Additive manufacturing: scientific and technological challenges, market uptake and opportunities

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Additive manufacturing (AM) is fundamentally different from traditional formative or subtractive manufacturing in that it is the closest to the 'bottom up' manufacturing where a structure can be built into its designed shape using a 'layer-by-layer' approach rather than casting or forming by technologies such as forging or machining. AM is versatile, flexible, highly customizable and, as such, can suite most sectors of industrial production. Materials to make these parts/objects can be of a widely varying type. These include metallic, ceramic and polymeric materials along with combinations in the form of composites, hybrid, or functionally graded materials (FGMs). The challenge remains, however, to transfer this 'making' shapes and structures into obtaining objects that are functional. A great deal of work is needed in AM in addressing the challenges related to its two key enabling technologies namely 'materials' and 'metrology' to achieve this functionality in a predictive and reproductive ways. The good news is that there is a significant interest in industry for taking up AM as one of the main production engineering route. Additive Manufacturing, in our opinion, is definitely at the cross-road from where this new, much-hyped but somewhat unproven manufacturing process must move towards a technology that can demonstrate the ability to produce real, innovative, complex and robust products.

Introduction

Additive manufacturing makes 'objects' from a digital 'model' by depositing the constituent material/s in a layer-by-layer manner using digitally controlled and operated material laying tools. This broader definition of Additive Manufacturing essentially highlights four main components:

- A digital model of the object, which can vary from a pizza slice to an aero plane wing
- Material/s that are consolidated from the smallest possible form for example liquid droplets, wire, powder to make the object
- A tool for laying materials and
- A digital control system for the tool to lay the material/s layer-by-layer to build the shape of the object.

AM is thus fundamentally different from traditional formative or subtractive manufacturing in that it is the closest to the 'bottom up' manufacturing where we can build a structure into its designed shape using a 'layer-by-layer' approach. This layer-by-layer manufacturing allows an unprecedented freedom in manufacturing complex, composite and hybrid structures with precision and control that cannot be made through traditional manufacturing routes [1,2]. A good example of this can be a bone tissue engineering scaffold, the aim of which is to provide tissue support *in vivo* while mimicking the porous and permeable

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hierarchical architecture of bone. Conventional methods of replicating bone scaffold have been proven difficult in mimicking the interconnected porous network structure however using X-ray micro-computed tomography (X-ray μCT) image coupled with computer aided design (CAD) can create design files that can be processed using AM reliably [3].

Some of the potential benefits [4,5] of additive manufacturing can be summarized below:

1. Direct translation of design to component
2. Generation of parts with greater customization with no additional tooling or manufacturing cost
3. Functional design allowing manufacturing of complex internal features
4. Flexible and lightweight component manufacturing with hollow or lattice structures
5. Ability of direct manufacturing of components to their final (net) or near final (near net) shape with minimal to no additional processing
6. Potential to approach zero waste manufacturing by maximizing material utilization
7. A great reduction in overall product development and manufacturing time leading to quicker transfer to market
8. Smaller operational foot-print towards manufacturing a large variety of parts
9. On-demand manufacturing, moving away from projection based manufacturing and
10. Excellent scalability.

The success of additive manufacturing, however, lies in how well this manufactured 'object' serves its intended use in the market. Translating the superiority and convenience of AM in creating shapes and structures into useful products is critical for its adoption in industrial set-up. Commercial success will also depend on how firmly one can assure that properties of *materials* in the desired shape or structure actually meet certain accepted, pre-defined standards [6] while the cost of production remains competitive. In other words, the *market* uptake of products made via AM (the *making*) will happen when parts produced via AM will confirm the intended properties through appropriate measurement or *metrology*. This inter-twinned relation between market, making, materials, and metrology is shown in Fig. 1 in the backdrop of a Celtic symbol for strengths, and would be realized as such when considered together.

In this article we outline the scientific and technical challenges associated with the making, materials, and metrology of AM products that will determine its market uptake and the realization of its commercial opportunity. In the backdrop of several excellent reviews and books on AM that are available [7–10], we emphasize that the current enthusiasm on the market opportunity and the ability of making through additive manufacturing routes must be well matched with solving materials related challenges and adaptation of suitable metrology. Materials and metrology are thus the two key enabling technologies that has to progress beyond its current state of the art to translate AM from rapid functional prototyping to genuine industrial manufacturing.

The making

AM has originated from the layer-by-layer fabrication technology of three-dimensional (3D) structures directly from a CAD model.

