

Metal Additive Manufacturing MSc – A pioneering global master’s course for leaders of future manufacturing

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Abstract: This chapter covers the design of world's first MSc in Metal Additive Manufacturing (AM) with industry- and academia-driven considerations and objectives, as addressed in the European-Commission-funded project that saw the course developed over a period of three years. Then, the chapter covers the delivery and evolution of the course at Cranfield University, with its unique strengths and far-reaching activities in the field of large-scale metal AM. Finally, the chapter also covers case studies and innovative pedagogical tools introduced since 2019, providing a useful reference to broader stakeholders.

Keywords: Additive Manufacturing, Postgraduate Education, MSc Course, Certified Training, Skilled Workforce, wire plus arc, masters by research

1 Introduction

Additive Manufacturing (AM) is a rapidly growing field with widespread applications in multiple industries around the world and even in space [1]. The last two decades show an increase in demand of large scale additively built components mainly due to the drive to reduce weight and carbon footprint, the goal of manufacturing sustainability, the need of logistical simplicity, and the high potential for improvement of functionality and performance. AM can also lead to a more sustainable manufacturing environment. Ford and Despeisse [2] identified four major categories where AM is affecting the sustainability positively: material input processing, make-to-order component, product and process redesign and, closing the loop. As a result of all these advantages, the global 3D printing market was valued at \$22.39 billion in 2023 with a projected growth from \$27.52 billion in 2024 to \$150.2 billion in 2032 [3](*3D Printing Market Size, Growth, Share & Industry Analysis, 2024*) (*3D Printing Market Size, Growth, Share & Industry Analysis, 2024*).

Commercialisation of AM process dates back to the early 1980s. A brief history of evolution of this technology can be found in Singh & Singh [4]. Metal AM first commercialised in 1990s with the introduction of laser metal sintering machine by EOS. Metal has a much higher melting point when compared to polymeric structures. The crystal structure and chemical properties of a metallic material make it more complex when compared to polymeric or non-metallic material AM. With laser as a heat source, metal powder was found to be the most suitable form of feedstock even with the additional health and safety hazard precautions necessary for storage, handling, feeding and recovery associated with a powder feedstock. Later, with evolution of laser as power source, and more understanding of powder metallurgy, metal AM grew very fast with laser metal sintering / melting and directed energy deposition (DED) in the form of blown powder. For more recent DED processes, weld wire is directly fed in an electric arc or an electron beam to enable faster deposition and higher

efficiency of material utilisation. There were also processes such as metal binder jetting and sheet laminations which came into prominence for metal AM.

The design and manufacture of a part by AM involves a complex relationship between the process, microstructure and the resultant properties [5]; understanding and exploiting these to our advantage would play a critical role in a more widespread adoption of Metal AM. However, Thomas-Seale et al. [6] noted that graduates only gained a general overview of AM and lacked the hands-on experience or an in-depth understanding of the technology. Therefore, such “gap” between what is expected from the industry and what is actually delivered by academic institutions needs to be minimised to support and accelerate the growth of the field.

The ADMIRE project [7] was a joint effort between various industrial and academic partners to reduce this skills gap. It resulted in creation of the MSc in Metal AM at Cranfield University, whose current offering is deeply rooted in addressing and providing relevantly skilled workforce for this growing industry – whether they are established manufacturers or start-ups looking to make their mark.

The present chapter will describe the mechanism of creation of the course from its birth with the ADMIRE grant through to the present day offering. Before discussing the course itself, the Welding and Additive Manufacturing Centre (WAMC) based at Cranfield University will be introduced along with some of its facilities to carry out (and disseminate) world-class research in metal AM. This is key as the [WAMC](#) features unique hardware and process capabilities that were instrumental to the planning and delivery of the course. Then the Intended Learning Outcomes (ILOs) of the course will be given; these are used to inform the course content and set student expectations. We will then talk about the course development including the course’s birth and initial (pilot) runs. This section will also include some of the theoretical (and pedagogical) underpinnings for the course content, challenges and quality control to ensure the course’s standards and teaching doesn’t suffer. Once an understanding of the course formation and theory is achieved, we believe it would enable the reader to appreciate the present day offering even better. Therefore, the chapter will subsequently present the different components of the current course; this includes the different modules (taught component) and projects (research component) that a student is expected to undertake during their period of study. This will then be followed with a section on how the course aligns with the requirements of the AM industry including some proactive measures by the course team and a couple of case studies. Finally, the future of the course will be mapped such as the changes made due to student feedback and the wider industrial and/or research community requirements.

2 Welding and Additive Manufacturing Centre

The Welding and Additive Manufacturing Centre (WAMC), erstwhile known as the Welding Engineering Research Centre (WERC), was established in 1961 to deliver a course on Welding Engineering. This flagship course is still in existence after 60 years. Reflecting on the requirement of an industrial scale manufacturing facility, the Centre have been relocated within the Cranfield University campus in 2003 to establish over an area of more than 700 m², with two large overhead cranes of 20T capacity. This shows the tremendous commitment of Cranfield University towards developing and maintaining the Centre. In 2004, through an Engineering and Physical Sciences Research Council (EPSRC) grant, the Centre acquired an 8 kW continuous wave laser for welding of thicker sections. The Centre was renamed Welding Engineering and Laser Processing Centre (WELPC) in 2010 and renamed

to Welding and Additive Manufacturing Centre (WAMC) in 2023, to better highlight the research and educational activities at the time.

The centre has been engaged in active research of Wire Arc Additive Manufacturing (WAAM) as early as 1995 where a gas metal arc welding process was used to manufacture parts for industrial sponsors (information from communication with Prof John Norrish, previous Head of Centre of WAMC between 1975 and 1995). Some components of parts built at WAMC are shown in Figure 6.1.1 Figure 6.1.



Figure 6.1.1 Nickel alloy components for flight applications [Image taken from a presentation by Prof John Norrish]

The Centre is also equipped with the most advanced fusion welding power sources, a range of laser welding and metal processing systems such as peening, sculpting etc., robots and component manipulation systems, instrumentation facilities and a host of accessorial facilities for in-process and post manufacture processing and heat treatments.

