challenge the students. The turbine shaft was manufactured using a number of different materials and processes for the students to examine and hence understand the precision required, which is most appropriately achieved through turning.

TABLE I. TURBINE FIXED PARAMETERS

Turbine Feature	**Fixed Parameters**
	Measurement
Turbine Base Thickness	1 mm
Turbine Dia	Ø35.5 mm
Turbine Height	7 mm
Inner Ring Dia	Ø14 mm d
Turbine Base Mounting Hole Dia	Ø6.90 mm
Turbine Top Mount Hole Dia	Ø4.40 mm

In this case the students were required to consider the following parameters in their designs: Inclusion of an inner support ring, Blade radius, Blade angle, Blade thickness, and the Number of blades. A number of base dimensions were given to allow for compatibility with the testing rig itself as seen in table I. The students had to complete the turbine printing within a 40 minute period. The turbine performance as well as characterization had to be all completed within the 1.5 hour prototyping lab. Two example turbine blade prints are seen in in fig 3, showing some of the design variations seen between the student designs.

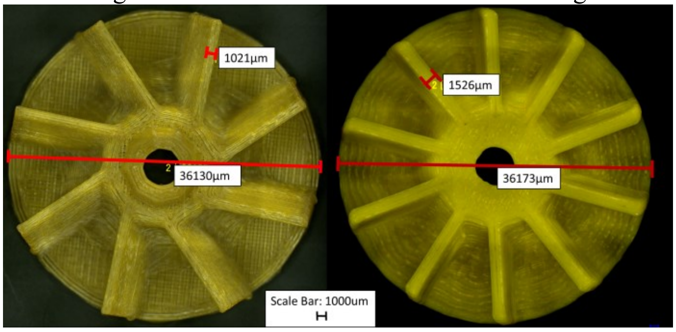

Fig. 3. Example turbines: (Left) Printed turbine blade with 8 blades, steep blade inclination and 1021µm blade thickness, (Right) Printed turbine blade with 10 blades, less blade inclination than left turbine and 1561µm blade thickness (scale bar 1000 µm).

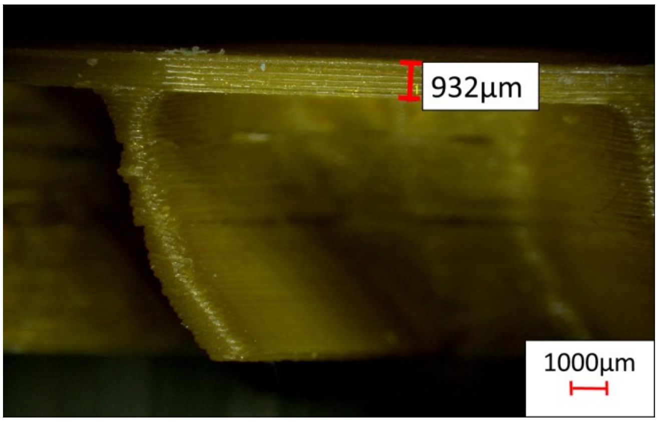

Fig. 4. Sideview blade inspection showing the measurement proceedure and layering morophology inspection (Scale bar: 1000 µm).

Each student group had to determine what printing settings to use for the prototyping. Once the prototype was printed they could examine the finish, quality, any failures that may have occurred and test the turbine on the rig. A low pressure airline with a constant air pressure of 0.5 mPa, was used to test the prototypes, inputted directly into the house supply point. The maximum turbine speed was recorded by a tachometer (Standard AT6 tachometer 2 – 99999 RPM) as part of the functional evaluation of the prototype turbine blades.

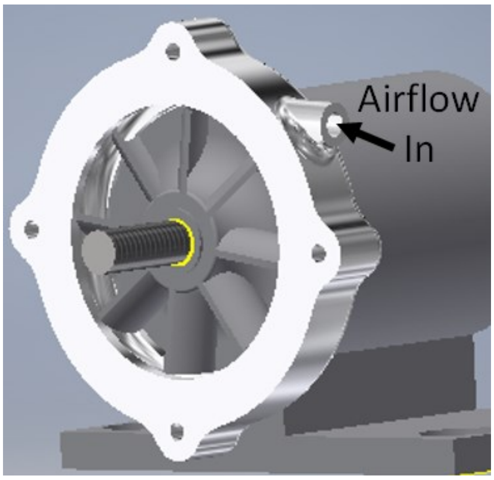

Fig. 5. Schematic of the testing rig used to evaluate the turbine assembly.

The turbine testing rig assembly is shown schematically in fig 5. It is important to note that all major components of the rig were AM printed thus helping to facilitate the low cost approach. The turbine shaft was the only component requiring machining with two 688-2RS ball bearings used for mounting the shaft in the mounting unit. In addition to evaluating the turbine speed, the dimensions of the turbine were evaluated using both calipers and a Keyence microscope inspection examples shown in fig 3 and fig 4. The latter technique was also used to evaluate layer morphology. After the turbines of all the student groups had been tested a feedback sessions was provided. This included details on the overall turbine performance as well as dimensional, morphology and design information on the winning turbine design. An invited lecturer from industry also provided an in-depth overview of factors influencing turbine performance. A key requirement of the report written individually by each student was to describe the reasoning for the design that they had proposed, along with suggested design improvements that they would now incorporate based on the feedback.

