

Picture to parts, one thin metal layer at a time

Wouldn't it be nice to be able to make an intricate part, true to its drawing, in one step without having to assemble multiple components? Is there a sensible way to produce just a few customized parts soon after the design is completed without having to set-up any new equipment? And, can it be produced on demand without having to train a new workforce?

Engineers have dreamed of these exciting possibilities for many years. Today, additive manufacturing (AM), a process of building a part from its drawing, one thin layer at a time, layer-by-layer, enables engineers to realize these lofty goals in many cases. The process of manufacturing three dimensional parts from a computer picture file, often referred to as 3D printing or AM, has been around for about 20 years, but has attracted considerable interest in recent years. Widespread availability of low cost home printers for polymers, the advent of commercial AM systems for metallic materials and government incentives for advanced manufacturing are thought to be contributing factors for its recent surge in visibility. AM is particularly useful for making intricate parts or components requiring spatially variable chemical composition that cannot be easily made any other way. In the current manufacturing processes it is unthinkable to make complex new parts without any additional capital investment or highly trained man power. By overcoming these limitations, additive manufacturing has opened up a new exciting paradigm of manufacturing. Its potential for disrupting the current manufacturing paradigm is so compelling that numerous major newspapers and magazines from Economist to Forbes to Business Week to Guardian in England have covered it with huge enthusiasm. AM is already used to make parts from a variety of polymeric and metallic materials, including very high melting point alloys, and its applicability for other engineering materials is currently being explored.

General Electric, the largest manufacturer of jet engines, is starting the world's first factory for additively manufactured jet engine fuel nozzles in Auburn, Alabama in 2015. Currently, each fuel nozzle is an assembly of about twenty individual parts.¹ In the future, the additively manufactured nozzles will be fabricated in one step without any assembly. They will be made by laser melting of alloy powders, layer by layer, in 20 micrometer thin layers.¹ So each layer will have a thickness of about one fifth of a human hair. The fuel

nozzle, shown in Fig. 1(a), will totally eliminate the need for any assembly of components. GE also claims that the fuel nozzles made by the AM process will be five times as durable as the current ones.¹

Additive manufacturing is often used for polymeric materials. A recent news item illustrated one such important use.² An astronaut inside the international space station was in need for a piece of hardware, a ratcheting socket wrench. There was no immediate resupply mission planned and so NASA did not physically take it to the space station. Instead, what they did set a new space age record.

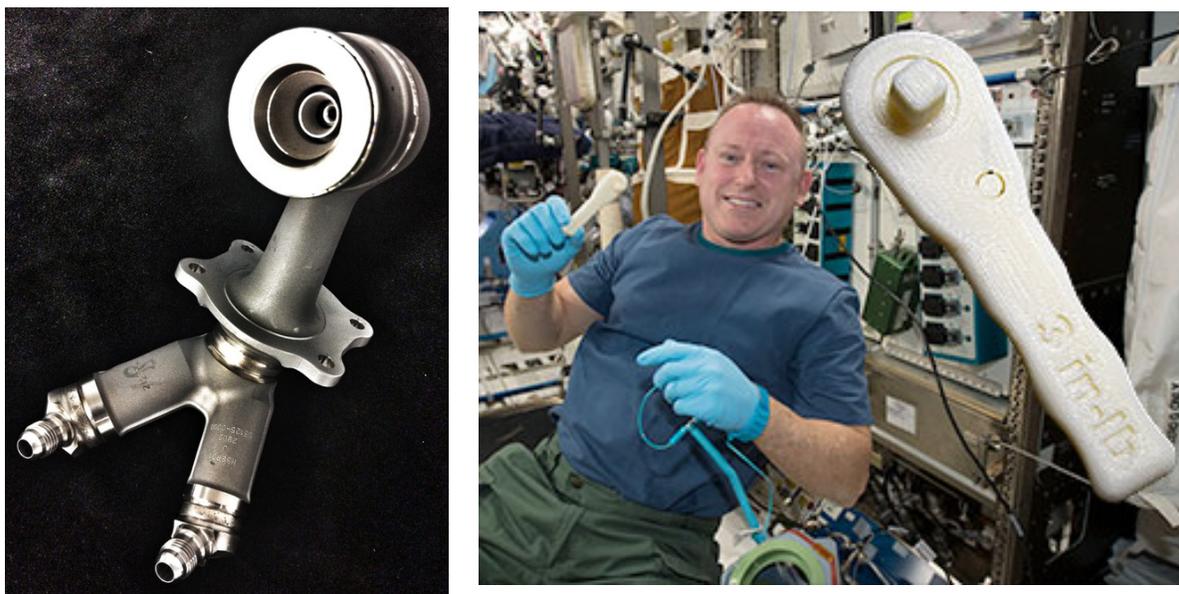


Fig. 1(a): The figure on the left shows a GE jet engine nozzle made by the AM process.¹ Fig. 1(b) on the right shows Bruce Wilmore, commander of the international space station showing a ratchet wrench made with *Made In Space's* 3D printer.²