The Centre has an annual turnover of more than £2.5m of which about £2m of research income from industrial and fundamental research activities from technology readiness level of 1 (proof of concept) to about 5 where the manufacture and performance of a component is validated in laboratory and relevant environment.

As a complex manufacturing process, metal AM has several aspects, such as component modelling, design of building principles, process performance and suitability, modelling of processing parameters and their impact on component, metallurgical quality, property and performance validation and others. The technology is still evolving and a lot of potential is yet to be realised. Therefore, quality training and production of future generation manufacturing leaders in this area are vital for future sustenance of this technology. Right level of training and implementation to achieve full potential will impact the UN security council goals 4, 9, 12 and 13 on quality education, industry-innovation and infrastructure, responsible consumption and production, and climate actions, respectively [8].

3 Course Development

3.1 Course Formation

As briefly discussed in the introduction, the present MSc was developed through the ADMIRE project [7], funded by the European Commission and delivered through a pan-European consortium comprised of Cranfield University, the University of Birmingham, GKN, the Manufacturing Technology Centre (UK), University of Bremen (Germany), Instituto Superior Tecnico (Portugal), the European Welding Federation (Belgium), and IREPA Lasers (France). The main goal was to create the MSc in Metal AM.

ADMIRE set out to respond to the urgent industrial need for the qualification of AM workforce. Universities, companies and students (the “triangle”) were to design a Metal AM Executive Joint Master degree with a set of innovative features: a multidisciplinary scientific scope; a modular structure promoting hard and soft skills, based on Learning Outcomes described in Knowledge, Skills and Competences; with learner-centred, self-direct and work-based learning approaches, enabling flexible learning paths, including a problem-based one, whilst holding an international teaching staff trained in entrepreneurship, coming from industry and academia.

Note that the level of the MSc was equivalent to the European Qualifications Framework (EQF) level 7 [9]. The EQF was introduced at European level to harmonise higher education across the many countries of the EU.

3.1.1 Needs analysis

The ADMIRE consortium carried out extensive survey campaigns involving possible students and industrial parties, as future employees and future employers, respectively. The objective was to confirm that a cohort of people interested in the course existed, and to align the skills students would learn to those required in an engineer working within the AM industry. Finally, the survey was intended to highlight particular areas of the course syllabus, and structure that would then be considered important for the success of the course.

3.1.1.1 Student Questionnaires

A survey was conducted among students from various countries, including Austria, Denmark, France, Germany, Greece, Italy, Portugal, Turkey, the United Kingdom, and others. The results revealed that most participants had limited work experience, though 49% reported having used an AM machine. While 70% rated their materials science knowledge as good, very good, or excellent, only half considered their CAD/Design skills to be of the same calibre. These findings provided insight into the prospective students' baseline knowledge.

The majority of respondents expressed interest in the course to specialize in metal AM, explore new processes in the field, enter the growing AM technology market, or pursue a career in the sector. Hands-on experience with AM machines and significant interaction with industry were deemed important or very important by most. Preferences for module structure were also recorded, with over 80% favouring a mix of general compulsory modules and optional specialized modules in areas like industrial sectors, materials, or AM processes. Fewer than 20% preferred curricula focused solely on specialized modules. The most popular specializations were industrial sectors (over 37%), followed by AM processes (22%) and materials (17%), while only 5.1% were interested in quality and inspection. In industrial topics, design, structural integrity, and metallurgical analysis and characterization ranked as the top priorities.

There was a strong preference for individual dissertation-style projects, whether as industrial assignments or theses. Students also sought a variety of assessment methods, with an individual project forming a key component of evaluation. Additionally, respondents highlighted the need for diverse learning materials, such as tutorials, videos, handbooks, and a materials database. For support services, industrial links were the highest priority, with over 78% valuing industrial experience and about 70% emphasizing access to suitable learning facilities. Both academic mentorship (over 60%) and industrial supervision (59%) were also highly rated.

Most students preferred a full-time course, but a notable minority favoured intensive blocks or part-time study. Preferences varied based on individual circumstances, with recent graduates leaning towards full-time study and working professionals opting for more flexible formats that accommodate their employment commitments.

In terms of funding, the majority of respondents indicated they would cover the costs themselves, while smaller groups anticipated support from EU, national, or company sponsorships.

3.1.1.2 Industry Questionnaires

Two industry-specific surveys gathered feedback from experts and professionals in the field, with 126 responses collected from the first survey and 88 from the second. Insights from the industrial managers' questionnaire highlighted the key areas of knowledge and expertise that a metal AM engineer should possess (Table 6.1.1Table 6.1).

Table 6.1.1 Responses for the training topics required for a qualification in metal AM

Topics	Percentage
1. AM Processes	90%
2. Metallurgical Analysis and Characteristics	87%
3. Structural Integrity	85%
4. Numerical Modelling	82%
5. Standards	80%
6. Costs	80%
7. HS&E	77%
8. Post-Processing	76%
9. Topology Optimisation	73%
10. Non-Destructive Testing	73%
11. Pre-Processing and Material Handling	72%
12. Design	71%
13. Certification and Validation	68%
14. Testing/ QC	60%

Managers emphasized the need for advanced knowledge in AM processes, post-processing, pre-processing, and material handling. Other topics were considered to require intermediate levels of expertise.

The survey further explored the balance between theoretical knowledge and practical skills for each topic. About half of the topics were expected to involve an even split, with 50% focused on theoretical understanding and 50% on hands-on skill development. However, certain topics were deemed to require exclusively theoretical knowledge, particularly those involving desk-based or regulatory tasks. These included health, safety, and environmental considerations (HS&E), standards, certification, validation, and cost management.

3.1.2 Focus Groups

Focus groups involving universities, prospective students, and industry representatives were held in the UK, Germany, and France to validate the survey findings. While the main results were largely supported, discussions highlighted that an increasing number of engineering students in the UK are already pursuing master's degrees, making them less likely to enrol in another. This emphasized the need for the Metal AM MSc to offer sufficient appeal and clear differentiation from traditional Materials Science MEng/MSc programs.

Regarding course content, industrial stakeholders suggested the program should provide basic coverage of all AM processes, with practical experience delivered through group projects or a thesis that allows students to specialize in a specific area. They also stressed the importance of including topics such as modelling, simulation, quality control, and design processes. Unlike the student respondents, industry representatives felt that direct use of an AM machine was not essential, as engineers in industry are unlikely to operate the equipment themselves. However, they agreed that students should develop a solid understanding of how AM machines work, common challenges, and how to integrate them effectively into industrial workflows.