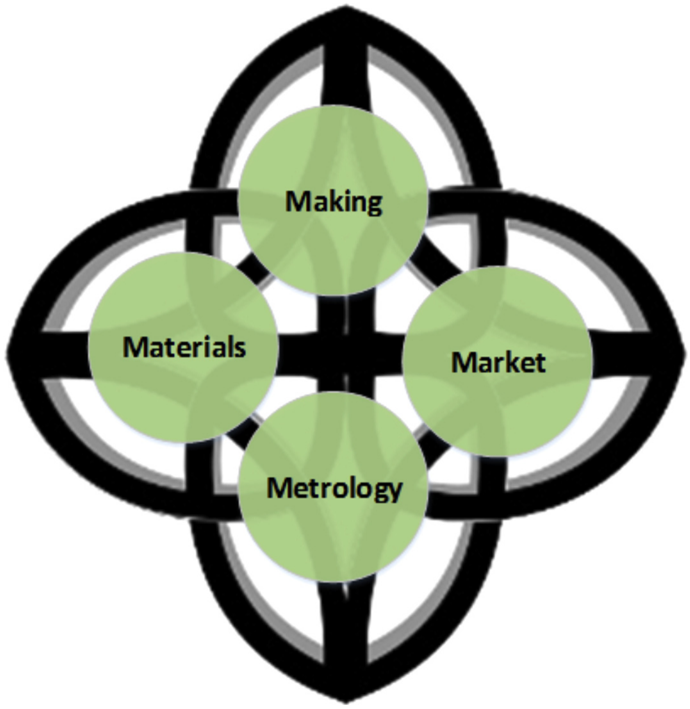

FIGURE 1

The four M's (4Ms) of additive manufacturing: Materials, Making, Metrology and Market.

AM has now developed into both a rapid tooling and a manufacturing technology and is rightly positioned in bringing forward the so called Fourth Industrial Revolution. The AM approach of making is versatile, flexible, highly customizable and, as such, it is highly suitable for most sectors of industrial production. The primary focus of AM has remained on customization of low volume, high value added products that can be manufactured quickly. Leading automobile manufacturers are now making engine components with AM that can be driven on road; the Food and Drug Administration (FDA) of the Unites States of America has approved for human use devices manufactured via AM; international space station has an AM machine for making parts and components in space [11].

AM is capable of producing fully functional parts in a wide range of materials including metallic, ceramic, polymers and their combinations in the form of composites, hybrid, or functionally graded materials (FGMs). Among these materials, polymers have been widely used perhaps due to their widespread use in the 1st generation machines designed primarily for rapid prototyping [12–14]. The technology, however, are not limited to polymers or other polymeric materials only. All types of materials including metals [15–18], ceramics [19–22], nanomaterials [23], pharmaceuticals and materials of biological origin [24] can be translated into 3D shapes and structures using AM.

The International Organization for Standardization (ISO)/ American Society for Testing and Materials (ASTM) 52900:2015 standard classify standard, AM processes into seven categories:

(1) binder jetting (BJ);
(2) directed energy deposition (DED);
(3) material extrusion (ME);
(4) material jetting (MJ);

(5) powder bed fusion (PBF);
(6) sheet lamination (SL); and
(7) vat photopolymerization (VP).

Table 1 summarizes the basic principles, example materials manufactured, advantages and disadvantages of each of these seven systems. It also indicates major manufacturer of tools for the given AM technology.

In AM, the material layer is deposited or directed best while it is in a fluidic state. Obviously, polymers and polymer based products such as polymer matrix composites, hybrids and FGMs generally offers conveniences they require relatively lower processing temperature and manufacturing in the ambient without any vacuum and inert gas environment. Polymers have relatively lower melting and glass transition temperatures, which make it easier to flow at a relatively lower temperature than that of ceramics and metals. The achievement of curing and bonding upon cooling in polymers is also easier. Bonding involving metals and ceramics are not as easy to achieve due to their high melting temperatures. The advantage of solid state sintering process that involves surface melting of metals or ceramic particles, followed by grain growth, is often the preferred route to obtain a consolidated solid structure or shape for hard materials. However, direct laser melting of ceramics [25] or metals [26,27] have been shown to work as well.

Among the heat source, high power lasers have been widely used, especially for metals, to form fusible liquid metals [28]. Other sources such as a plasma torch or an electron beam can be used as well. Ceramic structures can also be made with the help of binders and fluidizer [29]. High temperature post-processing may be required for further densification and burning off any binder, if necessary. Lasers are particularly advantageous in metal additive manufacturing both as a melting source and as cutting tools for trimming shapes and surface finish. While laser dominates as the preferred heat source in both powder bed and powder feed processes electron beam source are also used especially in manufacturing relatively small build volume parts. In general, powder and wire feed methods can generate medium to large volume free forms (please see Table 1).

General manufacturing challenges for AM lies in the development of self-contained, robust, user-friendly, safe, integrated system to provide required deposition scan motion, and speed, high feature-volume resolution with concomitant energy for part fabrication and dimensional control. Other challenges pertaining to AM products are surface finish, part size, variations in product quality from machine to machine and between batches of productions, and a lack of fundamental understanding of the impact of operational variables on part quality.

For metals, there should be adequate shielding from oxidation, which can significantly compromise the quality and usefulness of the final product. Currently, inert gas shielding is quite popular. In many cases, especially for manufacturing objects with non-ferrous metals a vacuum of the order of 10^{-3} to 10^{-4} or even a reducing environment may be required. The power range, repetition rate, wavelength of the laser, and the flexibility of the laser point to enable creating a 3D object are important. While for polymers, a low power heat source, light or ultrasound can be sufficient a high laser power is required for metals. Since ceramic materials are poor thermal conductors a relatively lower power laser can be used but care must be taken to avoid thermal shock. Laser powers generally vary from 0.1 W to 10 kW. The wavelength of laser can be selected in the range of the ultraviolet (UV) to mid infra-red (IR) depending on the material, process and product type.