A student survey was carried out to provide information on the prior knowledge of the students in 3D modeling and additive manufacturing, and get their evaluation of the interest and relevance of the course for their learning experience, value in relation to design, additive manufacturing, and overall satisfaction with digital prototyping. A further objective was to help provide information on how the experience aided the student's understanding of the design process. Useful data and insights were also expected from the student comment section. This survey is based on the work of Meyers who looked at the introduction of design through 3D printing [17]. The survey questions are detailed in the results section.

III. Results and Discussion

As demonstrated in table II, all the engineering students in this study had some prior knowledge of 3D design. Indeed 22% have substantial experience. Contrastingly for 3D printing the majority have limited experience with a good balance between no experience and some experience, around 20% each.

TABLE II. PRE COURSE SURVEY QUESTIONS TO UNDERSTAND PRIOR KNOWLEDGE IN THE AREAS OF DESIGN AND ADDITIVE MANUFACTURING

Prior to Course	**Prior levels of knowledge before completing the activity**				
	No Prior Knowledge	***Knowledge of experience, but no experience***	***limited observation (1 experience)***	***Some prior experience/ exposure***	***Substantial prior experience /exposure***
Q1	0.00%	1.47%	11.76%	64.71 %	22.06%
Q2	8.82%	22.06%	44.12%	19.12 %	5.88%

Q1: Had you ever been exposed to any form of solid modelling software?
Q2: Had you ever been exposed to 3D printing?

Table III shows the results of the feedback in relation to the learning experience, engineering design, increased interest and satisfaction with prototyping. In all cases it is seen that the results are very positive with an average score of 4.16 out of 5.00, across all fields. The highest scores and lowest variance are seen from the learning experience feedback.

TABLE III. POST COURSE SURVEY QUESTION RESULTS TO GAUGE THE RESPONSE AND LEARNING EXPERIENCE OF THE STUDENTS

Result	**Survey questions on a Likert scale out of 5 (higher value is a more positive response)**				
	Interesting learning experience	***Relevant learning experience***	***Valuable engineering design experience***	***Increased interest in 3D printing technologies***	***Satisfac-tion with printed part***
Av.	4.3	4.4	4.1	4.2	3.8
Median	4.25	5	4	4.75	4
St. Dev	0.7	0.7	0.9	0.9	0.9
Var.	0.55	0.49	0.73	0.89	0.8

There is slightly higher variance in relation to the valuable design experience and increased interested in 3D printing. Based on the survey the majority of the group was in the limited observations group, meaning that their interest in 3D printing may have either been high or low due to personal preference. Similarly, for the design experience this is dependent on the student's own preferences, with the vast majority having had experience of solid modelling software. Considering this for future iterations it may be effective to have different levels of challenge available within the course for the students. For example, for students who had no prior knowledge, which in this case is zero, then a parametric design may be appropriate, whereby a list of variables can be used to determine the turbines design and the student see these changes in real time in the CAD package. This parametric design approach seen in fig 5 is easily applied within Autodesk Inventor. This base parametric turbine design model was prepared as part of the course development for the case that a group had no CAD experience. For more advanced CAD users the design process could require more involved simulation and design considerations expanding beyond the turbine, for example with the incorporation of Computational Fluid Dynamics (CFD).

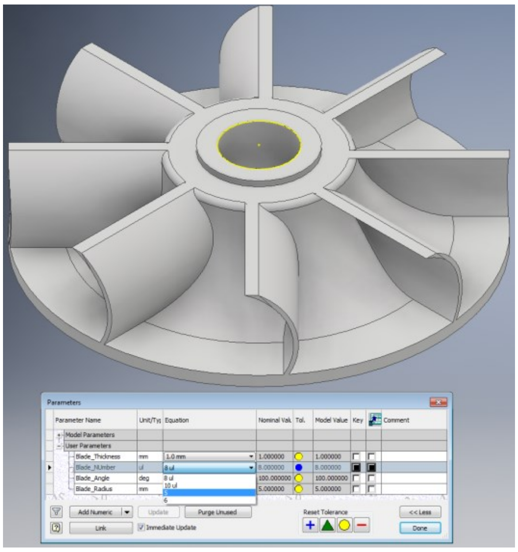

Fig. 6. Parametric design which can be applied for no design experience.

