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# 3D printing a jet engine: An undergraduate project to exploit additive manufacturing now and in the future

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ABSTRACT

If 3D printing (3DP) is to lead to the revolution in material efficiency, component design and manufacturing suggested by many commentators, the next generation of engineering graduates must be equipped with a sound understanding of the process. Often for students to have significant exposure to 3DP, they must undertake a research project as part of a postgraduate degree. However, undergraduate projects with a more limited scope provide an ideal opportunity to get experience of the technology, its benefits and limitations. Here we describe a project designed to allow students to gain first-hand experience of the technology by giving them the freedom to manufacture a 3DP jet engine. Unfortunately, factors outside of our control meant that the jet engine remains untested. However, it was always envisaged that the major benefit of this teaching project would be the significant understanding gained by the students. While it is hard to objectively judge this, we feel that the project has achieved these aims and hope this will lead to an increased awareness of 3DP in industry and help the next generation of engineers to efficiently design components specifically for 3DP.

## 1. Introduction

3D printing (3DP) was hailed by journalists as a new industrial revolution at least 5 years ago [1]. Listing the numerous benefits of 3D printing has become a staple of many academic papers since then. As the advantages became more apparent, the interest from industry and academia has also increased significantly. However, if the step change in manufacturing predicted by many commentators is to happen, a large pool of young engineers with a sound understanding of the process must be available for recruitment to allow industry to harness 3DP benefits. Unfortunately, current undergraduate degree courses often contain limited exposure to 3DP. Traditionally delivered lecture courses can provide theoretical knowledge, but the detailed practical understanding required by the next generation of manufacturing engineers requires more hands-on experience.

In order to address this gap in the undergraduate training provided by the University of Sheffield, a final year project was developed where students had the opportunity to experience first-hand some of the issues arising when manufacturing with 3DP. A small scale jet engine was chosen to be manufactured for a number of reasons, the obvious relevance to aerospace engineering students being one. Furthermore, the level of complexity was high enough to provide a significant challenge, while not becoming unmanageable. It also provides a relatively easy way to measure the success of the project for the students: did the engine run? Importantly, a jet engine can be regarded an “exciting” application. When testing it, there is an abundance of visual and acoustic signals that it is indeed running and generating useful power!

In this paper, we will describe the method with which this project aims to introduce 3DP technology to the university curriculum, outlining the learning objectives of the project and highlighting the difficulties the course leaders are likely to face during such an endeavour. We hope to show how a successful outcome in terms of student satisfaction and learning can be achieved with a relatively short time scale and limited financial expenditure, even when the project was delayed by factors outside of our control. This project aims to be cumulative in nature, with each year building upon the previous. It is run as a teaching module and thus the measure of success of the project is whether the students are able to use the knowledge of 3DP gained in roles they undertake following graduation. We have therefore highlighted the key learning points for each stage of the project. Of course, these rewards cannot be easily quantified, and certainly not for a number of years. However, we hope to provide a blueprint for other institutes to run similar schemes and ensure 3DP is utilised to its maximum potential in the future. Unless explicitly stated, the undergraduates themselves conducted all the activities described below.

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## 2. Generating the initial design

Designing then manufacturing a working jet engine from scratch would be an arduous task, and unlikely to be achievable during the limited person-hours available during a final year undergraduate project. Instead, it was decided to base the first iteration of the 3D printed engine on an existing hobbyist engine (EHE) available for purchase. Thus, the detailed aero/thermo-dynamic design aspect (beyond the scope of this project) was removed, and if it were possible to recreate exactly the EHE through 3D printing, the engine should run. The ability of an engine produce sustainable thrust depends not only on each individual component but also how they interact with each other. The danger of designing a new engine is that identifying a root cause of failure to run would be nigh on impossible. Finally, the EHE provides a benchmark with which to compare the performance of the printed engine.

In order to extract geometric information about the EHE, first it was necessary for the students to dismantle the entire system into its constituent parts, while recording exactly how components fitted together. Following this, the students decided which of the parts were possible to 3D print; for example, there was little point attempting to print small screws. In addition, it was decided that the main shaft through the engine would be preserved and not printed, alongside various fuel valves and pipes. It was also unfeasible to print a glow plug to ignite the fuel mixture.

The combustion chamber, compressor, diffusor, nozzle and turbine were laser scanned to produce STL files. Unfortunately, the STL files produced contained numerous errors, and significant processing was required before these could be used to generate build files. The inlet and compressor shroud, which are relatively simple geometries, were manually measured and converted to a CAD file. All the components of the engine, including those not to be printed, were assembled within a CAD package to ensure that all the separate components fitted together correctly, see Fig. 1.

### 2.1. Learning outcomes for students

Interpretation of laser scanning data into workable CAD model; STL repair (as engineers who have worked with converting complex CAD files into STLs will know, this a very useful skill!).

