4.1 Introduction

Imagine a component that is so convoluted and with such intricate detail that it would be impossible to manufacture, or impossible to manufacture in one go. Figure 4.1 illustrates the problem; machining this out of a solid would simply not be possible. Precision casting by a process in which the mould can be burnt-off or removed mechanically might do the trick but would involve many manufacturing steps and considerable skill. It could be made in parts and then joined together to create the overall shape followed by intricate machining to get the dimensions and surface topology as required. All this amounts to a nightmare, great expense and a lot to time to achieve the finished product.

Now conduct a thought experiment in which the object is cut into thin, parallel slices without any loss of material. The patterns in each slice are captured on a computer, which then is used to drive a metal-printer which recreates each slice, overlays them in sequence, resulting ultimately in the three-dimensional shape in more or less its final form. This can be repeated as many times as is necessary. This algorithm can itself be digitally created using engineering design tools. It is important to realise in this process, that the method used for printing is less important than achieving the shape and properties in the final structure.

A simple chess piece, the castle, can be made much more elegant and desirable if it contained structure within, rather than just a solid lump illustrating the concept of a castle. Figure 4.2 shows how the 3D printing process can create internal features with re-entrant angles that would be impossible to make by any other process with the precision required. The chess piece suddenly becomes an item that enthrals. The skill in making this object is first in creating the concept, then in expressing it digitally and in choosing the right material for the job, in this case a ceramic which communicates rigidity and quality which a plastic in general would not. Furthermore, the chess piece is unlikely to be subjected to stresses and strains, so a metal is not necessary either.
Fig. 4.1 An abstract metal object that is made depositing thin layers on top of each other in a sequence that reproduces the desired shape.

Fig. 4.2 The ceramic chess piece that is a castle, with a spiral staircase leading to the battlement, accompanied by a spiral hand-rail at the centre.

An additive manufacturing facility can in principle switch at a moments notice to the production of a different part once a digital design is available. This can have life-changing consequences. The COVID-19 pandemic led to a massive shortage of components for ventilators and equipment for the protection of medical staff. AM facilities in many parts of the world switched to the production of these vital goods, sometimes with innovative design features. In fact, the rate limiting factor was not the ability to manufacture but to get approval for the use of equipment in medical scenarios.
The International Space Station is resupplied at regular though long intervals compared with the normal shopping practices on Earth. When a ratcheting socket wrench was required, a digital file was sent electronically by NASA to a desktop AM machine located in the orbiting space station. The machine then built a wrench including the movable parts, all in one piece, layer by layer in 104 layers from polymers. On completion, an astronaut simply retrieved the wrench and used it with good effect, Fig. 4.3. This was the first time an object designed on Earth was manufactured in space.

Metallic foams are used in sound damping, to provide rigidity in structures and have an advantage over polymeric foams in that they resist fire. They can form substrates for gaseous reactions. Their density can be less than that of water. Some applications require specific pore-geometries which present ideal opportunities in additive manufacturing. Figure 4.4 shows an open-pore metallic foam created in this manner. A metallic hollow-sphere is also illustrated—such spheres can have enormous specific strength (strength divided by density) so they can be used in lightweight construction with the advantage that additive manufacturing permits the design of such spheres as opposed to the acceptance of geometries limited by conventional manufacturing processes.

Figure 4.5 shows the distribution of revenues from consumer products, automotive, health care, aerospace, marine and other industries. The viability of these products in the context of AM depends on the ability to manufacture more easily than using conventional methods. Nevertheless, if the component is sufficiently sophisticated, then it becomes possible to manufacture it more rapidly than conventional methods given the avoidance of excessive machining, assembly and inspection.
Fig. 4.4  Additively manufactures metallic hollow-sphere and open-pore foam

Fig. 4.5  Examples of metal printing in diverse industries. Each colour indicates an industry sector, i.e., consumer products, automobile, health care and other industries. The pictures represent a part in an industrial sector. For example, GE’s fuel nozzle is a part used in aerospace industry. The revenue from all printed parts in the aerospace industry is 13% of the total revenue of all metal printed parts from all industrial sectors. Currently, the revenue generated by metal printing is growing but small compared with the total manufacturing industry [2]