3.1.3 Market Status

In 2018, very few formal training courses existed to specifically address metal AM at a master's degree level (Table 6.2Table 6.2.2). These were designed to cover the whole AM domain and include information of AM of both polymers and metals.

Table 6.2.2 Existing programmes at Postgraduate level when the course was created (2018)

Course	Institution	Entry Requirements
MSc in Additive Manufacturing	Anglia Ruskin University (UK)	Bachelor's degree: Engineering/Maths/Science/Product Design/Related.
MSc in Additive manufacturing and 3D Printing	University of Nottingham (UK)	Bachelor's degree: Engineering /Science
MRes in Additive Manufacturing and Advanced Manufacturing Technologies	University of Sheffield (UK)	Bachelor's degree or Relevant professional experience
MSc in Advanced Materials and Additive Manufacturing	University of Derby (UK)	Bachelor's degree: Chemistry/Biology/Geology/Engineering/Subject related
2nd level Specializing Master in Additive Manufacturing	Polytechnic University of Turin (IT)	Master's degree: Engineering/Nanotechnologies for information and communications technology
MSc in Additive Manufacturing	Penn State University (USA)	Bachelor's degree, or four-year Associate's degree from an accredited institution in engineering, engineering technology, manufacturing, materials science, or related field.

Therefore, for the MSc to succeed, it was paramount to differentiate it sufficiently from these pre-existing courses, in terms of content, structure, delivery, and student support strategies.

3.2 The Intended Learning Outcomes

Based on the findings of the needs analysis, the Intended Learning Outcomes (ILOs) were designed:

- ILO 1: evaluate the applicability of Metal AM to real use cases
- ILO 2: assess the impact of metal AM and other net-shape processes to a component's material, microstructure and mechanical properties
- ILO 3: design parts for AM and analyse loads to predict structural performance
- ILO 4: evaluate the impact of metal AM on cost, operations and supply chain against conventional processes
- ILO 5: evaluate the requirements of health and safety legislation in relation to AM, and demonstrate knowledge of the National, European and International standards relating to quality assurance in AM
- ILO 6: evaluate the quality of data and determine its relevance in research and industrial context
- ILO 7: communicate effectively results of developments, proposals and analyses to specialist and non-specialist audiences, both orally and in-writing
- ILO 8: plan, organise, undertake, and analyse research and industrial projects to increase knowledge and understanding of AM, and to evaluate the application of AM technology in industry also from a cost perspective
- ILO 9: propose new developments to solve AM technology problems, individually or as part of a team
- ILO 10: plan and manage research projects at the cutting edge of technology, show self-direction in the performance and analysis of research, and show on-going interest in advancing knowledge and skills.

Error! Reference source not found. Note that these were also validated by the “AM MSc Council” which was an industrial steering board providing oversight. Additionally, when developing the ILOs, we avoided certain verbs as discussed by Newton et al. [10]. In completing the Metal AM MSc course, and achieving the associated award, the student should successfully demonstrate their learning achievement.

2To deliver the ILOs, seven taught modules and two project modules were designed and developed, as shown in **Error! Reference source not found.** Table 6.3, which complement each other and collectively cover all aspects of the course ILOs.

Table 6.3. List of taught and project modules in the MSc course of Metal AM

Modules		Delivery Methods	Learning Hours	Formative Assessment	Summative Assessment
Taught	Metal AM Processes	Lecture, tutorial, demonstration, hands-on practice	40 (contact) + 160 (independent)	Individual presentation	Individual coursework
	Metal AM Metallurgy	Lecture, tutorial	20 (contact) + 80 (independent)	Self-assessment questions	Exam
	AM System Design	Lecture, hands-on practice	23 (contact) + 77 (independent)	Individual formative assignment	Individual coursework
	Finite Element Analysis for AM	Lecture, tutorial, demonstration, hands-on practice	31 (contact) + 69 (independent)	Individual presentation, group discussion	Individual coursework
	Post Processing for AM	Lecture, tutorial	26 (contact) + 74 (independent)	Group discussion	Individual coursework
	Management of Manufacturing Quality	Lecture, hands-on practice	40 (contact) + 60 (independent)	Group presentation	Individual coursework
	Operations Management	Lecture, group activities, self-reflection	32 (contact) + 68 (independent)	Group presentation	Exam
Project	Group Project	Student-led group working with supervisory meetings	20 (contact) + 380 (independent)	Peer review, project meeting discussion	Group presentation, group coursework, individual coursework
	Individual Research Project	Supervision meetings	20 (contact) + 780 (independent)	Individual presentation, project meeting discussion	Thesis

3.3 Teaching Pedagogy

Before discussing the actual course, we will spend the following section going more in depth about how the different topics were delivered pedagogically and how certain challenges, some common across the board and others unique to our particular course were overcome. Finally, the present section will end with a discussion of how we are maintaining the quality of the learning and student experience over the years and into the future.

Although the ILOs of the course were described in the previous section, we did not describe how we would deliver these to the students i.e., how the teaching and learning happens. Deacon & Hodgkinson [11] used different pedagogical strategies such as scaffolding, authentic learning and reflection to develop their master's course. This multi-level approach was also used by Tavella [12] for their MSc course wherein they used a mixture of lectures, group discussions/exercises and different feedback mechanism to deliver content. Therefore, when designing and developing our Metal AM programme, we also tried to incorporate different pedagogical strategies and approaches; activities such as case studies/industrial visits, lab/project work and tutorials contribute to the authentic learning, and theories (in lectures) contribute to the scaffolding element for students who may need additional help in certain areas.