For the first time, they sent a digital picture file electronically to a computer attached to a desktop additive manufacturing machine 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. At the end, an astronaut simply pulled out a 4.5 inch long and 1.3 inch wide wrench from a desktop machine, made of the same plastic used to make the LEGO bricks.² Once the picture file and the machine were available, it was not at all a difficult job.

Since metals and alloys are the most widely used engineering materials, this article is focused on additive manufacturing of metallic materials. In particular, we start by

examining the commonly used AM processes for metallic materials and the important features of the process and the products. We also discuss the printability of important engineering alloys, identify the important unsolved problems and examine the current status and the broader impact of the AM technology.

Printing metallic parts

In order to form a metallic part from metal powder or wire by AM, a moving heat source such as a laser beam* or an electron beam melts an alloy which subsequently solidifies. The trajectory of the heat source is determined from the computer picture of the part. The alloy is supplied in the form of powders or solid wires depending on the specific process.

Either a continuous wave carbon dioxide laser or a solid state Nd:YAG or Yb fiber laser is used in the two laser-based processes to make parts from powders. In the powder bed fusion (PBF) process, shown schematically in Fig. 2(a), 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 alloy is deposited. In the directed energy deposition (DED) system shown in Fig. 2(b), the powder is supplied by a powder feeder co-axial with a laser beam. Both the laser beam and the powder feeder moves with respect 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 part is lowered slightly so that the focal point of the laser is not altered with respect to the deposition surface.

Both PBF and DED often produce finished parts with fine features that do not require further machining. However, these processes are fairly slow and they take considerably longer time to build parts than casting or injection molding. In the DED process, the larger particle size used to facilitate their easy passage limits the feature fineness. On the other hand, PBF uses finer powders to achieve smaller features. PBF uses a much higher laser scanning speed than DED. As a result, PBF receives less heat per unit length of the deposit, the layers are much thinner and they cool much faster.

In the electron beam AM (EBAM) systems, when large parts are made with a high energy heat source at high material deposition rates, the parts usually retain a larger amount of heat for a longer duration and the cooling rates are slower than both the PBF

* Selected technical terms are explained in the appendix

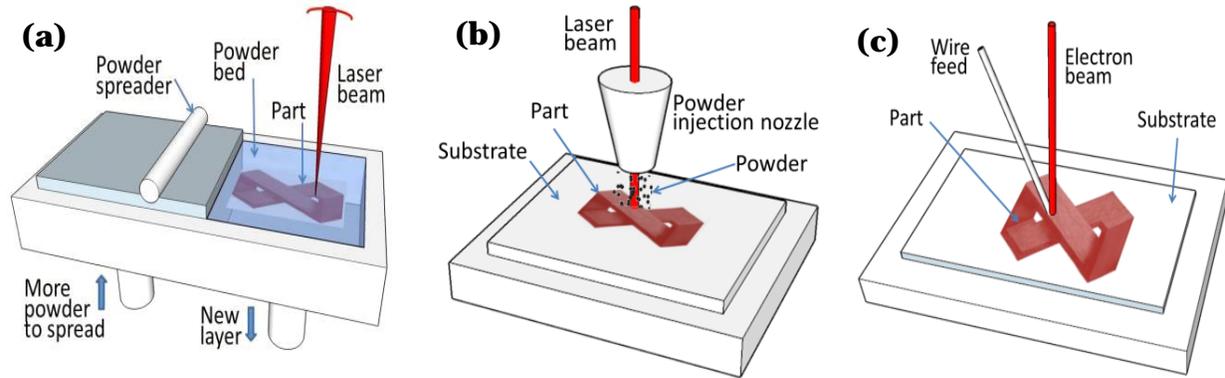


Fig.2 Schematic diagrams illustrating the commonly used additive manufacturing processes for metallic materials: the powder bed fusion process on the left, the directed energy deposition system in the middle and the electron beam AM process on the right.

and DED powder base systems. We will discuss how cooling rates affect structure and properties in a subsequent section. Often products larger than 30 cm x 30 cm x 30 cm are produced in near net shape by melting of a wire followed by some machining. In some cases, high deposition rates are obtained by using two wire electrodes simultaneously. In addition, wire based AM processes that use welding power sources are also gaining popularity, partly because wires are more easily available than powders.