## 3. Design for 3DP

With the CAD files in place, it was necessary to consider how to produce components with the necessary material properties. Powder bed fusion was chosen as the 3DP technique with which to manufacture components. An electron beam melting (EBM) system (Arcam A2) and a selective laser melting (SLM) system (Renishaw AM250) were considered by examination of existing artefacts and initial test prints. SLM was chosen for all the components (Fig. 1) as it is able to produce the complex geometries and fine features required, e.g. compressor blade tips, and produces material with a lower surface roughness than EBM [2]. The relative disadvantages of SLM, such as the requirement for a stress relief cycle following 3DP, were accepted by the students as price worth paying for the higher resolution possible.

In addition to the design, consideration was given to the relative cost of AM by the students. It became apparent that in this case 3DP would cost considerably more than conventional techniques, mainly as a result of the relatively high feedstock and machine time cost. However, while the initial intent was to simply replicate an existing engine, it was envisaged that subsequent project teams would make modifications to the original design and also employ new materials for their manufacture. These steps become relatively trivial when using 3DP, as compared to conventional casting approaches. Indeed, this was exemplified to the students when working with an external engine manufacturer who requested a new prototype to be made which required an extra build, approximately two days, in comparison to long lead times (~6 months) required to manufacture and test new moulds.

It was decided that all components would be manufactured with melt strategies released by Renishaw. It was stressed to the students that changing the melt parameters can have a huge influence on the quality of material produced, but due to time constraints, there was not

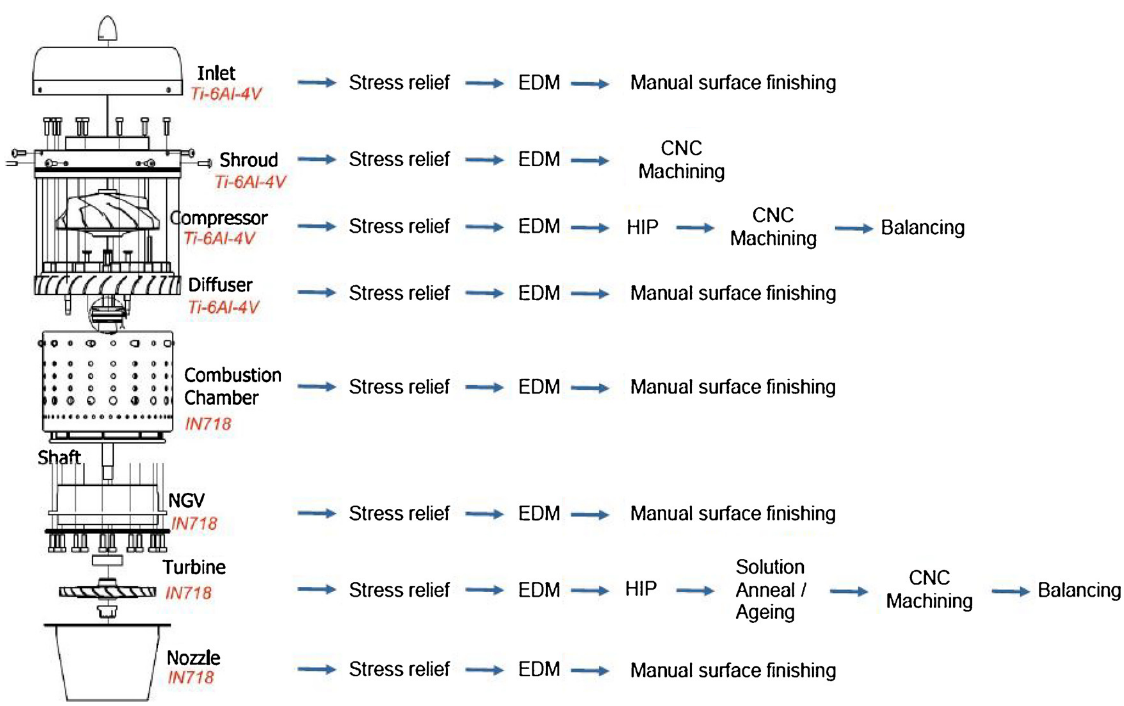


**Fig. 1.** Components to be 3D printed and the post processing steps required. Note that the casing has been removed for clarity and underwent the same post-processing as shown for the inlet.

the opportunity to explore either developing new materials or modifying existing strategies. Thus, a layer thickness, power, exposure time, point distance, hatch spacing and focus offset of 30 μm, 200 W, 50 μs, 75 μm, 65 μm and 0 mm, respectively, were used for Ti-6Al–4 V, and 60 μm, 200 W, 80 μs, 70 μm, 90 μm and 0 mm for IN718.

For components interacting with the airflow prior to the combustion chamber, and the engine casing, Ti-6Al–4 V was utilised, due to its strength and the large amount of literature regarding its use in 3DP. Orienting the parts within the build chamber was the first challenge, alongside providing support structures. It was necessary for the students to test a number of orientations and support structures before a system was identified that provided good quality parts and was able to resist the significant residual stress build up that can lead to part distortion or cracking [3].

Components beyond the combustion chamber were manufactured with IN718 to enable them to withstand the high temperature airflow. A slightly different approach to supporting this different material was required, highlighting one of the subtleties of 3DP to the students.