Further, we also used Chickering and Gamson's seven principles for good practice [13] which has been further developed by Chickering and Ehrmann [14] to take advantage of modern online delivery methods as guide to formulate our classroom delivery. These practices along with how we have incorporated them in our MSc programme are listed in Table 6.4 Table 6.4.3; these include steps taken by Cranfield University for all their courses as well as specific points local to the Metal AM programme:

Table 6.4.3 Seven Principles of Good Practice [13] [14] in Cranfield's Metal AM Program

Good Practice	In Cranfield's Metal AM Programme
Encouraging contact between staff and students	Full-time students attend regular Face to Face lectures where interaction between staff and students is encouraged. Part-time students are expected to attend in person at least three modules wherein they can get to know their staff and peers. Multiple industry visits where students can interact directly with companies in the AM field.
Cooperation and reciprocity between students	Multiple group activities and a group project to encourage cooperation and interaction between the students.
Active learning techniques	Students have practical sessions and/or demonstrations in a lab that support their theoretical learning. Industrial visits also help them understand how their learning may be applied in an industrial setting.
Prompt feedback	Formative assignment feedback given within a week and a deadline of 20 working days for the summative assessment to ensure prompt feedback. During the project work, regular meetings ensure feedback is given on the work regularly.
Time on Task	Students take part in multiple tutorials wherein they practise their learnings. They have further time on their task during the project work where they also learn by "doing".
High expectations	Feedback and marking, particularly during the formative assessment, is quite stringent to ensure that the students meet and exceed the level required from them. Additionally, during the project work students are given ownership of the task with high expectations communicated them.
Respect and include diverse talents and ways of learning	Learning in the course doesn't happen only through lectures, as mentioned previously, lab work/demonstration, tutorials, group/project work etc. all contribute to an enhanced and diverse learning experience. Additionally, if a student requires additional aid, a specific student plan is developed by the university that identifies what needs to be taken into account and distributed to the team.

In addition to presenting and delivering content to the students, care was also taken in designing the assessments to check if learning has happened and deliver prompt feedback. They were varied between the modules based on the specific requirements as a universal approach to assessments will not allow deep learning and cater to a diverse student population [15]. Rubrics are given to the students when they must submit individual course work i.e., assignments. As stated by Hawe et al. [16], rubrics not only help the students structure and revise their work, but they could also help them get started with their writing. Therefore, it is believed that making rubrics significantly increases the student experience and was thus included within our course.

We also ensure that feedback is given quickly; this would not only help the students but also the staff since they could check if concepts were understood or if they needed to be revisited [17]. This was particularly true for the formative assessments in certain modules like Additive Manufacturing Systems Design and Post Processing for AM.

Although every effort was made to ensure that the students had the best learning experience during the programme, there were certain obstacles that had to be overcome, two of which are described below as an example.

3.4 Course design challenges

Although certain generic challenges in designing and developing the course were discussed earlier, there were a couple of specific challenges that needed to be addressed during the course's evolution:

One challenge was the type of content shown to the class. As argued by Riener & Willingham [18], although different content can increase student interest and attention, value is only added if the (multimedia) content suits the content being taught rather than it catering to different learning styles. Therefore, instead of using multimedia to simply repeat the same message, we tried to use them in a way that made the student think about the topic in hand. For example, when discussing the importance of developing statistical studies and inferring the results, a video was shown on how they can be designed to deliver opposite results. As the video was shown during the end of a session on statistics, students' engagement was retained and the content allowed them to put their gained knowledge into a broader context and better understand the implications.

Further, although the multiple industrial visits brought value to the course, organising and coordinating these activities was a challenge in terms of the logistics and effective communication between the various stakeholders. Therefore, to overcome this, one member of the course teaching team takes responsibility for all the visits and leads them; this ensures there is a single point of contact and any discrepancies can be identified and resolved.

3.5 Ensuring Quality

To ensure the quality of delivery, most staff members have completed at least one module (out of two) of a Postgraduate Diploma in Academic Practice and as such are recognised as Associate Fellows of the Higher Education Academy (HEA). The Programme Director and one of members of the teaching team are Fellows of the Higher Education Academy. Therefore, the staff members who deliver on the course are also aware of the need to ground learning activities with certain theories as and when needed. They are also aware of the different learning styles and how the content can/should be modified to suit the individual variations in learning.

In addition to the individual lectures gaining accreditation from the HEA, the course itself has certain built-in processes to ensure that the quality of the course and fairness to the students are maintained. One such mechanism is that the assessments for each module are marked by a member of the teaching team and is then independently moderated by another member. As a matter of principle, moderation is carried out by sampling of the scripts to check the higher, lower and failed assignments and whether the assessment of the assignment was conforming to the ideal answer submitted by the first academic of a module. This is done to ensure that the marking is fair and any mistakes such as totalling and/or missing sections are identified and corrected. Usually, the module leader is responsible for the marking, and the deputy module leader moderates it.

The assessments themselves are further checked by an external examiner to ensure that they are designed appropriately in a broader context beyond Cranfield University, i.e., they test the ILOs and other relevant content. Whether it is an exam, individual coursework or another type of assessment, the question(s) along with the answers (which could either be a model script or a key) are independently assessed by the external examiner and returned to

the module lead with appropriate feedback. The external examiner also checks a sample of the answer scripts (or assignments) to see that the marks are logical and fair. Finally, they also meet some of the students to explore their level of satisfaction and to see if they have/had a satisfactory learning experience. The feedback from the external examiners (along with those of the students') are thoroughly studied up to the Pro Vice Chancellor's level to check that the deliverables of a course are met and if there is cause for concern in running the course.

The Metal AM course team also conducts an Annual Reflective Review every December, as a regular monitoring procedure for course quality assurance, which is submitted to and approved by the university academic assurance committees and governing body. In the annual review, the changes and innovations to the course in response to the feedback of the students or external examiner are described and reflected. Furthermore, the innovations in course content, delivery mode and/or assessment for approval and implementation in the coming year are also considered. The annual review is an important mechanism to enhance the strengths and address the weaknesses of the course and ensure that the course is carefully maintained and continuously improved to deliver the intended learning outcomes and learner experiences.

4 Specifications of the MSc in Metal Additive Manufacturing

In this section, the actual Cranfield Metal AM MSc course is presented with specific details. Generally, a Cranfield University MSc course is roughly divided into three sections: taught modules, group project module and individual research project module, which account for 80 credits, 40 credits and 80 credits, respectively, as shown in Figure 6.2.4Figure 6.3. Such a course structure enables provisioning of a broad range of learning activities and experiences that lead to acquisition of both theoretical and practical knowledge about different aspects of the academic discipline, and development of both specialist and transferable skills. This course structure is also aligned with the requirements and expectations from other key stakeholders such as UK Quality Assurance Agency for Higher Education, Engineering Council, and professional institutions which have their own criteria for course accreditation. Diverse methods for delivering these modules and assessing students' performance are employed to ensure the course is suitable for students with different learning preferences and effective for them to demonstrate the achievement of course learning outcomes and get feedback for further improvement.

