Additive Manufacturing: Production process considerations for metal and plastic

Guidance for SMEs

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Introduction

About Additive Manufacturing

Additive Manufacturing (AM), or 3D printing, is not a new concept but has been developed over the past 30 years. In recent years the benefits and competitive advantage that AM can offer UK industry across sectors, in particular manufacturing, has had a growing focus by government, businesses and their customers.

“In 2017, an estimated $1.13 billion was spent on materials for all additive manufacturing (AM) systems worldwide, including both industrial systems and desktop 3D printers. This represents an increase of 25.5% over the $903.0 million spent in 2016. The market segment grew 17.5% in 2016 and 20.0% in 2015. These estimates include sales of liquid photopolymers, powders, pellets, filaments, wires, sheet materials, and all other material types used for AM.”

“This rapid growth is forecast to continue and accelerate over the next decade. It is estimated that the UK can win up to 8% or £5 billion of this rapidly growing global market, forecast to reach £69 billion by 2025. This will have a strong effect on protecting existing jobs (63,000 by 2020) while also generating new employment.”

In 2017 this was put at the forefront of UK industries by the publication of the Additive Manufacturing UK National Strategy 2018-25.

The aim of this guidance

Many UK small and medium-sized enterprises (SMEs) have been slow to adopt the AM process due to a lack of understanding on whether AM is right for them, the potential business benefits, and the need to change their tried-and-tested business models.

This guidance aims to support SMEs in gaining an understanding of AM processes to assess whether the AM process is the right choice based on their requirements. A common approach for SMEs to assess if AM is right for them is essential.

The guidance outlines the key questions businesses need to answer to help feed into their design, material selection, production run and to identify opportunities that add value (e.g. improved performance, lightweighting, and supply chain value) that are critical for AM to deliver benefits to the business.

1 Scope

This document gives guidance to assess the feasibility of the design for additive manufacturing (AM) parts and the selection of the relevant AM production process via the:

- material extrusion process, also known as fused deposition modelling (FDM) or fused filament fabrication (FFF) as a production method (see Annex A); and
- metal powder bed fusion process as a production method (see Annex B).

This document is for use by those looking to adopt AM technologies and key questions to ask before adopting the technology.

2 Terms, definitions and abbreviations

For the purposes of this private standard, the following terms and definitions apply.

2.1 Terms and definitions

2.1.1 added value

where a part or product is manufactured using AM where the combination of complexity, unique geometry, being unable to be manufactured by any other means and low volume create an added value service.

2.1.2 additive manufacturing

technologies that build 3D objects by adding layer-upon-layer of material
NOTE These technologies can be applied whether the material is plastic or metal or other material.

2.1.3 directed energy deposition

powder fed or metal wire fed AM systems
NOTE This is also known as laser metal deposition and laser cladding.

2.1.4 electronic beam powder bed fusion

powder bed AM process where a thin layer of metal powder is selectively melted by an electron beam
NOTE This process is similar to selective layer melting.

2.1.5 fused deposition modelling

where a thermoplastic filament is heated and extruded through a tapered nozzle turning the plastic to a liquid at the tip where it is deposited layer by layer via a machine control system then solidifying the liquid and fusing it to the layer below as it cools creating a solid 3D printed part.

2.1.6 selective layer melting

powder bed metallic AM process designed to use a high-power density laser to melt and fuse metallic powders together.

2.2 Abbreviations

For the purposes of this private standard, the following abbreviations apply.

AM	additive manufacturing
CAD	computer aided design
CMM	co-ordinate measuring machine
DED	directed energy deposition
DMLS	direct metal laser sintering
EMB	electron beam powder bed fusion
FDM	fused deposition modelling
FFF	fused filament fabrication
PPAP	part production approval process
SLM	selective laser melting
SME	small and medium-sized enterprise
SPC	statistical process control

3 Do you need AM?

3.1 The 10 key AM questions

From an initial enquiry to an additive manufacturing SME there are 10 key questions that should be asked before a customer adopts AM.

1. What is the volume of AM parts required?
2. Have other manufacturing methods been considered?
3. Has the part been designed for AM?
4. Could further added value be incorporated in the design?
5. Is 3D CAD data available for AM part production?
6. Does the part require industry regulations or acceptance standards?
7. Which material and AM processes are suitable for the part?
8. What are the critical features and part specifications?
9. Are further secondary processes to be carried out after build?
10. Is the AM part a repeatable batch production run?

3.2 Understanding the 10 key AM questions

Further considerations and assumptions are provided for each key question to help businesses gather the information needed before producing an AM part.

1. What is the volume of AM parts required?

The volume of AM parts should consider the following questions, including but not limited to:

a) Does the volume of AM parts fall into low volume or mass production? (e.g. <100 = low volume, 15 000 parts = mass production). It should be noted that AM suits lower volume production.
b) What is the part size? Part size should be considered in volume production.
c) How many parts could you fit on an A3 sheet of paper?