Table 1 shows several important features of the three most common AM processes. 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 higher productivity.

Table 1: Characteristics of different additive manufacturing processes.^{3,4}

	Powder bed fusion (PBF)	Directed energy deposition (DED)	Electron beam deposition (EBDM)
Maximum deposition rate	160 gm/hr	500 gm/hr	9 kg/hr
Energy deposited /length per layer	Low	Medium	High
Maximum part size (cm x cm x cm)	50 x 28 x 32	200 x 150 x 75	579 x 122 x 122
Powder size	10 μm or larger	40 μm or larger	wire feed
Surface roughness	4 to 10 μm	7 to 20 μm	needs machining
Fineness of features	0.04 to 0.2 mm	0.5 to 1.0 mm	Sub-millimeter features difficult
Average system price	450,000 to 600,000 euro	500,000 to 800,000 euro	-

When the power is turned on

The physical processes that take place during AM are complex but important because they affect the structure, properties and serviceability of the parts. Perhaps the most important aspect of all three AM processes is the heating and melting of the alloy powder or the wire used to build the part and the subsequent cooling and solidification of the molten alloy. In the DED and EBDM processes, the alloy starts receiving heat even before they reach the build surface. For example, in the DED process, the powder passes through the laser beam and absorbs heat during flight, although it does not melt. In the EBDM process where one or more wires are used, the extent of heating of the wire depends on the specific location of the feed wire with respect to the electron beam. A portion of the laser or electron beam energy impinges on the growth surface, the powder or the wire melts quickly and the molten pool continues to absorb energy. In all AM processes, a liquid pool forms directly under the heat source and moves with the heat source.

The highest temperature on the melt pool surface is attained directly below the heat source and the temperature decreases with distance from this location. Since the surface tension depends on temperature, a strong spatial gradient of surface tension develops on the surface. Spatial gradient of surface tension is a stress, known as the Marangoni stress which makes the liquid move from regions of low to high surface tension. So, inside this tiny molten pool, the liquid alloy recirculates rapidly at very high velocities. At these high velocities, the convective transport of heat is the main mechanism of heat transfer in the melt pool.

The motion of the liquid metal is important, because it mixes the liquid metals in different regions and transports heat within the molten pool. The circulation pattern strongly affects 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 of the part. The solidification morphology and the microstructure affects the mechanical properties of the part and the serviceability of the component produced.

Since liquid metals are opaque, it is difficult to experimentally determine the motion of the liquid metal. A recourse is to mathematically model metal flow in the molten pool by numerically solving the equations of conservation of mass, momentum and energy with appropriate 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 has also been acquired from numerical modeling.

In figure 3 the computed motion of liquid metal in various locations of the molten pool is shown by arrows.⁵ Only one half of the molten pool is shown to visualize metal velocities both on the surface and in the longitudinal symmetry plane. Since the molten pool moves with the heat source, snapshots of the molten pool at different locations are shown. Different colors in these figures indicate different temperature bands. Velocities shown by the black arrows range from several hundred mm/s upto about a m/s depending on the location. Velocities of similar magnitudes were also reported in laser welding.