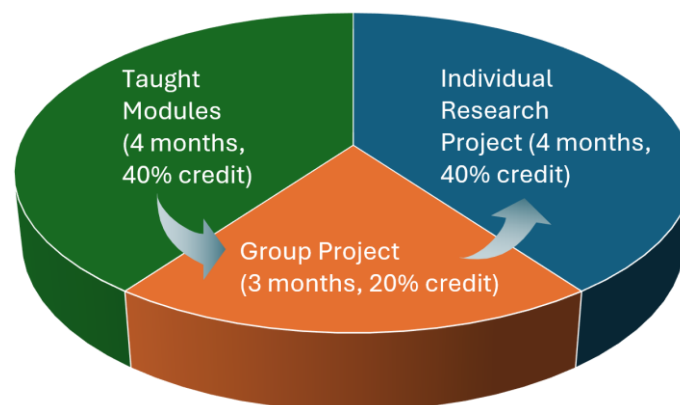


Figure 6.2.4 Typical structure of a MSc course in Cranfield University

The students who register for the MSc course are also offered another two exit routes of postgraduate diploma (PgDip) and postgraduate certificate (PgCert), which can be also chosen as the target award in the first place. For the PgDip qualification, the students need to successfully complete all the taught modules plus the group project (full-time student) or dissertation (part-time student), while PgCert award requires the accumulation of 60 credits (or more) through the assessment of compulsory taught modules including Metal AM Processes, AM System Design and Management of Manufacturing Quality, and two elective modules from Metal AM Metallurgy, Post Processing for AM and Finite Element Analysis for AM.

4.1 Taught modules

The aim of the taught modules is to equip students with both fundamental and practical knowledge, as well as technical and communication skills, for meeting the requirements of a master's degree in Metal AM. The taught modules were created based on the course ILOs and employed diverse methods and durations for delivery (Table 6.3). All these taught modules are compulsory and briefly summarised as follows:

4.1.1 Metal AM Processes

This module introduces the students to different AM technologies and net-shape processes. Subjects cover both powder and wire processing technologies and include topics on laser processes such as laser sources and optics, wire and powder melting through an energy source such as laser, arc and electron beam, and interactions between the material and the energy source.

4.1.2 Metal AM Metallurgy

The metallurgy module takes an in-depth look at the different metals used in AM. Therefore, individual sessions for different steels, aluminium, titanium and nickel alloys are included. In addition, the students will also learn about the joining of dissimilar materials and residual stresses during this module.

4.1.3 AM System Design

This module is roughly divided into two subtopics. The first part will primarily focus on exposing the students to the various resources and methods available to carry out and present their design effectively such as statistical methods, library resources, referencing etc. The second half of the module will allow the students to learn about the various components that make up an AM cell including (but not limited to) an introduction to sensors, shielding, robots, jigs and fixtures.

4.1.4 Finite Element Analysis (FEA) for AM

The FEA module introduces the students to the key phenomena and problems associated with FEA for metal AM. In addition, they are also taught the basic theory underpinning FEA including its mathematics, different formulations for elasticity, plasticity and heat transfer. The module also allows the students to work on and get familiar with a commercial FEA package and provides extensive hands-on experience.

4.1.5 Post Processing for AM

Since post processing is a critical part of an AM operation, this module explores the various routes that can be followed. Therefore, topics such as thermal post processing for various

alloys, cold work methods, mechanical and chemical post processing are taught. The students also learn the impact of these methods on the properties of the built part.

4.1.6 Management of Manufacturing Quality

In this module, the students are taught about quality control for AM components. Apart from learning about the standards that would affect AM parts, the students are also exposed to the various inspection and testing processes that would allow them to determine the quality of their production; topics including both non-destructive and destructive testing are covered here.

4.1.7 Operations Management

In this module, the students are exposed to the core factors of managing operations and the concept of flow in operations. The students are taught the basics of production and finances management associated with manufacturing and service activities. There is also an introduction to management of quality, maintenance, information system and customer demand.

Most of these taught modules/topics also contain a laboratory practical demonstration and/or an industry visit when and where possible to allow the students to gain a more holistic picture of the technologies and techniques and develop hands-on experiences.

4.2 Group project

Group projects in this program are designed as consultancy-style assignments, typically sponsored by industry partners. These projects allow students to tackle real-world problems for actual clients, helping them gain essential technical and transferable skills such as teamwork, resource management, reporting, and presentation abilities. By applying the technical knowledge acquired in earlier taught modules, students also develop skills in project management, independent research, and collaboration. The aim is to provide practical experience in addressing industry-relevant challenges that demand multidisciplinary team-based solutions.

Group sizes range from four to eight members, depending on the complexity of the project. Each student is expected to contribute fully and fairly, with contributions assessed through objective measures such as meeting attendance, fulfilment of assigned roles, documented records of tasks completed, and constructive participation in team discussions, verified by staff and team members. Therefore, the contribution is assessed both through self-reflection as well as objective measures.

Students choose their projects from a list of available options, ranking their preferences. Wherever possible, their top choices are allocated, taking into account project demand. Many projects are based on real industrial challenges or university-led feasibility studies for innovative research ideas, embodying the principles of problem-based learning by engaging students in solving open-ended problems.

Recognizing the importance of communication in modern engineering, the program includes a group oral presentation requirement. This exercise helps students refine their presentation skills, respond to complex questions professionally, and articulate their findings effectively. Each group submits a comprehensive written report and delivers a presentation to industry partners or a professional audience, integrating both technical and commercial aspects of the project.

Part-time students have the option to substitute the group project with a dissertation on an approved topic. Alternatively, they can complete the group project or dissertation off-campus, integrating it into their existing organizational context, providing flexibility to accommodate their professional commitments.