2. Have other manufacturing methods been considered?

Considerations for other manufacturing methods include but are not limited to:

a) High part complexity, multi-part count reduction, reduced assembly time, lightweighting, multi-function etc. which all suit the AM process.
b) Flat and easily formed parts might suit other manufacturing processes such as CNC machining. For example, basic 2D shapes could be made easier via other methods such as CNC routing or water jet cutting, etc.
c) Other tooling methods are available for low volume production and are considered more economical than AM.

3. Has the part been designed for AM?

The design of the part should consider the following, including but not limited to:

a) Has design for the AM processes been applied at the product design stage? [1)]
b) Design for conventional manufacturing methods are already well known in industry and applied.
c) Design for AM is a new way of thinking about design; AM specialist guidance should be sought.
d) Existing conventional components can be manufactured by AM; however, advice on part design for manufacture provided by the manufacturer should be sought in the early stages (i.e. the start of the design process).
e) For AM / layer-by-layer manufacturing the different processes might require changes to the 3D design principles. These design principles should be guided by the manufacturer and materials and differ from each AM process
f) Self-supporting structures usually result in time and cost savings including, minimizing the secondary process operations.
g) Material selection, densities and achievable tolerances should be recorded at the design for AM stage.
h) Individual AM process specialists should advise on the design principles required at this stage to suit the selected production process.
i) Finite element analysis (FEA) or other computational simulations of the 3D data to determine mechanical performance (static/dynamic) and fatigue as appropriate may be sought from various third party software specialists.

4. Could further added value be incorporated in the design?

An additional question that should be considered to assess further added value is:

a) Could you incorporate any further features to add further value? For example:

multi-part to single or fewer parts (e.g. merging complex assemblies);

design optimization (e.g. FEA or optimized topology could deliver production or long-term benefits);

lightweight designs (e.g. flight or transport efficiency gains);

[1)] Further information is available from:
https://www.d4am.eng.cam.ac.uk/publications/ProjectReports/D4AMLiteratureReport [4].

a stronger supply chain by adding novel features to help reduce further production steps;
built-in part identification to create ease of traceability;
novel 3D geometry to improve the end use functionality;
green benefits of parts over the lifecycle of the product; and
the consideration of intellectual property rights.

5. Is 3D CAD data available for AM part production?

3D CAD data that is relevant for production of an AM part includes but is not limited to:

a) Most accepted 3D CAD file exchange formats include for example STEP, IGES, and X_T.
b) Stereolithography (STL) file format is the industrial default file format.
c) For STL file exporting, care needs to be taken in selecting a suitable resolution.
d) Low resolution STL files results in faceted (flat areas) which are highly visible on the final part and result in poor build quality and failure to meet tolerance specifications.
e) STL file size on high complex parts can be large when exporting in a high resolution setting.
f) Advice should be sought when unsure of an optimal setting and resolution.

*NOTE See also Clause **4** for further guidance on file formats.*

6. Does the part require industry regulations or acceptance standards?

Reviewing the need for required industry regulations or acceptance standards includes but is not limited to:

a) The level of conformance might vary by industry sector, for example:
   1) **Low level**: for non-critical generic part use, little or no certification might be required.
   2) **Mid-level**: the food and beverage industry requires regulation adherence to fulfil its hygiene standards.
   3) **High level**: aerospace and nuclear sectors require in-depth material and part end-to-end traceability to satisfy in depth standards such as, AS 9100.
b) Consultation with AM process specialists at the early stages is advised to see how well the processes are suited to validation to the specific sector regulatory requirements.

7. Which material and AM processes are suitable for the part?

The suitability of the material and AM processes should consider the following, including but not limited to:

a) Selecting comparable AM like-for-like materials to help identify the chosen AM production process.
b) For some applications the material specification leads to a singular AM process option.
c) Defining material properties (e.g. high temperature allows a greater freedom of the AM production process options available for example, specific plastic and metal materials can be used).
d) Designing for a specific AM process does not always allow it to be produced successfully on another AM process.
e) Specialist advice should be sought when selecting the material and AM process.

8. What are the critical features and part specifications?

The critical features and part specifications to identify include but are not limited to:

a) 3D data files do not show critical areas or dimensional tolerances.
b) To detail critical features a 2D drawing needs to be produced to set out the areas that require further thought, for example:

surface finish;

tolerance information; and
whether holes require post-processing (e.g. diameter information).

c) Further information applied might specify a tapped thread requirement, or a bore tolerance on the final part which needs further processing.
d) All non-specified areas on the drawings are treated as generic build and post processing parameters set out by the chosen AM process.
e) Each AM process has varied achievable tolerances, advice on critical features is advised at the early design stages as they can affect the ability to build and could add to the required post processing costs.

9. Are further secondary processes to be carried out after build?

To assess if further secondary processes are required the following points should be known, including but not limited to:

a) Secondary processes require additional documentation to set out details of any post-processing steps required. For example, thermal heat treatment, surface modification, oils, chemicals, paints and abrasives to be used that are accepted by the end customer.
b) Test coupons might be required to test the secondary processing methods ahead of final part production.