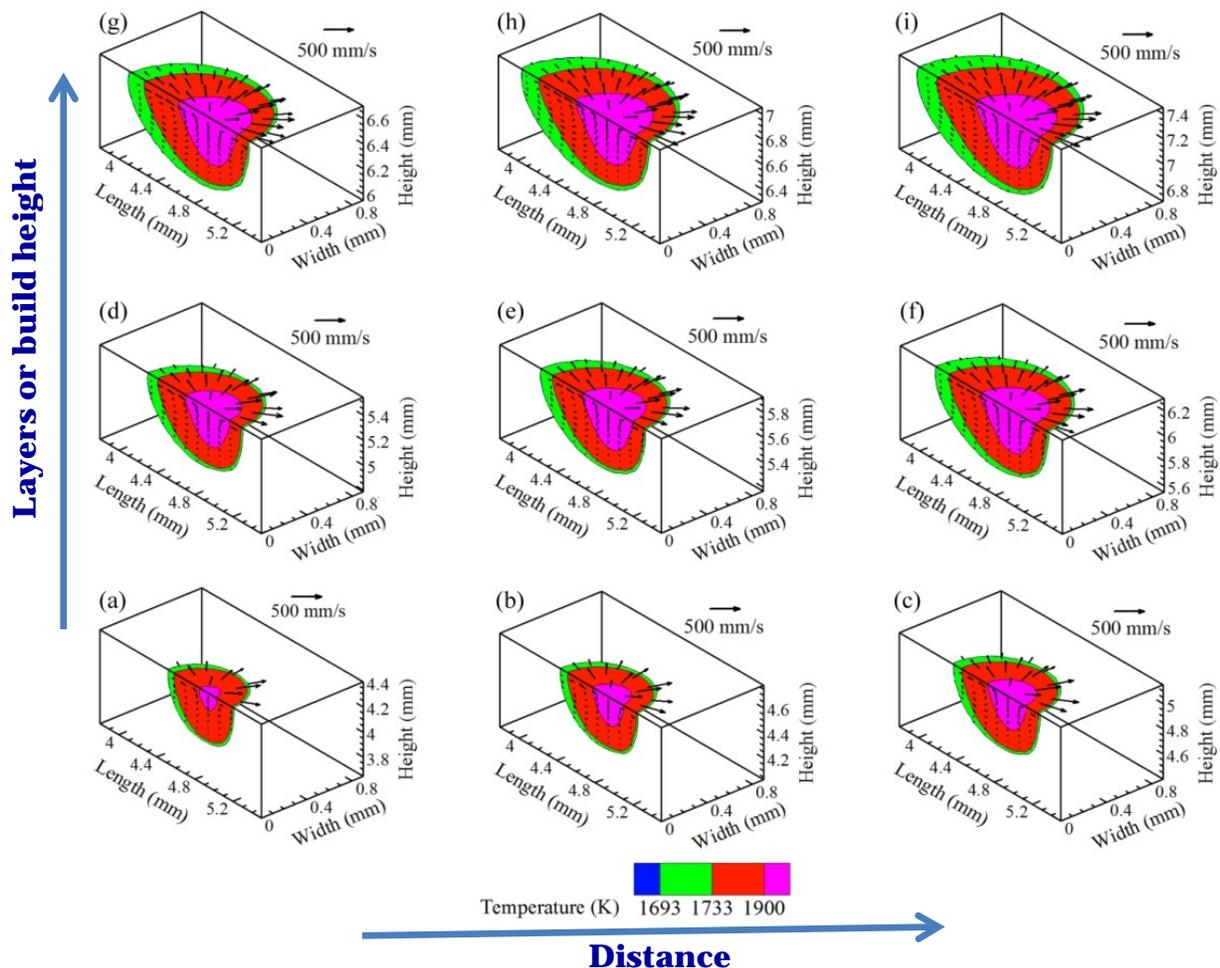
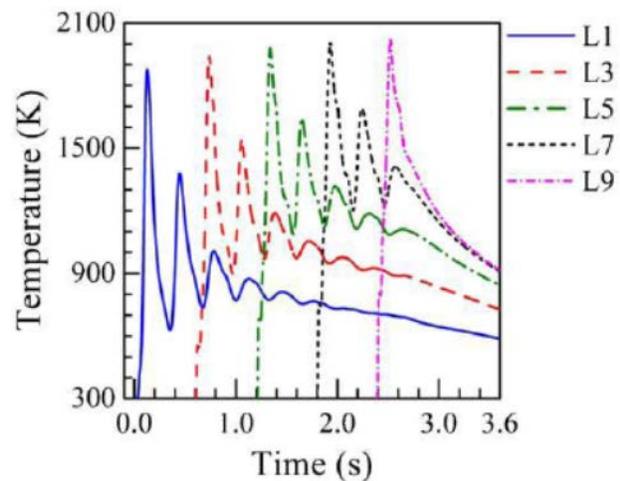


Fig. 3 Computed melt pool shape, temperature and velocity fields in the (a) first, (b) second, (c) third, (d) fourth, (e) fifth, (f) sixth, (g) seventh, (h) eighth and (i) ninth layers at mid-length for a laser assisted multi-layer deposition of 316 stainless steel at a laser power of 210 W and scanning speed of 12.7 mm/s.⁵

The progressive growth of the size of the melt pool in a nine-layer structure is contributed by the spatial variation of the heat transfer rates. Heat transfer from the molten pool into the substrate becomes more difficult with increasing distance from the substrate. The reduction of heat loss results in larger melt pool and higher peak temperatures in the upper layers.

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 shows the computed thermal cycles⁶ at different locations inside a part. Temperatures at the mid-height and mid-length of several layers are shown as a function of time. The first and the strongest one 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 is often changed by the subsequent thermal cycles depending on the specific temperatures and times. These thermal cycles affect the evolution of microstructure of the part and the eventual mechanical properties of the deposited layers.