4.3 Individual research project

Students will be provided with a list of individual project options and asked to rank their preferences. Whenever possible, their top choice will be allocated, considering the demand for specific projects. These thesis projects are typically aligned with real industrial challenges or university-led feasibility studies exploring innovative research ideas.

The individual project allows students to showcase their ability to conduct independent research, think creatively, contribute to knowledge, and solve practical problems tied to real-world needs. Upon completing their research, students present their findings to a panel of academics and industry experts, followed by the submission of a detailed research thesis.

For part-time students, it is common for the research thesis to be conducted in collaboration with their workplace, with support provided by the university to ensure alignment with academic and industrial objectives.

4.4 Assessments

To ensure learning has taken place and the ILOs met, students are required to complete summative (graded) assessments for all their modules, in the form of exam, individual coursework, group coursework, group presentation, and thesis (Table 6.5). The report on individual coursework needs to be submitted after 20 working days since the completion of the taught module, while the project report / thesis needs to be submitted by the end of the project. Exams take place on the standard dates set by the university. The assessment tasks are challenging and enable students to demonstrate a full range of skills and attributes. A course-level summative assessment strategy for mapping the award ILOs is set up to ensure all the ILOs are achieved on completion of the course (Table 6.55). In addition, diverse types of formative assessment facilitating rapid feedback and timely improvement are also employed in all modules (Table 6.3).

Students will write employability relevant policy briefing documents to equip them with the skills they require to succeed in the field of metal AM, and to address the specific award ILOs 1-6. Students then have opportunities to develop their communication skills, as they are required to give group presentations as well as individual presentations. These are assessed by roving committees of independent academics and/or invited industry experts.

The ability to work effectively in groups is a highly desirable skill which has translated into ILOs 7,8 and 9. The research project addresses ILO 10 and takes the form of a thesis, typically written following the structure of a research paper. Students are expected to illustrate and present their work at the end of the project.

Table 6.5. Summative assessment of modules mapped to course ILOs

Modules	Award ILOs									
	ILO 1	ILO 2	ILO 3	ILO 4	ILO 5	ILO 6	ILO 7	ILO 8	ILO 9	ILO 10
Metal AM Processes	ICW		ICW	ICW						
Metal AM Metallurgy	EX	EX								
AM System Design				ICW		ICW				
Finite Element Analysis for AM			ICW			ICW				
Post Processing for AM	ICW	ICW								
Management of Manufacturing Quality	ICW				ICW					
Operations Management				EX						
Group Project						GCW	GCW GPRES ICW	GCW	GCW	
Individual Research Project						THESIS	THESIS	THESIS	THESIS	THESIS

Abbreviations for the assessment methods: ICW: individual coursework; EX: exam; GCW: group coursework; GPRES: group presentation.

4.5 MSc by Research

For those students who want to go down the part of only research and in-depth self-driven learning, a route to award of MSc by Research is also available at Cranfield University. The scope of the MSc by Research programme is much broader and the Cranfield's option closest to Metal AM is the MSc by Research in Manufacturing and Materials. The students would focus on a metal AM related research project and audit the taught modules of the Metal AM MSc course, thereby getting comprehensive training and benefiting from the learning resources provided in the Metal AM course.

Normally, each student is allocated a primary supervisor and a co-supervisor. There are regular progress meetings that follow the structure of a PhD project, albeit in a more condensed form. There is no expectation that the research work should lead to a conference or a journal publication, however there are instances of this happening and the students are definitely encouraged to work towards this, compatibly with the time pressure and the post-degree availability of the candidate.

5 Alignment with Industry

5.1 Accreditation

Accreditation by Professional Engineering Institutes forms a vital part of the course in terms of its quality control and also to attract the future leaders in the field. Accreditation by a Professional Engineering Institute will allow a student with relevant industrial experience to obtain a chartered engineer status after completion of the course. In terms of professional development and growth, having chartered status can be a significant milestone for a candidate who wants to become a future leader in his chosen field of activity in any manufacturing sector. The Centre looks to get accreditation from all the five professional engineering institutes for both the courses offered from here. The list of the institutes are given below,

- Institute of Mechanical Engineers (IMechE)
- Institute of Materials, Minerals and Mining (IoM3)

- Institute of Engineering and Technology (IET)
- The Welding Institute (TWI) and
- Royal Academy of Engineering (RAEng)

Currently the course has been accredited by IMechE and RAEng. The authors are expecting to receive from the rest of the professional engineering institutes within two years.

In order to achieve the PEI accreditation, a course needs to be mapped to the learning outcomes necessary to become a chartered engineer in line with Accreditation of Higher Education Programmes (AHEP) in the broad areas of “Science and Mathematics”, “Engineering Analysis”, “Design and Innovation” and “the Engineer and Society”. AHEP [19] contains the latest learning outcomes necessary to be accredited so that an engineer from the course can obtain a chartered status after completion and with necessary industrial experience

5.2 Industrial Advisory Board

The WAMC offers two courses a) Welding Engineering and b) Metal Additive Manufacturing. An industrial advisory board was constituted to examine the appropriateness of the courses in terms of their industrial suitability and how they comply with the broader guidelines and initiatives that academic and research institutes are laying out.

Constitution of an informed and relevant industrial advisory board is an essential aspect of informing and steering the direction of a course. It keeps it viable both in terms of its suitability to industrial research and development community, and attractiveness to the students.

In this regard, it is important to mention that the metal AM course complies with the European guidelines on course content for engineers involved in AM by DED. The current industrial advisory board comprises of an international team from leading industrial bodies covering different sectors viz., energy, aerospace, metal additive system manufacturing, civil nuclear applications and with wide variety of experiences in welding and AM.

5.3 Industrial Visits

During the course, regular visits to various industries and facilities are organised for the students to appreciate different Metal AM-related techniques and facilities in the real industrial environment. The students were provided with opportunities to learn from the industrial presentations, live demonstrations, hands-on experiences, and group discussions. In addition, the industrial visits enabled the students to directly talk to industrial experts regarding both technological applications and personal career developments. Examples include visits to companies of WAAM3D, GKN, Lincoln Electric, Fronius and KUKA.

The Metal AM students also benefited from industrial guest lectures, which provided first-hand information about industrial approach, applications and impact of Metal AM technology. In addition, the unique styles of industrial experts for teaching provided diversity in the way that lectures were delivered. These guest lecturers are from companies such as WAAM3D, Airbus, Lincoln Electric and Technip.