10. Is the AM part a repeatable batch production run?

To assess if the part is in a repeatable batch production run the following considerations should be identified, including but not limited to:

a) The number of components being produced in any one build is individual to each AM process and machine type.
b) Variations such as X & Y build dimensions, and the volumetric Z height add further options to batch production runs.
c) Optimal number of components produced per build is subject to part size, build orientation, build envelope and AM process.
d) The quantities being produced do not fall into the normal 1, 10 and 50 off. Rather a more specific part per build multiplied by number of production runs might be more cost effective.
e) Advice on batch production run efficiencies should be given by the AM process specialists.

4 File formats for AM

4.1 STL format

There are many CAD models of component geometry and these representation models vary from one system to another. The STL file format has been used as a de facto standard file format as the standard interface to convey geometric information from CAD software packages to AM systems.[2)] This format is used in many AM systems to deliver the component geometry from the design programme to the AM system. The STL file consists of triangular facets representing the outside skin of an object. The STL file is a facet model derived from precise CAD drawings and therefore is an approximate model of the part.
Advantages of the STL file include; simple method of representation of 3D data and data transfer.

[2)] Jacobs, 1992 [5]

Disadvantages include; the STL file contains redundant data and can be very large, geometry flaws, such as gaps, overlapping facets, can exist in the STL file which may lead to a requirement for file repair. This may take considerable time, but also may be irreparable. The AM operator may return a non-repairable file to the customer/file generator for repair. In addition, the STL file needs to be saved at a high enough resolution to avoid the generation of facets in the STL model. These facets are non-repairable and if this file was to be used in the build the part would be built as faceted. For example, a cylinder would not appear round rather it would have multiple flat facets all the way round the cylinder. The file supplier may be asked to save their file at a higher resolution or supply the file in another format. Very large STL files may also take a long time to slice and in this instance the file supplier may be asked to supply a file of a lesser resolution. Once an STL file has been created from a CAD model conversion back to a CAD/solid model is unsuitable as information is lost and the model is not the same as the original. For 3D scanning a STL can be produced from the acquired data point cloud for reverse engineering of components.

4.2 Initial graphics exchange specification (IGES) format

IGES is a file format used to exchange graphic 3D data between commercial CAD systems.[3)] IGES files contain geometric, boundary and topological information. The IGES file provides a precise CAD model of the part and the file format is widely used. The IGES file can be large and some AM software systems may be able to slice the part but other AM software systems may require the file to be converted to an STL format. If build supports are required, such as for SLM, they cannot be created in the IGES format.

4.3 Standard for the exchange of product data (STEP) format

The STEP model data file format is a CAD file format usually used to share 3D models between users with different CAD systems and is defined in ISO 10303. This file format is newer than IGES. The geometric 3D data of the part is generated as a solid rather than the surface model of the IGES file. This file format is now more commonly used than IGES.[4)]

4.4 Additive manufacturing file (AMF) format

AM technology has advanced from production of simple parts to complex parts with a wide range of shape, textures and colours and with it an open standard file format. AMF has been developed in ISO/ASTM 52915:2013. This format has been designed to allow any CAD software to describe the shape and composition of any 3D object for fabrication on any 3D printer.

4.5 3D manufacturing format (3MF)

3MF is being developed by an industrial consortium involving many of the AM machine manufacturers. It is a 3D printing format that allows design applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers. This format differs from STL as it can contain colour, material information and mesh topology.

NOTE Further information is available from: https://3mf.io [6].

[3)] Reed et al, 1991 [7]
[4)] Marjudi et al 2010 [8]

4.6 File format considerations

Generation of 3D CAD geometry of the part may be produced in multiple software programmes. The final export format of the files may be dependent on the options in the software used. The customer should confer with the AM provider on the quality and suitability of any of their supplied files.

For all 3D representation file formats no information of dimensions, hole requirements, other part specifications, or tolerances are contained within the file. Software developers are working to add this type of information within 3D file formats. Additional information should be supplied in a 2D reference drawing or as a list of specifications to the AM operator.

The original file supplied by the customer may be altered or changed through 'repair' steps (see **4.1**) and a new version of the file may be created by the AM operator.

Annex A (informative)

Production process for plastic

A.1 FDM - General

The guidance in Annex A establishes the manufacturing process options and procedures for the manufacturing of plastic components using the FDM process on Stratasys production technology.

Other terms associated with this process are FFF and material extrusion to name a few.

A.2 Quotation checklist

These are general considerations to be made during the quotation and design stages prior to machining which are outlined in **A.2**.

A.2.1 Part information

Information required to successfully quote an FDM thermoplastic part should consist of:

a) A 3D data file, STL format preferably, if not other 3D file formats can be received via various other exchange formats such as IGES, STEP etc.
b) The chosen thermoplastic material required to manufacture the part such as ABS, Polycarbonate or Ultem 9085. Material data sheets are available with basic test data to allow a suitable choice to be made.
c) Build resolution is defined by the layer thickness ranging from (0.18-0.5) mm, this differs for each material so seeking advice on the build matrix options is necessary.
d) A 2D drawing of the part is advised to set out the manufacturing method, build direction, material, quantity and any notes relevant to the part such as tolerances, critical features, surface finish, and referencing the company's internal standards for the manufacturer to follow ensuring procedures are incorporated to an acceptable level.
e) Post-processing considerations are documented and understood at the quotation stage to enhance the part after machining. Options such as metal plating, smoothing, resin sealing and paint spraying are some of the options available, and advice should be sought from the manufacturer for finishing options.