Critical parts were identified as those that rotated, and the integrity of the material was investigated by cutting, grinding and polishing sections of the compressor/turbine blades. This revealed a level of porosity that appeared independent of blade orientation but could be locally higher when supports were present, which was used to inform support design. In addition, gas pores were observed to occur frequently thin sections, in particular in rows offset from the edge of the sample. Such a pattern of gas pores has been previously observed in EBM material [4], unfortunately, it is also likely to have a significant detrimental effect on the fatigue performance of the material [5]. More detail about the factors affecting the performance of 3DP material is available in the literature [5–7].

Several components, particularly the compressor and turbine, required certain features to be finished to a tolerance exceeding what is currently possible with as-built 3DP components. Hence, computer numerical controlled (CNC) machining was determined to be necessary following manufacture. Students were required to both identify a suitable CNC machining technique and adapt the part designs to meet the requirements of said technique through conversations with external machining companies.

### *3.1. Learning outcomes for students*

3DP, the reality of what is possible; advantages/disadvantages of different 3DP systems; engineering around the limitations; materials selection; importance, and design, of support structures.

## 4. Post-processing

In Fig. 1, the post printing steps required for each component have been identified in the order they were applied. Without stress relief, components had a tendency to crack on removal from the baseplate. The porosity identified in critical components meant the students decided to hot isostatically press (HIP) all these parts prior to running the engine. Sectioning and examination of HIPed parts confirmed that pores had been removed, whereas in contrast the stress relief had little influence on the pore fraction. The bore of the compressor and turbine were spark eroded to produce an interference fit on the shaft. Spark erosion was also used to remove the support structures to ensure a smooth surface and produce a groove for the gasket on the compressor shroud. Finally, the 3DP jet engine was assembled, as shown in Fig. 2.

### *4.1. Learning outcomes for students*

Manufacturing cost estimation; heat treatments required following printing; avoiding issues through careful application of treatments; HIPing; designing for 3DP and machining; mechanical assembly.

**Fig. 2.** Photograph of the 3DP jet engine produced by undergraduate students.

## 5. Testing

A video of the test of the EHE is available online [8]. The EHE produced a thrust which increased with engine speed, while the temperature of the exhaust remained consistent at ~1015 K (Fig. 3a). However, a catastrophic failure of the engine occurred at ~83 kRPM, whereby all the turbine blades detached from the hub and were ejected at high speed from the rear of the engine [9]. Fig. 3b shows the failed turbine hub. Unfortunately, for health and safety reasons, this meant that the testing of the 3D printed component was delayed beyond the submission of this article. However, it is clear that the next iteration of the project will involve a level of failure analysis to ensure that the same outcome can be avoided when testing the 3DP engine.

## 6. Learning outcomes for course leaders

Giving the students specialist roles was found to be far more effective than simply giving the team an objective. For instance, a student with more metallurgical experience was assigned the role of assessing the integrity of the material, while those with more CAD and design were able to specialise in build file preparation. Thus, the role of specialists and their differing responsibilities within project teams was made clear to the students.

It is notable that, while this project started as an internal university project, as it progressed, a number of external industrial partners saw the work being carried out and made the decision to back the project and lend expertise and/or use of facilities. The extra exposure of the students to industry was the first unexpected benefit of the project. If we were to this course afresh our view os that it would be beneficial to

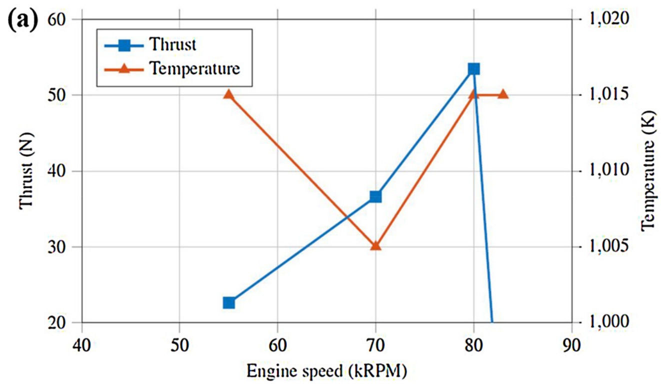



**Fig. 3.** Testing of the EHE (a) temperature and thrust measurements prior to failure, and (b) showing the failed turbine hub.

all to involve the industrial partners early on and have them act as mentors to the team and help with design and manufacture.

In addition, this project involved printing some complex geometries, which required new support structures to be developed. As such, it was not just the students who increased their knowledge of the best way to pre-process, orientate and manufacture intricate structures!

## 7. Summary

A project was designed and tested with the goal of introducing more 3DP experience to undergraduate education. The theme of the project was chosen to be the manufacture and testing of a 3D printed jet engine. Unfortunately, for reasons beyond our control the printed engine remains untested. However, the intention of the project was never to build a highly efficient engine, instead, the aim was to give the next generation of engineers significant experience of 3DP and in particular the opportunities and barriers this exciting new technology presents when being considered for a safety critical application. The project in this respect was highly successful, with substantial knowledge imparted. In addition, the enthusiasm from students was clear, with many returning back to do more practical work after they had submitted their final thesis. It is therefore very hopeful that these individuals will be able to take up emerging opportunities in industry to push 3D printing technology to new heights.

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