Fig. 4: Calculated thermal cycles in a laser assisted DED of 316 stainless steel at a laser power of 210 W and 12.7 mm/s speed.⁶ The symbols L1, L3, L5, L7 and L9 indicate thermal cycles in the first, third, fifth, seventh and ninth layers, respectively. The monitoring locations are at the mid height and mid-length of each layer.



The substrates that are 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 the peak temperatures 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 structural asymmetry of the part. Since the structure affects properties, the properties may also be inherently different at different locations.

Evolution of structure and properties

The heating and the cooling rates within the build depend on the specific locations and the variables selected for the deposition process, particularly the scanning speed, power, power density, and the thermo-physical properties of the alloy. The cooling rate during solidification affects the shape or, more formally, morphology of the solidifying alloy. As the alloy cools further, phase transformations occur and they determine the microstructure of the part. Table 2 gives a rough idea of the range of reported cooling rates during solidification which ranges between tens of degrees to several thousand degrees Kelvin per second. The significant variations of cooling rates indicated in the table originate from the variations of process parameters, part geometries and the traverse paths of the heat source, all of which influence heat transfer within the part. As a result, the mechanical properties of the parts vary significantly depending on the process used, process parameters selected including the deposition scheme. For example, significant differences in the microstructure, strength and ductility of Ti-6Al-4V parts, all made by AM have been reported in the literature. Among the properties tested, poor ductility has been attributed to the lack of fusion defects. When the parts were made with adequate overlap of fusion zones to avoid the lack of fusion defects, the loss of ductility was not pronounced in Ti-6Al-4V parts.

Table 2: Reported cooling rates in additive manufacturing of alloys. LENS is an acronym for laser engineered net shaping which is a direct energy deposition system.

AM process	Alloy	Heat source	Power and speed	Cooling rate	Reference
LENS	316 Stainless steel	Laser beam	478 W, 5.9 mm/s	100K/s at the solid liquid interface	7
LENS	316 Stainless steel	Laser beam	212 W, 9.3 mm/s	1000K/s at the solid liquid interface	7
DED	316 stainless steel	Laser beam	210 W, 12.7 mm/s	3000 K/s at the solid liquid interface in the third layer	6
EBAM	2219 Aluminum alloy	Electron beam	1950 W, 8.5 mm/s	5 K/s to 350 K/s at the solid liquid interface depending on the substrate preheat	8

At any location within the part, the cooling rate decreases with temperature. So the cooling rates which determine the kinetics of important phase transformations are lower than the cooling rates during solidification indicated in the table. Also the layers that are closer to the substrate cool faster since the substrate is a heat sink. As a result, microstructures and the resulting mechanical properties often vary spatially within a part.

The morphology of the solidification structure depends on the temperature field which depends on the traverse pattern of the heat source consistent with the computer picture of the part. Consider for example the two beam scanning patterns, one where the heat source travels along the same direction and another where the direction alternates for the deposition of a nickel base IN 625 alloy shown in Fig. 5.⁹ Under the conditions of these depositions, the solidification occurs as columnar dendrites epitaxial to the substrate. Figure 5 shows the differences in the growth directions of the primary dendrites. When the scanning direction is the same, the orientation of the primary dendrites remain same in all