4.2  Advantages and Disadvantages

Some of the aspects of the additive manufacturing process have been described above, but it is useful to present the big picture before dwelling into detail, Table 4.1.
| Advantages                                                                 | Disadvantages                                                                                           |
|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| Complex shapes that are difficult to produce by conventional manufacturing processes can be printed | Productivity is limited because components are created in a stepwise manner. Resolution is limited by this step size (defined by powder size, layer thickness), both in the raster pattern and the thickness of the two-dimensional slice |
| Economical use of material given that final finishing of the product is all that is required | Surface roughness can present challenges—for example, the cooling channels in jet engine turbine blades can be less than 1 mm in diameter |
| Relatively small capital investment in manufacturing equipment             | High productivity requires banks of printing machines                                                  |
| Ability to rapidly switch to production of different components           | Residual stresses and distortion can compromise metallic components                                    |
| The print-on-demand model can be implemented                              | Limited availability and limited variety of metallic powders or wires at affordable cost. In contrast, the alloys available for conventional manufacture have many orders of magnitude greater variety and lower cost |
| Customised parts can be produced without new tooling or equipment         |                                                                                                        |
| Functionally graded components possible by using different “inks” during the creation of a single component | Structural integrity of critical metallic components is difficult to achieve.                             |
| Rapid prototyping                                                         | Metallic components usually have less than 100% density                                                |

### 4.3 Metal Printing Processes

The heat sources required for metal deposition include continuous-wave carbon dioxide lasers, solid-state Nd:YAG lasers, Yb fibre lasers, electron beams and electric arc. Alloy powders or wires are commonly used as feedstock. A moving heat source melts an alloy layer by layer which subsequently solidifies. The trajectory of the heat source is determined from the algorithm for the part to be manufactured.

In the powder bed fusion process, shown schematically in Fig. 4.6a, the bed is lowered by a small distance after each layer is deposited, a roller spreads a thin layer of powder over the part and its surrounding area before another layer of the alloy is deposited with the help of a laser or electron beam [3]. In the directed-energy deposition system shown in Fig. 4.6b, the powder is supplied by a powder feeder co-axial with a laser beam. Both the laser beam and the powder feeder move relative to the part. The powder particles are heated during their flight and after they impinge on the part. After each layer of metal is deposited, the substrate is lowered slightly so that the distance between the heat source and the deposition surface does not change. A laser beam, an electron beam, or an electric arc can be used as a heat source.
source for the directed-energy deposition process. Either a stream of powder or a wire feed can be used to build components.

Table 4.2 shows the main features of the common metal printing processes which can help select the optimum method for the intended component. They all take considerably longer times to build parts than casting or injection moulding. A larger powder particle-size or wire diameter limits the resolution possible, making it more difficult to achieve fine features. The powder bed process uses finer powders to deposit intricate features; greater scanning speeds are also possible compared with the direct energy deposition method. Consequently, the powder bed fusion method is associated with less heat input per unit length of the deposit, the layers are much thinner, and they cool much faster. Smaller laser spot diameters and finer powders allow better control of geometric features in the parts. Slower deposition rates produce improved surface quality using thinner layers at the expense of productivity.

When large parts are made they tend to retain heat for a longer duration and the cooling rates are relatively slow. Often, items larger than $30 \times 30 \times 30$ cm are produced in near net-shape by melting of a wire followed by machining. High
deposition rates are achieved by simultaneously using two wire electrodes. Wire based techniques that use welding power sources are gaining popularity, partly because of the ready availability of wires that would normally be used in welding technologies.

4.4 Uniqueness of Printed Parts

The printing of metals is attractive because it can produce components that cannot be easily and economically produced by conventional manufacturing. Jet engine fuel nozzles are now made routinely in a custom-designed factory [4]. In the past, each fuel nozzle was an assembly of about twenty individual parts. They are now partially manufactured by laser melting of alloy powders, layer by layer, in 20 µm thin layers (one-fifth of the thickness of a human hair). The fuel nozzle, shown in Fig. 4.7a, reduces the number of assembly steps required and it is claimed to be five times as durable as the conventional nozzles.

Metal printing offers additional opportunities to create components with site specific chemical composition and properties. The nuclear industry often uses joints between steel and nickel alloys, the latter being more resistant to elevated temperature exposure. An abrupt change from one to the other causes huge changes in the vicinity of the joints, in particular, the partitioning of carbon on to the steel side where it locally embrittles the structure. This abrupt change can be mitigated by designing a joint where the chemical composition varies gently from the steel to nickel alloy. This can easily be achieved using directed energy deposition to create a compositionally graded joint as illustrated in Fig. 4.7b. All that is needed is to feed different proportions of the component powders during deposition.