5.4 Industrial Case Studies

5.4.1 Case Study 1

A case study of a full-time student’s individual research project is briefly introduced here. The industrial partners provided input and support to the definition, implementation and

exploitation of the project. The project was proposed as part of a large industrial research programme led by Weir Group, an end user of metal AM technology. Cranfield University was a consortium member of this research programme and responsible for formulating technology concept and testing the feasibility of new development to meet Weir Group's need of a high deposition rate, high quality WAAM process. Specifically, the student's project was aimed to develop an automated interlayer wall height monitoring and control technique using a coherent Range-Resolved Interferometry (RRI) sensor (Figure 6.3.6Figure 6.3), which has a clear industrial background and application prospect.

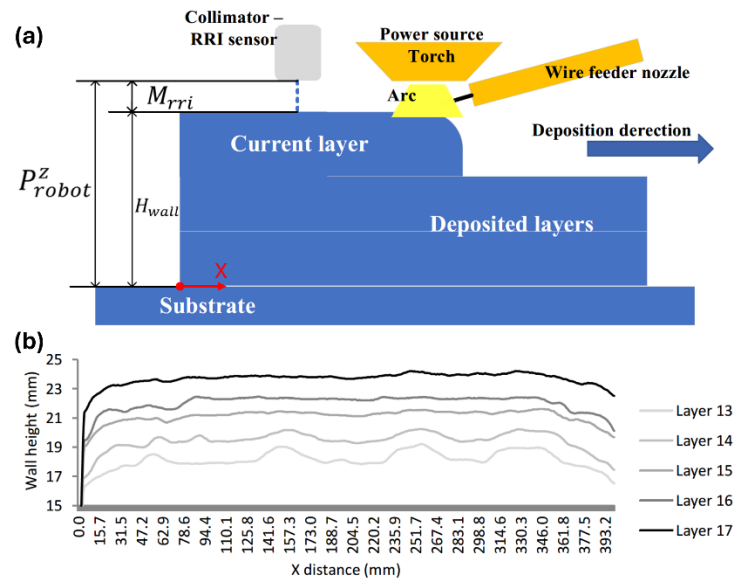


Figure 6.3.6 Case study of a full-time student's individual research project on WAAM interlayer wall height monitoring and control: (a) the schematic of experimental setup (M_{rri} : RRI measured distance; P_{robot}^z : position of robot; H_{wall} : wall height); (b) the measured wall height and implemented wall height compensation for the layer height variation that occurred during the deposition of Layer 13 [20]

In the project, the student applied the comprehensive knowledge and skills that he gained from the taught modules to tackle the research challenge, which involved the development of the technology itself and the pathway to delivering the potential impact. The student enjoyed the access to the WAMC's state-of-the-art WAAM facility and the full support of the academic and technical team. In particular, he had the opportunity to propose and realise his own idea within the well-defined research scope, working with a group of researchers and technicians for preparing for and carrying out the research. Given the collaborative nature of the project, beyond the technical aspects, the student also enhanced his communication skills through reporting and presenting his research progress and achievement in the meetings with the industrial partners. Furthermore, based on the student's thesis, a journal paper was written and published [20]. The diversity of the activities and outputs in the project provided the student with great learning experience. After completion of the project, WAAM3D company, a WAAM technology supplier and also a member of the Weir Group-led consortium, explored a route to commercialisation of the technique developed in the MSc project. The student also benefitted from the close link with the company and joined the WAAM3D as an AM engineer after he graduated from the MSc course. It is exciting to learn that WAAM3D has further extended the student's research and integrated the technique into their WAAM software packages, demonstrating the seamless transfer of knowledge from university to industry and the real-world difference and impact that a MSc research project of the Metal AM course makes.

5.4.2 Case Study 2

The other individual research project which has been exemplified as a case study, was performed by a part-time student with their employer an internationally renowned aerospace manufacturer. In this research, productivity in laser powder bed for manufacturing of nickel alloy Haynes 282 was studied. The important part of the study was to perform a set of controlled experimentation varying the three factors, laser scanning speed, hatch distance and depth of penetration or layer thickness. The viable process window for 100 and 150 μm depth were identified while it was observed that there is no viable process window if the target layer thickness is 200 μm . Figure 6.4.7Figure 6.4 explains the finding for 100 and 150 μm layer thickness.

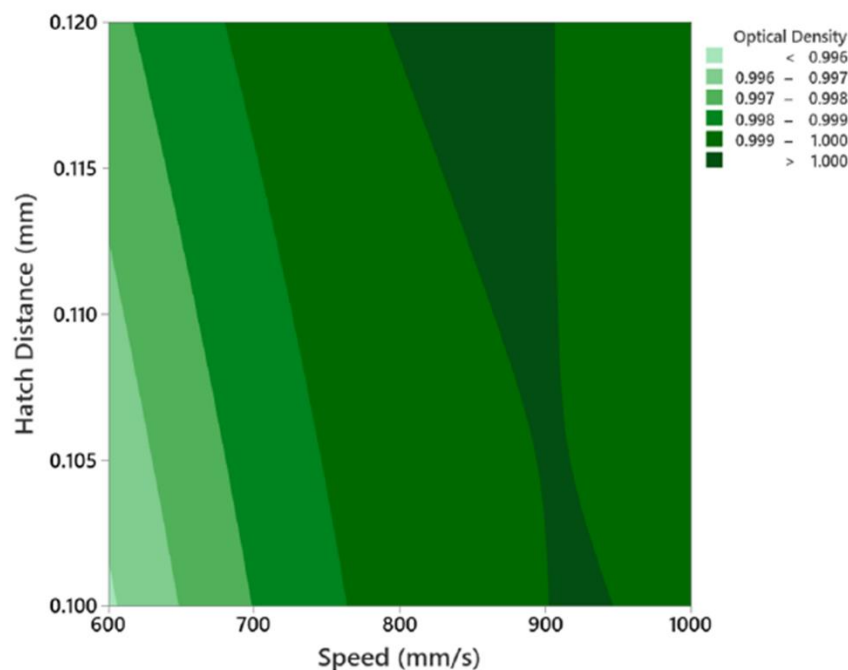


Figure 6.4.7 The operating regime of different hatch distances and laser scanning speeds to obtain 100 μm layer thickness

The experimental work was supplemented by metallographic observation and relative density analysis. This complemented the overall objectives of the project. The essential idea in an individual research project is to impart the necessary skillset in a candidate to perform controlled experimentation and develop the ability to individually lead a project. The formation of individual research projects always keeps this as its topmost priority to ensure induction of such skillset in a student or researcher.