A.2.2 File orientation and preparation

Using the machine software provided the following processes are followed:

a) The 3D data is orientated into the correct X,Y,Z direction specified on the production drawing. If no specifics are given the orientation is set by the manufacturer based on previous knowledge and good practice.
b) The FDM machine of choice is selected based on part size, material and build layer thickness.
c) Standard software parameters are generally accepted to allow a satisfactory build however, various overriding parameters can be changed such as:
    - **Layer thickness (Z height)** - layer build thicknesses are generally defined as (0.18 0.25, 0.33 and 0.50) mm, however some platforms may have further options available. This also defines the extrusion tip on the machine which range from a T12 (0.18 mm) to a T40 (0.50 mm).

    - **Contour material width** - extra control in the software allows experienced users to fine tune this setting to allow optimal part quality to ensure a more robust product to meet the customer's requirements. This is usually in a range of (0.4-0.68) mm but other systems may differ.

- **Raster fill direction** - this is a parameter defined in the processing software to allow added build control during the slicing of the 3D CAD model, parameters can be defined by the customer or the manufacturer to ensure the optimum settings for part manufacture.

- **Raster air gap** - a parameter or setting that can allow parts to be built with increased control for advanced users with the end part to be manufactured in mind. This allows added value to be factored in during the manufacture, and is generally for parts with large wall sections.

- **Support type** - the normal default support type is acceptable, however further options of sparse and breakaway allow enhancements that could benefit the post-processing of support removal.

- **Visible surface** - allowing an overriding parameter for more experienced users to enhance the exterior look of the final product when used in conjunction with other advanced settings.

- **Part interior style** - this parameter allows experienced users to change the part build structure and have accurate control when producing highly complex parts and specific high value customer standards for production.

d) Once the software parameters are defined the software slices the 3D data with the desired settings, this creates a build file or a .CMB file that is machine code to then allow the part to be sent directly to the production machine.

A.2.3 Machine preparation prior to production

Guidance from the machine manufacturer on regular machine maintenance should always be followed, however, internal additional steps should be considered, for example:

- checking the tip wipers for wear ahead of production to allow a clean tip wipe ahead of each build layer;
- checking the purge chute is clear preventing a backlog during production;
- checking that the build chamber is clear of debris and a new sacrificial build sheet is placed in ahead of each production run; and
- ensuring that the correct material and a sufficient amount is loaded prior to pressing go on the machine.

A.3 Part removal after build

After the build is complete the parts can be removed from the build chamber. Care should be taken as heat is involved and the relevant personal protective equipment (PPE) should be worn.
Each different designed 3D printed part needs an individual approach to support removal and the relevant care should be taken when using generic tools to aid the process.
Tools such as plyers, chisels, scrapers, side cutters and Dremel tools are an example of equipment required to aid support removal.
Critical features on the part set out at the quotation stage need more high-end engineering tools, for example drills, reamers and threaded inserts.
Surface finishing specifications set out at the quotation stage require extra tools such as orbital sanders, fillers, varying grades of sandpaper to achieve the customer specification.

A.4 Part inspection and quality

General prototyping only requires an overview quality check prior to shipping.

Additive manufactured production parts may have to follow a more stringent process defined between the manufacturer and customer at the quotation stage; these may include procedures such as statistical process control (SPC) checks or follow the production part approval process (PPAP) automotive quality standards.

Equipment used to satisfy this element of quality could range from Vernier calipers, Micrometer, hole gauges, depth gauges, co-ordinate measuring machines (CMM) or maybe more advanced surface laser scanners are required on complex 3D shapes.

All relevant paperwork to satisfy the production element of AM should be supplied with parts to complete the parts being delivered to the customer. This differs between industry sector such as automotive and aerospace and should be agreed at the initial customer audit stage.

Where full material traceability is required it is important to supply a material certificate of conformity to allow batch production to be controlled.

Annex B (informative)

Production process for metal
B.1 Metal AM processes

B.1.1 Direct metal laser sintering (DMLS)/Selective laser melting (SLM)

Selective laser melting (SLM) can be considered to be a subcategory of direct metal laser sintering (DMLS) / selective laser sintering (SLS) /direct laser sintering (DLS) which are all generic metal powder bed fusion AM processes.[5)]
For these AM processes, the 3D CAD model is sliced into a number of finite layers and uploaded to the SLM machine. The required thickness of powder is laid down onto the build plate and the laser is directed to melt the boundary and inside of the part. A further layer of powder is added and the laser again melts the powder within the parts next sliced layer.
The process is repeated with the melted particles fusing to form the component layer by layer. The component is built in either an argon or nitrogen environment. The 3D component formed is of near net shape and may require post-processing (e.g. post-machining to the required dimensions, or polishing to improve surface finish). Build supports anchor the component to the build plate and are used to support the part during the build, where applicable, and to avoid deformation due to residual stresses.
These build supports are removed by the AM operator as part of the post-processing operation. A wide range of materials is available for SLM/DMLS/SLS. These include Aluminium alloys, Cobalt based alloys, tool steels, Nickel based alloys, stainless steels, Titanium alloys, precious metal alloys and Copper alloys. Material trade names for these materials vary between manufacturers.