![Fig. 4.7](image)
(a) (b)

**Fig. 4.7** (a) The tip of the GE jet engine nozzle made by the AM process [4], made by laser powder bed fusion, in one step. (b) Compositional profile of a functionally graded joint between a nickel alloy 800H and a Cr–Mn steel [5]. The points are measured values of concentrations in layers directly deposited using a laser as the energy source. Image adapted from [5] with the permission of Elsevier
Metal printing now routinely makes customised products such as patient-specific implants and legacy products where the supply chain no longer exists.

4.5 Underlying Principles

The physics associated with additive manufacturing process affects the microstructure, properties, and the ability to service the manufactured components. Metal printing involves heating and melting of the feedstock, followed by solidification of the liquid and then cooling in the solid state. In the direct energy processes, the feedstock receives heat even before reaching the build surface and may absorb heat during flight before impinging on the deposition surface, which also receives heat directly from the source. The powder or wire therefore melts quickly and the molten pool is propagated along the predetermined track.

The highest temperature on the melt pool surface is attained directly below the heat source and then decreases with distance from this location. Surface tension is a function of temperature so its variation with position creates the so-called Marangoni stress on the surface of the molten pool, which makes the liquid move from regions of low to high surface tension.

The three-dimensional flow of liquid metal in the pool is important because it affects both the dissipation of heat and the mixing of the feedstock with the molten metal from the pre-existing layers. However, it is difficult to determine the motion experimentally since liquid metals are opaque and the pool is small and moves rapidly. A recourse is to simulate metal flow by numerically solving the equations of conservation of mass, momentum and energy with initial and boundary conditions [5, 6]. This approach of simulating liquid metal velocities in a computer rather than by direct experimental measurement is widely adapted in engineering practice. Most of our current knowledge of the flow of liquid metal in AM originated from numerical modelling. Figure 4.8a shows the computed flow pattern inside a molten pool during powder bed fusion. The liquid metal moves away from under the heat source to the periphery of the liquid pool, turns around and recirculates. The speed and orientation of circulation determine the extent of convective heat transfer and the mixing of the hot and the cold fluids in the pool.

The circulation pattern obviously influences the temperature distribution in the liquid alloy, its heating and cooling rates, solidification pattern, and the evolution of various solid phases that make up the microstructure. The solidification morphology, grain structure and the phases that form define the microstructure and the mechanical properties of the printed component.

An important consequence of building parts layer by layer is the temperature excursion that each location of the part experiences. Unlike most other materials processing operation, in AM each location of the part experiences multiple temperature peaks. For example, Fig. 4.8b shows the computed thermal cycles at various monitoring locations inside a part. Temperatures at the mid-height and mid-length of several layers are shown as a function of time. The first temperature peak
corresponds to a position of the laser beam just above the monitoring location. The subsequent peaks occur during the deposition of the upper layers. So, at each location, the microstructure and the grain structure of the alloy that forms after the first thermal cycle are often changed by the subsequent thermal cycles depending on the specific temperatures and times. These thermal cycles affect the evolution of microstructure and the eventual mechanical properties of the part.

The substrates used in AM are effective heat sinks. As a result, the peak temperatures attained in the lower layers close to the substrate are somewhat lower than those in the upper layers [6]. In the upper layers the distance from the heat sink increases and the peak temperature rises because of the reduced heat loss. So, the thermal cycles are inherently spatially dependent. An important consequence of this result is the microstructural asymmetry of the part. Since the structure affects properties, the properties may also be inherently different at different locations. Each location in the component experiences multiple thermal cycles and phase transformations, grain growth, residual stresses, distortion that affect the mechanical properties of the component.

4.6 Evolution of Structure and Properties

The structure and properties of alloys depend on their thermal histories that are affected by many variables such as the scanning speed, power, power density, scanning pattern, part geometry and the thermo-physical properties of the alloy. All these variables affect heat transfer within the part, which control temperature profiles and cooling rates. Given the many causative variables and their wide range of values, it is no surprise that the cooling rates reported in the literature for the
printing of a stainless steel in Fig. 4.9 show a wide range as a function of processing variables [2]. The heat input, i.e., the energy deposited per unit length, has a seminal influence of the cooling rate. The wide range at the same time provides an opportunity to customise the cooling rate for specific properties. The cooling rate may not of course be uniform throughout the component, which will lead to corresponding variations in properties that must be taken into account in the design process.