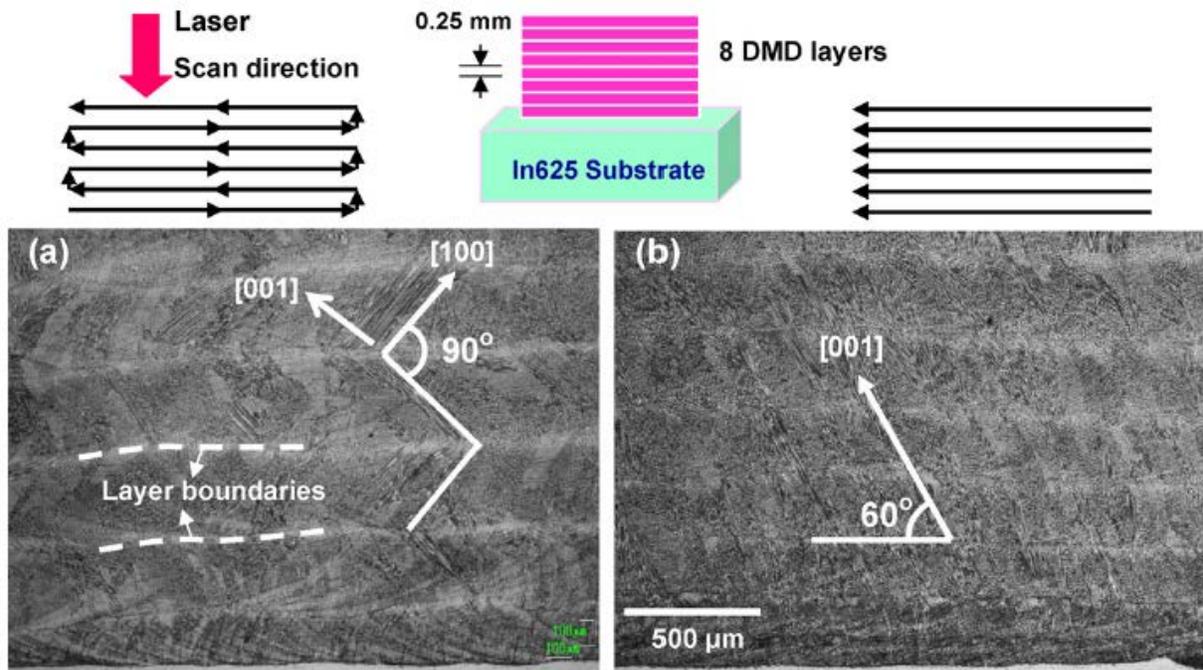
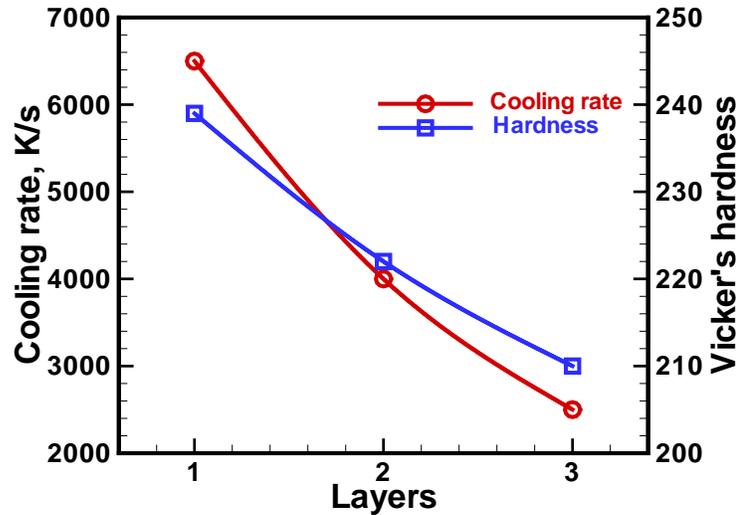


Figure 5 Influence of heat source travel direction on the growth pattern of primary dendrites in IN 625 alloy.⁹

layers. In contrast, when the alternate direction scanning is used, the growth angle of the primary dendrites changes in alternate layers.⁹ The orientation shift occurs because of the differences in the heat flow direction in the scanning modes of two successive layers.

Fig. 6: Calculated cooling rates in a laser assisted DED of 316 stainless steel at a laser power of 210 W and 12.7 mm/s speed.⁶ Cooling rates and the measured hardness values at mid height and mid-length of each layer.



Even within the same part, location dependent cooling rates result in spatial variations of solidification structure, microstructure and properties. In particular, the spatial variation of cooling rate often make the local mechanical properties close to the substrate different from those of the upper layers. Faster cooling often results in finer microstructures and stronger and harder layers close to the substrate as shown in Fig. 6.

Spatially variable mechanical properties are also contributed by the preferential orientation of the grain structures along the heat flow direction. For example, during the deposition of Ti-6Al-4V parts by AM, at high temperatures grains of a body centered cubic phase called beta grow along the build direction and this directional growth pattern adds to the asymmetry of mechanical properties.

Printability of alloys and common defects

Are some alloys inherently more printable than other alloys? One way to view printability is to examine susceptibility of different alloys to form common defects during AM. Special care needs to be taken to avoid defects such as distortions, lack of fusion and compositional changes owing to selective vaporization of alloying elements. In extreme cases, severe localized distortions and other defects may affect serviceability of parts. It is important to understand the origins of these defects in order to mitigate them.

The main parameters that affect the localized distortion, their mechanisms of action and remedies are indicated in Table 3. Apart from the variables listed in the table, the scanning sequence adapted, the time gap between two successive layers, periodic stress relief and the nature of the alloy being deposited, particularly the volume changes involved in phase transformations are important for the residual stress and distortion of the part.