B.1.2 Electronic beam powder bed fusion (EBM)

In this process the machine distributes a layer of powder on the build platform which is then melted according to the sliced layer of the CAD file. The build platform is lowered by the layer thickness and a further layer of powder added. The electron beam melts the powder according to the CAD design and this process is repeated until the components are completed.
EBM requires supports structures, just like any other metal AM process. But in EBM, the supports do not need to extend all the way to the build platform or any other solid part. Instead, supports can start anywhere within the powder, allowing for the build volume to be entirely filled with parts. Supports can be from as little as 3 mm long to about 25 mm maximum, depending on component size.

B.1.3 Directed Energy Deposition (DED)

For this process a laser beam is utilized as the energy source and the metal material either powder or wire is passed through a nozzle. The laser or electron beam is focussed on the substrate, either a build platform or a component for cladding or repair, a melt pool is created and the metal material, either wire or powder, is added to the melt pool.
The melted particles fuse and solidify to form the added layer of the material. The nozzle, with the laser or electron beam and material, moves around the substrate along the path directed by the sliced CAD model. Here layers of metal material are layered around the part (cladding) or are built up to form the component. DED can be utilized for repair and fabrication. Advantages of this

[5)] Kruth et al 2005 [9]

technique include the manufacture of large parts at lower temperatures. The components produced have a lower resolution and are fully dense without internal porosity or powder inclusions but usually require post-machining of critical areas to fit.
Materials available include Inconel, Cobalt based alloys, carbides, stainless steels and Titanium alloys. AM components may require post-machining, for example CNC post-machining to achieve net shape.

NOTE Further information is available from: http://www.twiadditivemanufacturing.com/capabilities/metal-processing/laser-metal-deposition/ [10].

B.1.4 Binder jetting

A powder bed AM process originally developed at MIT, USA, and commercialized in slightly different forms by Exone and Hoganas. An inkjet is used to deposit an 'ink' into a metal powder bed and this bonds the particles together where needed corresponding to the component slice. Further layers of powder are added with the directed application of the binding ink. This part of the process is carried out at room temperature. Once complete the part is debound and the material is either sintered to form the final component (Hoganas) or infiltrated with another metal such as bronze (Exone). No build supports are required in this process. Many other less mature processes are becoming available including desktop metal, mark forged, and sandmold printing amongst others which have the potential for quicker part production for small parts.

NOTE Further information is available from: http://www.metal-am.com/introduction-to-metal-additive-manufacturing-and-3d-printing/metal-additive-manufacturing-processes/ [11].

B.1.5 Material extrusion

In this process a printer heats and extrudes bound metal rods in a manner similar to FDM. The part is deposited layer by layer according to the sliced CAD model. The binder is then removed from the component using dissolving fluid and the component is placed into a furnace to deliver the sintering of the metal. The part is built at an oversize as the subsequent processes result in part shrinkage. The AM operator should advise on the management of CAD model and heat treatments used in this process. Materials available include Aluminium, copper, stainless steel, tool steel, copper bronze amongst others.

B.2 Process guidance and notes for SLM

The guidance provided in Annex **B** establishes the manufacturing process options and procedures for the manufacturing of metallic components using the SLM process on Realizer production technology.

B.3 Considerations for metal AM

B.3.1 AM design for metal AM

The 3D CAD drawing of the component design may be designed by the customer or the AM operator or another provider. File formats are described in Clause **4**. The CAD file is examined for suitability in its present format for production by the metal AM process. The CAD file is uploaded into AM software to determine the best part orientation and support strategies.

B.3.2 Build supports

Layer by layer AM manufacture can offer design freedom to produce complex components. Most metal AM systems utilize build supports to anchor the part to the build platform, to support

overhanging areas of the parts as well as internal supports within channels and hollows and to provide heat sinking of the part. The component may be built directly onto the build platform if the component is removed by wire erosion.
Overhanging areas such as two faces meeting at right angles need build supports to form this part; inclusions of chamfer areas may avoid the need for these build supports. Internal square or rectangle channels whose side is parallel to the build platform would also require build supports within the channel that may not be removable after the build.
Build supports would not be required if the square channel was rotated 45° and build on point. Round channels of smaller dimensions may be built without supports in some AM systems, the AM operator can advise on where the build supports are required in the design, to suit optimized orientation and if the design needs to be altered to avoid build supports in inaccessible areas for post-build removal.

B.3.3 Surface finish

Generally, the surface finish of an AM metal part as built is rougher than one produced by a subtractive process, for example CNC machining. Designers should determine if they require a machined finish, e.g. surface roughness (Ra) of <3 µm, on any surface that is accessible post-build and indicate this prior to build. The surface roughness on a metal AM part varies over the part and is dependent on the orientation of each facet in the build, the material used, the layer thickness and laser settings used to produce the part. Surface roughness acts as a stress concentration therefore affecting the fatigue life of the part which changes with any subsequent post-processing.