The morphology of the solidification structure is affected by the temperature field, which in turn depends on the scanning pattern used during deposition. Consider the two scanning patterns, one where the heat source travels along the same direction, i.e., always scanning from left to right and another where the direction alternates between left to right followed by right to left, in the context of the deposition of a nickel base alloy, Fig. 4.10 [7]. Solidification occurs by the epitaxial growth from the substrate of columnar dendrites, with growth direction influenced by that in which heat flows, which in turn depends on the scan pattern. The orientation of the dendrites is identical in all layers when the scan direction is maintained constant. In contrast, alternating the scan direction causes corresponding changes in the dendrite orientations between adjacent layers [8]. The orientations of crystals are important in determining properties because if they are all similarly oriented, they may not, for example, have the same fracture properties as when they are differently oriented (i.e., differently textures). Therefore, the deposition sequence matters as illustrated in Fig. 4.10. There are other properties, such as hardness, that are influenced by the chemical composition of the deposit. If the composition of a particular class of nickel alloys is expressed empirically in terms of a single parameter $\phi$:

$$
\phi = w_{\text{Ni}} + 0.65 w_{\text{Cr}} + 0.98 w_{\text{Mo}} + 1.05 w_{\text{Mn}} + 0.35 w_{\text{Si}} + 12.6 w_{\text{C}} \\
- 6.36 w_{\text{Al}} + 3.80 w_{\text{B}} + 0.01 w_{\text{Co}} + 0.26 w_{\text{Fe}} + 7.06 w_{\text{Hf}} + 1.20 w_{\text{Nb}} \\
+ 4.95 w_{\text{Ta}} + 5.78 w_{\text{Ti}} + 2.88 w_{\text{W}}
$$
4.6 Evolution of Structure and Properties

Fig. 4.10 Influence of heat source travel direction on the growth pattern of primary dendrites in nickel alloy [7]. (a) Dendrite growth direction when laser beam traverses left to right for all layers. (b) Computed dominant heat flow direction corresponding to (a, e). (c) Alternating dendrite growth direction as the scanning orientation reverses in successive layers, with corresponding information in (d, f)

Fig. 4.11 The dependence of Vickers hardness on chemical composition of nickel alloys. Various processing conditions were used. For details and the limitations of the analysis, see [7]

where $w_i$ is the weight percent of solute $i$, then $\phi$ is found to correlate strongly with the hardness of the deposit, Fig. 4.11. An exciting opportunity will arise when sufficient data on additive manufacturing are openly available so that they can be subjected to machine learning techniques to reveal quantitative patterns that can be used to make further advances. Such work has been developed using neural networks, for the powder bed fusion based on electron beams as the energy sources, to estimate the strength of the deposits [9].
4.7 Defects and Other Challenges

Porosity, lack of fusion, solidification cracking, residual stresses and distortion are issues that need to be improved upon for the qualification of printed parts. When alloys contain volatile elements, some might selectively evaporate leading to uncontrolled changes in the intended chemical composition.

Several mechanisms are responsible for the porosity formation. The feedstock may contain dissolved gases that are evolved during solidification to form small, spherical pores. In the powder bed fusion process, gases present in the inter-particle spaces may become entrapped. The very high-temperature vapour zone beneath an electron or laser beam may collapse due to instability of the power density or local changes in powder packing, leading to porosity when solidification occurs after the beam has left the locality.

Adjacent layers of deposit may not fuse together if the fused region does not penetrate the surface to a sufficient depth. Insufficient overlap between adjacent tracks in the scan or between layers may leave unmelted regions in between. So the appropriate choice of deposition conditions is vital to ensure a dense solid, and the conditions may differ with the types of material deposited. Figure 4.12a shows macroscopic defects that arise during the powder bed process due to a lack of fusion during deposition. In Fig. 4.12b, successive layers separate because the thermal contraction stresses that are not homogeneously distributed exceed the strength of the interface between the layers.

Solidification cracking occurs when the tensile stress due to volume shrinkage associated with the liquid→solid transformation, is such that during cooling, the shrinkage stresses exceed the strength of the solidifying region the elevated temperatures involved. The composition of the alloy, geometry of the deposited bead and scanning speed can all affect this type of cracking. Irregular cracks, up to a few millimetres in size can be generated. This type of cracking depends on the chemical composition of the alloy, particularly when it contains impurities such that the temperature range over which a mixture of solid and liquid is extended.