6 Future Direction

6.1 Student Feedback

Feedback from the students is a critical part of our course evolvment. Every year, we undertake a set of surveys that seeks to highlight what the courses strengths are and the areas of improvement. Based on these, we look to continuously improve the course. In the UK Postgraduate Taught Experience Survey 2023, the Metal AM course rated 4.39 out of 5, and the rating was particularly high in Recourses and Service (4.69) and Dissertation or

Major Project (4.64). In this section we show two examples of how student feedback was used to positively affect the course.

6.1.1 Redesign of the FEA module

For the first cohort of students in 2019, the Metal AM course adopted an existent module of Finite Element Analysis (FEA) at Cranfield University, which was designed to be generic and used structural problems as the main examples for the applications. The students recognised the module was helpful in understanding the basics FEA theory and developing software skills, but they would expect to learn more FEA knowledge and techniques specifically for AM. To address this feedback, in 2020 the course team created a new FEA module dedicated to AM, which provided a more tailored balance between the generic coverage and the speciality in AM (Figure 6.5.8). Many major changes were made. For instance, unlike the previous FEA module, the heat transfer problem in the context of AM is treated equally important as the structural problem in the new FEA module, since AM is a thermal process involving complicated heat transfer phenomena. Another major change is that more AM-related application examples are provided for understanding why FEA and other modelling techniques are needed for AM and how they help part designers, process developers, material scientists and structural engineers achieve their goals related to AM. The assessment of students' learning has been also changed, and the students are asked to conduct a course work specifically for AM modelling and simulation, from which the students' ability to generate an AM model and obtain and interpret AM simulation results are assessed. Since the overhaul of the FEA module, the students' satisfaction has been remarkably improved. The new FEA module with a focus on manufacturing modelling also arouses interest from other courses and now this module is also used by the MSc in Manufacturing Technology and Management at Cranfield University.

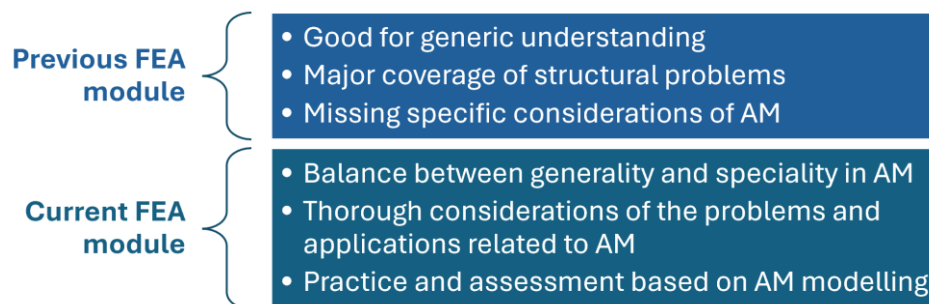


Figure 6.5.8 Overhaul of FEA module to address students' feedback

6.1.2 Laser Powder Bed Fusion Machine

In 2023, the Centre procured a laser powder bed fusion (LPBF) facility for teaching and, if applicable, for research and part building purpose. This facility was procured in response to students' comments on their learning experience where they mention that the lack of this facility may result in a gap in covering one of the most applied area of metal AM. Previously this part was covered by one of the academic collaborators, the Advanced Materials Processing lab in the University of Birmingham where the students used to visit for practical experience and research projects for laser and powder bed additive manufacturing. However, this new facility within Cranfield University will enable students to build parts and samples in house. Since its commissioning in 2023, one group project and two individual research projects were performed using the LPBF facility. The presence of this machine is

further exploited in manufacturing research of different types of hybrid material manufacturing such as metal-aerogel composite structures.

6.2 Enhancing the scope

Sustainability of a Master's course depends on its ability to modify its objectives, learning outcomes and thereby content as it evolves through the time. The academic team believe that the future sustainability of the course would depend on enhancing the scope further to attract more students from different fields and sectors of application. Therefore, expansion on the technical content of the course is being discussed to make it appealing to a wider community of engineers and enthusiasts. Incorporation of additive manufacture of polymer within the course and modify the title of the course to Material (instead of Metal) Additive Manufacturing is likely to make the course broader in its outlook. With this intent, the course team are planning to work with the Design group within Cranfield and draw upon their vast resources and expertise for fused deposition modelling and stereolithography facilities. In the teaching area, incorporation of a dedicated module on design, technology and prototyping would supplement to broaden the scope of the programme. With this broadening of the scope, the team expects to welcome more diverse range of students including civil, architectural and design engineering.

7 Conclusion

The chapter presented the development and delivery of the first global MSc in Metal Additive Manufacturing by identifying the need for the course through the preparation work done for European Commission funded ADMIRE Project. This also offered critical insights in developing the course content as well which was put together with certain theoretical underpinnings and pedagogy (discussed subsequently). Then the actual course in its current format is presented; the course is made up of a mixture of taught modules and research projects providing the student with a more holistic understanding and experience of metal AM. Another critical aspect of the course is its alignment with the industry; therefore, the authors also talk about how this close tie is achieved through the presence of an industrial board, visits and projects. Finally, the authors look at the future of the course and how it can be iteratively improved to continue to provide the skilled workforce needed for the ever-evolving landscape of metal AM and broader materials AM.

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Metal additive manufacturing MSc—a pioneering global master's course for leaders of future manufacturing

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Pei, Eujin; Monzón, Mario; Bernard, Alain; Gibson, Ian**

2026

Springer

https://doi.org/10.1007/978-3-031-94547-2_6

Martina F, Sun Y, Krishnaswamy S, Ganguly S. (2026) Metal additive manufacturing MSc—a pioneering global master's course for leaders of future manufacturing. In: Additive Manufacturing Teaching and Training Case Studies, Springer Nature Switzerland, 2026, pp. 101-125