B.3.4 Tolerances

The AM operator provides the tolerance suitable for different materials. AM metal components are built with the outside edge larger than the CAD file and the inner surfaces smaller than the CAD file therefore the tolerance given may be a larger range. The AM provider should be able to advise whether closer tolerances can be achieved per component. Holes requiring subsequent drilling and/or tapping should be clearly defined prior to the build.

B.3.5 Powder removal

For enclosed light weighted areas a powder removal system is required to remove the unmelted powder from enclosed/lattice filled spaces. Loose powder within the part is removed by the operator. The method for removal of powder is to be included, as failure to remove the powder increases the part weight. Powder removal holes/systems are welded shut after powder removal. Loose powder can consist of unbound powder particles, and partly fused particles. Some partly fused particles may be dislodged when the part is in use, so care should be taken to ensure that all powder is removed by the use of ultrasonic cleaning or other methods, especially for food, healthcare and other applications. Higher part complexity may increase the difficulty in dislodging powder in semi-enclosed or small spaces. Ultrasonic cleaning methods may be used to remove loose powder in complex parts. For further sealing of the part another abrasive or chemical post process such as grit blasting may be considered.

B.3.6 Build volume

The AM operator provides the size of the build volume available. The build platform, also known as the build plate, is made from the same material as the metal powder used. Some metal AM processes, such as SLM, can build one ‘layer’ of components and others, such as EBM, can build multi layers of parts and fill the whole build volume. The AM operator can provide the optimal number of parts per build for their AM process.

B.3.7 Part orientation

As a general rule of thumb, a part is orientated to maximize the self-supporting parts of the component, i.e. without build supports. The AM operator orientates the part to suit their AM process, minimizing the number of additional build supports required. Part orientation can also be dependent on surface finish requirements for certain surfaces and internal channels.

B.3.8 Part density

The final density of metal AM components is dependent on the AM process used as well as the machine settings used by the AM operator. Discussion between the designer and AM operator can ensure that there is no effect on the part design. In general, component density may be from 95% to more than 99% dependent on the AM process used. The AM operator should advise on the part density of the different materials they use. Metal AM part density can also be decreased to produce components with lower part densities (e.g. porous metal/metal foam).

B.3.9 Multiple parts assembly

Build volumes vary between different SLM AM machines from small (50x50x80) mm to large (>2 m long). Parts which are larger than the available build volume may be sectioned into segments and then welded together to form the final part. The AM operator can advise on part separation points taking into consideration customer defined critical areas. Inclusion of alignment markers or tabs on the different component parts allows for ease of assembly.

B.3.10 Part marking

Identification marks or other symbols can be included in the part design and can be either embossed or debossed. Part production series marking should be agreed prior to production.

B.3.11 Post-processing

The following treatments should be considered:

a) Heat treatment

During metal AM, heat generated from the melting of the metal and its subsequent cooling results in stress within the AM component. Heat treatment can relieve this stress. Some materials require heat treatment following the build, while others do not. The heat treatment procedure required to alleviate the stress of different materials and to develop the required material microstructure/performance is set out in published standards. Hot isostatic pressing (HIP) treatment can reduce porosity and close non-surface penetrating pores. The AM operator should be able to provide details of any heat-treatment performed on the AM part.

b) Surface treatments

AM customers should detail any post-processing requirements (e.g. synthetic oil only if post-machining, or surface finish required for further treatment or process). The AM provider may offer different surface finishes and should be able to provide their available specifications. Specialist finishing companies may provide further finishes.

For metal AM the component may be supplied as built, where build supports have been removed and no further finishing has been employed. The overall colour of the parts is dependent on the material but in general is not shiny, rather a dull colour. Sand blasting or bead blasting can reduced the overall surface roughness of accessible surfaces. Parts may be supplied in either of these basic finishes.

Some critical surfaces may be machine finished (e.g. CNC, finishing depending on the accessibility to the surface in complex components). Mass finishing can be employed to reduce surface roughness including high energy and low energy processes to remove material and polish. Internal surfaces, such as inside channels, may not be as efficiently finished in these processes compared to external surfaces. Guidance should be sought as to the finish required by the end user and agreed with the AM operator or other service provider.
Other surface treatments may be used including electropolishing, or coatings etc. Advice should be sought if the metal AM components are to receive a post-processing process that may be affected by other post-processing (e.g. the use of mineral or non-mineral oil).

B.4 DfAM - Component design

The considerations outlined in **B.3**, as well as the requirements for subsequent testing of final component influences the final design of the 3D component. Specialized software can be utilized to optimize the design for lightweighting and stress and simulate the part for finite element analysis etc. as well as for production by AM. Most AM operators are able to advise on the suitability of the part design for their AM system and any areas which require alteration to suit AM.
NOTE Further information is available from:
https://www.d4am.eng.cam.ac.uk/publications/ProjectReports/D4AMLiteratureReport [4].

B.4.1 Lead time

In general, lead time is dependent on AM machine workload, build time, and post-processing time including finishing and delivery. For production runs of multiple parts the AM operator or supplier can advise on optimum number of parts for production run(s) and lead time.