As demonstrated in table IV very positive student feedback was provided based on the insights gained and experience that they obtained. High scores are seen for design experience and interest in 3D printing, again showing the power of digital manufacturing in this context and the combined learning styles approach. The lowest score is seen from the satisfaction with prototyping. This can be accounted for by some technical issues with the printer whereby the printer didn't function correctly for one group. Looking at the median in this case shows the results are still in line with the other aspects. Comparing these results to Meyers [17] it is seen that although the groups within this case study had a higher level of prior knowledge over Meyers, similar results for table III were achieved. This shows the universal influence of digital manufacturing and AM in both studies. Results from table IV were lower than Meyers. This is perhaps due to the higher level of exposure to 3D printing in Meyers' study. For future iterations of the course it could be considered to have one prototyping stage and one final printing and testing stage to increase this aspect. In this way the students would be able to really experience the benefits of 3D printing and digital manufacturing by initially being provided with an evaluation of their prototype to be used for redesign of the final part.

TABLE IV. POST COURSE SURVEY QUESTION RESULTS TO GAUGE THE RESPONSE AND LEARNING EXPERIENCE OF THE STUDENTS

Result	Survey questions on a Likert scale out of 5 (higher value is a more positive response)	
	Indicate to what extend you agree: by taking this course I gained significant experience in the design process	*Indicate the extent to which this course assisted in the understanding of the steps in component manufacturing*
Av.	4.0	3.9
St. Dev	0.8	0.9
Median	4	4
Var.	0.66	0.72

Another interesting aspect observed during this study was the trend of the turbine speed results recorded over the test period. As seen from fig 7 there is a steady increase of the recorded speed obtained by the groups over the 4 weeks of the practical. The reason proposed for this trend is peer learning, whereby the student groups were discussing aspects of turbine design with each other in the common areas, and hence engaged in peer learning. This is evident from the speed results and reported by the facilitators in the complexity of designs presented. Moreover, the element of competition can be hypothesised from this, whereby as knowledge was gained about the possibilities and speeds recorded, other groups were motivated to supersede their peers.

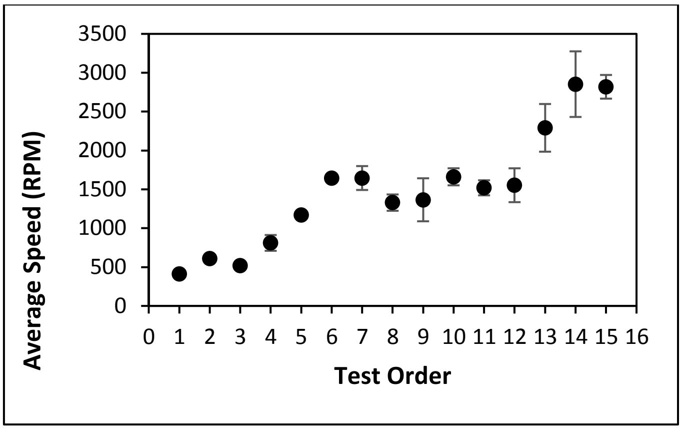

Fig. 7. Speed generated by the turbines according to the turbine test order demonstrating that peer learning was evident within the course.

The student feedback also highlighted the engagement the students had with the activity and their increased learning experience. Some examples of the direct student feedback received are as follows:

- "*This was a good practical lab where we were involved in the manufacturing process. I think this in the best way to learn a technique like 3D printing"*
- *"Best lab to date, very interesting*"
- "*Very interesting to see part being made in real time."*

These comments clearly show the level of engagement and desire to participate in this course.

From these comments it is clear that the students were engaged and motivated by this work, having been challenged, led their own learning and seen tangible results from their efforts. The freedom given to the students in relation to the design allowed them to be creative and truly experience the design process in a simulated real world situation, where the solution is unknown and some level of failure is productive and part of the process.

IV. CONCLUSIONS

The focus of this study was to develop an engineering undergraduate education and training programme in both digital manufacturing and materials processing, through the use of AM. A major objective was to engage the engineering students in the learning experience. This was achieved through applying different learning styles and approaches including lectures, video tutorials, self-motivated and self-led learning, research and design, whilst being able to work within a team and individually. These are all key elements of engineering education but moreover key skills required within industry.

It is clear from the recorded and presented results and feedback that the developed course has been hugely successful in achieving its goals. The results show that although the group was somewhat familiar with 3D modelling and design they all gained valuable design experience and valued the learning experience. Moreover, the physical product obtained by AM enabled the students to obtain direct feedback of their designs' performance and manufacturability. In some case numerous attempts had to be made to print the turbine however the students themselves learned from the experience and failures to create successful components.

As previously stated the engagement of the students with the design innovation could have been increased if there had been more than one prototyping session. Allowance for prototyping and then subsequent final production would be greatly beneficial for the next iteration of the course. The course has great potential as a platform learning experience to educate engineers in a number of critical areas of digital manufacturing, covering innovation, engineering design, manufacturing, simulation, and prototyping whilst being low cost and easily replicated. The results clearly show the success of the approach and the engagement of the students with the course but moreover with AM, digital manufacturing and the design process. The research questions posed at the start of this work have been answered with positive results, confirming the benefits of both digital manufacturing and AM in engineering education.

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