Table 3: A list of important variables that affect distortions of parts in additively manufacturing

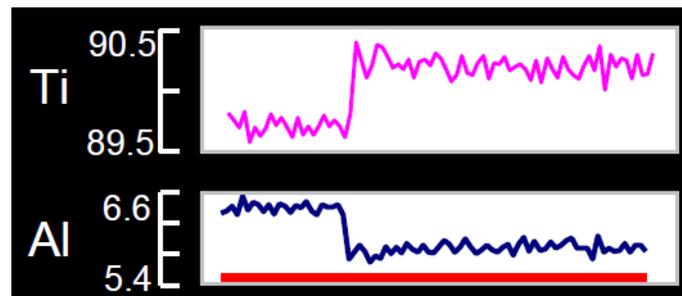
Variable	Mechanism	Remedy
Heat input per unit length which is the power of the heat source divided by the scanning speed	Larger heat input results in a larger pool of liquid and higher temperatures. Non-uniform cooling results in shrinkage and distortion.	Reduce power or increase speed or both. Smaller liquid pool results in reduced shrinkage and distortion.
Temperature coefficient of volume expansion	Larger volume shrinkage per degree of temperature makes an alloy more susceptible to distortion.	Thermal management to reduce peak temperature and cooling rate
Rigidity of an alloy structure	Rigidity is a property of a material to resist deformation under load. It is the product of stiffness and geometric factors.	Higher stiffness of a material and/or a thicker plate can resist distortion

The lack of fusion defects originate from inadequate penetration of the fusion zone into the previously deposited layer. The important parameters that affect the lack of fusion defects are the thermophysical parameters that affect the heating and melting of an alloy, characteristics of the heat source and other processing parameters that determine the geometry of the fusion zone during AM. These include the specific heat, density, heat of fusion, thermal conductivity, temperature coefficient of surface tension, viscosity, the power and power density of the heat source, scanning speed and the properties of the powder. Since the physical processes during AM are complex, comprehensive numerical models are necessary to accurately estimate the fusion zone geometry. For many deposition conditions, some alloys such as Ti-6Al-4V and Nickel base superalloys form deeper pools than carbon steels and are easily bonded with the

previously deposited layers. However, even for these alloys, lack of fusion defects are not uncommon because of inadequate heat source energy, high scanning speed, larger powder diameter and other inappropriate choice of AM parameters. Satisfactory penetration of the molten pool into the substrate of the previously deposited layer needs to be ensured to avoid this defect. A well tested numerical heat transfer and fluid flow model can help in this task to avoid the lack of fusion defect.

Most engineering alloys typically contain one or more alloying elements that vaporize rapidly at high temperatures. Manganese and chromium in stainless steels, magnesium and zinc in aluminum alloys and aluminum in titanium alloys are examples of alloying elements that are highly volatile and are selectively lost during high energy beam processing. Consequently, the chemical composition of the part built by melting of powders may be different from that of the original chemical composition of the powder. Fig. 7 shows a decrease in aluminum composition and a corresponding increase in titanium concentration because of laser melting. The literature in welding indicates that 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 minimize pronounced changes of chemical composition.

Fig. 7: Changes in the composition of Ti-6Al-4V owing to additive manufacturing.¹⁰



Contemporary challenges

Wider market penetration of AM will require solution of several critical problems. Here is an incomplete list of unsolved contemporary problems.

Smaller, slower and expensive: Fabrication of parts that are 1 cubic foot or larger in volume is a significant challenge now because of the low deposition rate of current AM systems. Net shape parts require good surface finish which is achieved by depositing very thin layers, often about 20 micrometers in thickness. As a result, the deposition rate is

very low. Printing of a part often takes typically from 12 hours to a day or more. Also, both the AM equipment and the alloy powders are expensive. A rough idea of the equipment cost is included in Table 1 and the cost of material is often about an order of magnitude higher than that for injection molding. What is needed is a paradigm shift from “smaller, slower, expensive” to “bigger, faster and cheaper” for AM to have a wider market share. Electron beam systems do provide higher deposition rates, particularly when multiple electrodes are used, but they require extensive machining and cannot be used for parts with very small features.

The heat sources of the future additive manufacturing processes may also be very different in shape and size from the heat sources we use today to improve the deposition rate and enable fabrication of larger components. Simultaneous use of multiple power sources, scanning with a larger rectangular heat source that can process an expanded area of powder bed are potentially attractive, but yet unproven ways of enhancing productivity.