B.4.2 Intellectual property (IP)

A non-disclosure agreement should be set up between all involved parties if required. Component designs created by the AM customer remain the IP of the designer. AM process methods remain the IP of the AM provider. Discussion of IP concerns and ownership should be discussed at the beginning of the relationship. Consideration should be given to the management of CAD files including the storage, transmission, and version control to prevent loss or alteration.

B.4.3 Start of process

The AM provider should provide the customer with an outline of available materials, AM process and build volume. The AM customer should discuss part specifications and post-processing requirements. A non-disclosure agreement may be sought before specific information is passed between the parties.
The AM end user should be advised of the AM provider's preferred CAD file formats and the CAD file is sent for initial assessment of the suitability of the design to be produced by metal AM process. The AM provider should discuss any design changes that might be required for the part to be produced. Any file defects or resolution issues may be identified at this stage.
If no 3D CAD drawing is available the AM provider may provide the service of drawing the 3D CAD design from a 2D drawing with specifications. For reverse engineered parts the original worn part

could be scanned or measured to produce a 3D CAD file and this file adapted to reflect the part prior to wear and tear or original drawing specifications.

B.5 Part specifications

B.5.1 Engineering drawing specification

This drawing may include the items listed in Table B.1.

Table B.1 – Engineering drawing specification elements	
Item	**Supporting information**
Material specification	Material data sheet.
Part dimensions	Hole diameters, tapping requirements etc. should be stated.
Surface finish requirements	Critical surface roughness requirements should be detailed.
Test requirements	Any mechanical testing to be performed on component, build test coupons etc.
Inspection requirements	Visual, mechanical ultrasonic etc.
Part marking requirements	Details to be included.
If the part has been previously manufactured by AM:	
Build orientation of component	As previously built, which may also include build supports.
Layer thickness	As previously built.

B.5.2 Development of specification

The AM provider and customer should discuss the requirements. Feedback of part specifications and the AM capabilities for the chosen material and AM process could be given to further define the part specifications.

If the AM tolerance range initially offered is to be smaller, a part development service may be offered by the AM provider where a specified number of parts are produced in series to determine the achievable specification range. This may form part of a pre-production run process that would define AM machine settings, build orientations and supports as well as post-processing operations.

The AM provider and AM customer may review design changes and part specification development several times prior to production runs.

B.6 Part production

B.6.1 AM process control documentation

The documentation for process control required should be discussed between the customer and the AM operator. The customer should define any industrial sector requirements, component specifications, finish, testing, inspection, component marking requirements and material specification. The AM operator should be able to supply documentation relating to their management of the AM process which may include the AM equipment used, equipment maintenance, build platform, build volume, part orientation, process post-processing, inspection equipment, build environment, powder handling and management, build set up, training and procedures, quality assurance and health and safety requirements. The amount and nature of the documentation required to be supplied between the parties should be agreed prior to production.

B.6.2 Material

Details of the AM metal powder material specification should be given. Material certificates may be available. For post-processed material data sheets may be available. For within-production material data may be produced by the building of testing coupons for tensile strength, hardness etc.

Customers may request details of the AM providers' material testing process to establish process control. AM providers may provide production run test coupons as part of large production run processes. Making standard tensile specimens can provide a guide as to the material/build performance. Customers should request further information if required.

B.6.3 Powder management

Powder management documented processes may include the powder storage, the use and reuse rate, and volumes including added, used, recycled, and waste. Powder handling processes include the health and safety management and procedures for movement of powder and the conditions that the powder is maintained in the machine. In addition, all powder handling should follow the material manufacturers' guidance to prevent explosive risk and suitable PPE for prevention of health hazards.

Powder management processes include the sieving and recycling of unused powder, powder removal from the machine and subsequent powder removal from the completed parts and waste disposal. Material management processes include measurements to demonstrate that the material is within specification and may include sieving and composition changes,

B.6.4 Powder cycle

Powder delivery systems vary between different AM machines. During the build within each layer added, some of the powder is fully melted to form the build and anchor supports and the component. The remainder of the powder remains unmelted. After the build is complete the excess unmelted powder is removed from the build volume. It is usually sieved to remove oversized metal particles and particles that are within the powder particle size range are returned to stock. The AM operator determines the number of use cycles that the powder undergoes.

B.7 AM machine process control

The AM machine is serviced and maintained as per the manufacturer's guidelines. Calibration and maintenance should be carried out by relevant service providers. AM providers should be able to provide documentation of their health and safety measures, standard operation procedures for maintenance, operation, validation builds and cleaning.

B.8 AM build specifications

The AM operator should keep a record of the information listed in **B.8**. Which information is supplied to the customer is agreed between the parties. For production runs of parts the information should be included in the production process control documentation for the component to ensure that a repeatable build is possible.

- **File version:** The initial CAD file is altered by the AM operator in order to deliver part specifications. This may include the addition of material for attachment to the baseplate and subsequent removal from the build platform and removal of anchor supports. The dimensions of holes and or channels may be altered for post-processing (e.g. drilling of holes, channel dimensions etc.). The dimensions of the part may be altered to reduce the tolerances in the final part. The correct file version should be noted and any changes made from the original recorded.