![Figure 4.12](image-url) (a) Lack of fusion defect in a nickel alloy during powder bed fusion [8], reproduced with permission of Elsevier. (b) Delamination in stainless steel deposits during powder bed fusion using a laser heat source [10], image courtesy of the University of Texas
Table 4.3 Important variables that affect distortion of components additively manufactured. Other factors such as the gap between successive layers, periodic stress relief and the volume change of transformation also affect the development of residual stress

| Variable | Mechanism | Remedy |
|----------|-----------|--------|
| Heat input, i.e., the power of the heat source divided by the scan speed | Larger heat input results in a greater pool of liquid and greater temperatures. Non-uniform cooling results in shrinkage and distortion | Reduce heat input. Smaller liquid pool results in reduced shrinkage and distortion |
| Temperature coefficient of volume expansion | Larger volume shrinkage during cooling makes an alloy more susceptible to distortion | Thermal management to reduce peak temperature and cooling rate |
| Rigidity of the alloy and constraint | Rigidity describes the ability of material to resist deformation, the product of stiffness and geometric factors | Higher stiffness of a material and/or a thicker plate can resist distortion |

Residual stresses are those that exist in a body even at equilibrium. They evolve during spatially non-uniform heating and cooling of the metal, thermal expansion and contraction, phase transformations and uneven distribution of plastic strains. Mitigation strategies include control of the substrate preheat temperature, shorter deposition length or scanning in smaller bits, more rapid scanning and thinner layers. A large preheat temperature can also be helpful in preventing solidification cracking. Table 4.3 lists a few methods to reduce the effects of residual stresses.

Most engineering alloys typically contain one or more volatile alloying elements. Manganese and chromium in stainless steels, magnesium and zinc in aluminium alloys and aluminium in titanium alloys are examples. Their selective evaporation changes the chemical composition, which may or may not be an issue. A reduction in peak temperature by selecting an appropriate power distribution pattern, higher heat source power that results in smaller surface-to-volume ratio of the molten pool, and faster scanning speed will minimise the problem.

4.8 Concluding Remarks

A distinguishing feature of additive manufacturing is its ability to create internal features such as cooling channels within an otherwise solid part. If deposition leads to distortion and surface roughness, then these internal features may not be as intended in the original design. A smaller liquid pool size with lower heat input can often help, but this must inevitably reduce productivity and increase cost.

Additive manufacturing is obviously a layer-by-layer process, so curved surfaces are approximated in a stepwise profile. A smaller step size is needed for a smoother macroscopic curvature, but it may ultimately be necessary to smooth the surface.
mechanically. Tiny metal drops and unmelted or partially melted powder particles ejected from or near the fusion zone (i.e., spatter) by high-speed metal vapours and gases, often land on the build surfaces and contribute to roughness. Large unmelted powder particles or “balls” are often found at the edge of the molten pool. High heat input may reduce the severity of the problem by melting large particles, but small powder particles also result in a smoother surface. Powders as fine as 20 µm have been used to ensure a better surface finish.

The scientific challenges include the interrelation between processing, microstructure, properties and performance, microstructure control, minimisation of defects, and poor solidification and grain structure. A better understanding can eliminate some of the trial-and-error used in fixing AM parameters. Similarly, rapid qualification of parts, overcoming geometric limitations, scaling-up, printing sequence, and the health and safety concerns of handling fine metal particles, are examples of technological problems. Commercial challenges include cost competitiveness, availability of feedstock and a need for standards.

To facilitate more rapid printing of large parts, multiple heat sources and wire feed mechanisms are explored, together with hybrid methods that use a combination of manufacturing technologies.

### 4.9 Terminology

| Term                              | Description                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------|
| Alloycling elements               | Elements in an alloy added to enhance its properties.                       |
| Columnar dendrite                 | Columns of tree like solid structures that form during solidification of liquid alloys. |
| Conduction                        | Mechanism of heat transfer in a stationary solid or liquid due to temperature difference. |
| Convection                        | Movement of liquids or gases. If hot gases and liquids are in a motion, they can carry significant amounts of heat with their motion. |
| Electron beam                     | A stream of energetic electrons capable of heating and melting alloys in a focused area. |
| Epitaxial growth                  | Atomic arrangements of a new growth layer conforming to the structure of the existing layer. |
| Laser beam                        | A device that can emit an intense beam of light through stimulated emission of radiation. A focused laser beam can melt and vaporise alloys. |
| Marangoni convection              | Flow of liquids from low to high surface tension regions.                   |
| Microstructure                    | The magnified pattern of a surface observed using a microscope.             |
| Solidification morphology         | Shape of the solids that form from the liquid alloys.                       |
| Surface tension                   | A measure of how closely molecules on the surface stick to each other.       |
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