Surface finish: During additive manufacturing, a liquid pool moves rapidly and moving pool often interacts with alloy powders. At a small distance away from the axis of the heat source, the unmelted powder sticks with the solid/liquid region and the quality of the surface finish of the part is affected by the particle size of the powder. Smaller particles melt easily during interaction with the molten pool. In some deposition systems, particles as small as 20 micro-meter diameter are used to obtain a better surface finish. However, the deposition of thinner layer also affects the deposition rate and a careful optimization of the deposition system is necessary. Where very fine powders cannot be used, a post-processing step is often required to finish the part.

Accuracy of internal features of parts: One of the distinguishing features of additive manufacturing from the other manufacturing techniques is its ability to create internal features such as cooling channels and piping in the interior of a solid part. Very often these parts suffer from distortions and surface roughness problems. Since the interior features are not easily accessible for machining, the quality of the manufactured parts are compromised if the features are not true to its original design. Smaller liquid pool size with lower heat input can often reduce distortion, but they also reduce productivity.

In addition to the issues discussed above, there are many other problems. These include the difficulties of generating computer printing files, sometimes called “stl” files from drawings of complex parts, and generating the right traverse paths for heat source to avoid distortion and the evolving field of efficient close loop control for AM. Providing adequate support for intricate parts with overhang features is also not a trivial task. Solution of many of these problems can be aided by a more complete understanding of various simultaneously occurring complex physical processes during AM. Such solutions will require sustained efforts.

Epilogue

In many ways AM evolved from welding's transformation in the digital age and, as a result, many of the lessons of fusion welding are important for AM, especially the common issues of interdependence of processing, structure and properties of metallic materials. One of the enduring lessons of fusion welding is that the experimentally determined relation between processing and structure needs to be augmented by sustained and rigorous physical and mathematical modeling in order to understand not just what structure and properties are obtained but why.

Meaningful quantitative understanding of AM is just beginning. AM is supported by a mature and sophisticated knowledge base of fusion welding, the awesome software and hardware capabilities of the digital age, and a global pool of technologically savvy and creative workforce. Although the pace of technological advancement has never been faster as a result of these unusually powerful synergistic effects, many important technological issues of AM are fairly difficult and will require sustained research and development efforts. An important parallel is that the current comprehensive knowledge base of fusion welding required many decades of intensive research and development. This reality has been recognized in recent literature¹¹ as shown in Fig. 8 where the development cycle of AM includes the initial exuberance and the need for “enlightenment” before a steady plateau of productivity is attained.

Although AM has enabled engineers to send designs of parts remotely to a machine, thus achieving a better integration between the design of a part and its manufacturing, it is by no means a panacea that can make a wide variety of cost effective and sound parts. Currently, for many metallic materials, AM is expensive, time

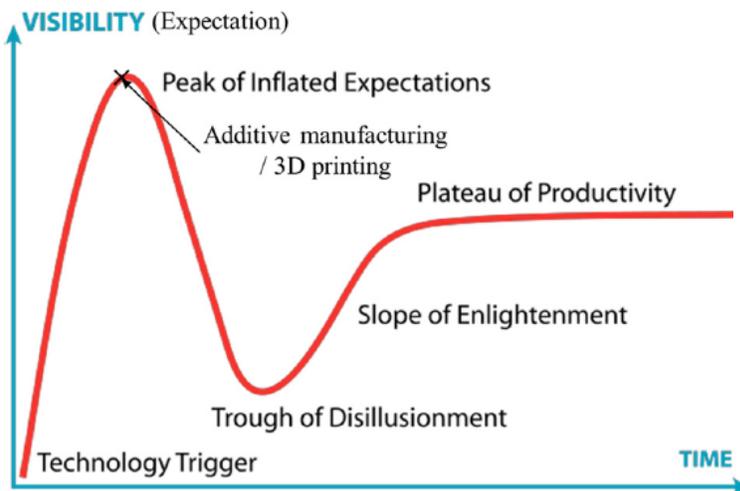


Fig. 8 Development cycle of additive manufacturing showing the initial exuberance, sustained development prior to reaching a steady plateau of productivity.¹¹

consuming and susceptible to quality issues which limit its widespread market penetration. Expansion of its ability to create cost effective, defect free, structurally sound, metallic parts will require sustained research and development to develop better understanding of processing, structure and properties in the coming decades. In the meantime, AM will steadily continue to expand its reach in manufacturing and augment the existing manufacturing processes in important specialized areas.

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APPENDIX – Meanings of a selection of technical terms

Alloying 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 vaporize 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.