- **Component build details:** The build orientation should be optimized and recorded. The required build supports are added and the final part with supports, sliced using the appropriate software at the required layer thickness. The position on the build platform for each component should be noted in the x,y and z planes. Machine settings and software versions used for each component should be recorded.
- **Build testing coupons:** The type, orientation, and position on the build platform should be recorded. Testing process documentation for each type of coupon.
- **Powder removal:** The methods for powder removal from the build platform and components are described in the AM process documentation. Customer specific requirements should be noted and followed.
- **Heat treatment**: Details of the heat treatment employed should be recorded for each material.
- **Removal from build platform:** The method used to remove the components should be recorded.
- **Post-processing**: If the part is to be machined the customer provides information on use of synthetic or natural fluids. Methods and materials used in sandblasting or similar, mass surface finishing or any other treatments used is recorded.
- **Quality assurance:** For part specifications an agreed number and specific dimensions are measured for the component and these noted. For batch production runs an agreed specified number of components are to be inspected. Measurement methods are defined and measurements carried out per the process method.

B.9 AM machine parameters

B.9.1 Build volume

Build volume is the volume of the build space in the build chamber. AM machine types can offer build volumes from small (60x60x80) mm, medium (250x250x300) mm to large (800x400x500) mm.

B.9.2 Build chamber

Metal systems build chamber environment is usually argon or nitrogen filled with <0.1% oxygen and is heated to a temperature to suite the metallic material being used.

B.9.3 Metallic powder

SLM AM systems employ metallic powder with different sized particles typically (15-45) µm, and the size range and distribution can vary between materials and different AM processes. The combination of small, medium and larger powder particles allows for the powder to pack together closely in each powder layer. Materials include stainless steel, tool steel, aluminium, titanium, Inconel, brass, and other alloys.

B.9.4 Layer size

The layer size is typically 50 µm thick, out of an available range of (20-100) µm. Some AM processes can offer layer thickness of up to 200 µm. The AM manufacturer can advise on the optimal layer thickness for individual components. Generally, decreasing layer thickness increases the overall build time and increased layer thickness decreases build time. Layer thickness also affects the surface roughness.

B.9.5 Build time

The build time is made up of a combination of the time to lay down each powder layer, laser scanning time per layer, machine set up and cool down and removal of build platform from the machine.

B.9.6 Machine settings

For SLM machines the amount of powder melted by the laser in each component layer can be altered by changing the laser settings in open source AM systems. AM machine manufacturers should give guidance on the different laser settings to be used for different materials.

The following settings should also be considered:

- **Laser power** – power settings are usually available in a range and are dependent on the laser type used as well the operational range suitable for each material.
- **Laser spot size** – the diameter of the laser at the point of contact with the powder layer. In general, spot size can range from (20-100) µm but the range can vary between machine types.
- **Laser spot distance** – the distance between successive areas of activity. This defines the overlap between areas melted by the laser. Alterations in spot distance can alter the amount of melted areas of weldpool overlap. The range is typically 20 µm.
- **Boundary or outline** – the laser settings can include a boundary or outline where the laser follows the outside edge of the component area to be melted. It can be included or omitted depending on component specifications and can alter the surface finish of the part.
- **Hatching** – the strategy that the laser follows to fill in the central area of the component within the outline or boundary. Hatching strategies include furrow where the laser path moves in straight lines, or in alternate directions like a furrowed field, and checked where the laser action fills in alternative squares in a different sequence. These different strategies are employed in order to reduce the heat generated in localized areas within the layer to reduce the overall heat stress in the part.
- **Build supports** – some AM machines allow different laser settings to be used for different build supports during the build.

B.10 Part production stages

The AM operator and customer should discuss and agree the following points:

- Materials available for metal AM and AM process outcomes, such as tolerances and surface finishes.
- Availability of CAD drawing of part, CAD formats and the suitability of initial CAD design for SLM AM.
- The need for a non-disclosure agreement and review of IP, if applicable.
- Customer defined part specifications and critical features such as tolerance on certain dimensions, surface finish on critical features, hole and tapping requirements, post-processing and documentation requirements.
- AM operator feedback on CAD design suitability for AM, ability to meet part specifications and post-processing requirements, cost and lead time.
- Sample production service for part validation prior to a large production run, which the AM operator may offer to complete.
- Quality assurance, including criteria for dimension measurements and number of samples for part validation.

- If necessary, contents of the process control documentation required to suit industrial compliance.

Following discussions the AM operator proceeds to:

- Define the optimal build orientation and build supports required to manufacture the part. For a production run, they define the optimal number of parts for the build platform, and record the part volume dimensions and position(s) on the build plate.
- Select the AM machine parameters settings for the part(s), slice CAD model and hatch with relevant software and upload to the machine. Proceed with build, using standard operating procedures and record all relevant process details.
- Remove excess powder from build platform, perform the relevant heat treatment process, remove parts from build platform and build supports. Post-process parts as per customer specifications and perform quality assurance.
- Despatch parts to the customer with agreed documentation, e.g. Certificate of Conformity.

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