Lasers can be generated using a range of sources including diode lasers to fibre lasers. The use of optical fibres can provide flexibility in transmitting the laser power to the machining tip with very high level of control and precision. Fine optical fibres are widely available with diameters in the submicron range and length in few kilometres. The optic fibres are used for transmitting UV and visible range of light. There is currently a significant shortage of optical fibres to transmit IR, especially mid IR (MIR), in sufficiently small tip size and long distance. The technology of MIR optical fibres has been relatively restricted mainly due to its current focus on military and space application. Suitable materials for transmitting MIR in its whole range of wavelength (2–20 μm) are rare, and the expertise is also limited. This activity should be expanded as MIR lasers coupled with appropriate optics and optical fibre transmission can provide a much robust heating source for a range of materials due to the high and selective absorption of materials, ranging from polymers to metals to ceramics. MIR can also be used for selective post-processing of multiple material components and metrological purposes.

Another interesting heat source for AM can be microwave radiation with frequencies between 300 MHz and 300 GHz. Microwave heating is slowly gaining interest and is now well known for sintering ceramics. While bulk metals reflect microwaves, powder metals will absorb microwaves at room temperature. This can be used for selective, effective, localized and rapid heating of metals [33]. A microwave probe or a needle can be used for localized fusion in a similar fashion to any directed energy deposition. However, unlike the far-field approach in laser heating, microwave uses a near-field effect which requires a close proximity or near-contact of the microwave source and the processed object. Microwave heating, a volumetric heating, is rapid and highly efficient. The fact that the mechanism of heating and sintering is fundamentally different from radiant/resistance heating in conventional sintering can help to avoid many of the radiative heat-transfer related problems. The degree of microwave absorption changes with temperature thus making the whole process non-linear but highly controllable and reproducible for a given system. Microwave can also be used for *in situ* metrology [34,35]. This area is still in its infancy as regard to the implementation in commercial AM operations and merits intense research in future.

The material: towards ‘designer's materials’

Discussions on AM can often be pre-occupied with elaborations on the manufacturing techniques, data communications and system changes with an ardent desire to drive forward the revolutionary paradigm of Industry 4.0 or Manufacturing 4.0. These discussions are often agnostic of the fact that manufacturing transforms materials into a part or a product. Materials thus play a hugely significant role in AM especially because the way AM handles materials is very different to the way conventional manufacturing handles materials. Machines and specific AM technologies are linked to certain types, forms and states of materials (Fig. 2). The AM machine and technique that can produce, for example, a Titanium-alloy component for medical application may neither be suitable to produce an Aluminium

Table 1

Basic principles, materials, advantages, disadvantages, typical build volumes and tool manufacturer of seven ASTM categories of AM: binder jetting (BJ); directed energy deposition (DED); material extrusion (ME); (4) material jetting (MJ); powder bed fusion (PBF); sheet lamination (SL); and vat photopolymerization (VP). Build volumes are rounded to nearest number for convenience. Materials types have been ranked in order of suitability and common use. Adapted from Refs. [30–32].

ASTM category	Basic principle	Example technology	Advantages	Disadvantages	Materials	Build volume (mm × mm × mm)	Tool manufacturer/country
BJ	Liquid binder/s jet printed onto thin layers of powder. The part is built up layer by layer By glueing the particles together	• 3D inkjet technology	• Free of support/substrate • Design freedom • Large build volume High print speed • Relatively low cost	• Fragile parts with limited mechanical properties • May require post processing	• Polymers • Ceramics • Composites • Metals • Hybrid	Versatile (small to large) $X = <4000$ $Y = <2000$ $Z = <1000$	ExOne, USA PolyPico, Ireland
DED	Focused thermal energy melts materials *during* deposition	• Laser deposition (LD) • Laser Engineered NetShaping (LENS) • Electron beam • Plasma arc melting	• High degree control of grain structure • High quality parts • Excellent for repair applications	• Surface quality and speed requires a balance • Limited to metals/metal based hybrids	• Metals • Hybrid	Versatile $X = 600–3000$ $Y = 500–3500$ $Z = 350–5000$	Optomec, USA InssTek, USA Sciaky, USA Irepa Laser, France Trumpf, Germany
ME	Material is selectively pushed out through a nozzle or orifice	• Fused Deposition Modelling (FDM)/Fused Filament Fabrication (FFF), Fused Layer Modelling (FLM)	• Widespread use • Inexpensive • Scalable • Can build fully functional parts	• Vertical anisotropy • Step-structured surface • Not amenable to fine details	• Polymers • Composites	Small to medium $X = <900$ $Y = <600$ $Z = <900$	Stratasys, USA
MJ	Droplets of build materials are deposited	• 3D inkjet technology • Direct Ink writing	• High accuracy of droplet deposition • Low waste • Multiple material parts • Multicolour	• Support material is often required • Mainly photopolymers and thermoset resins can be used	• Polymers • Ceramics • Composites • Hybrid • Biologicals	Small $X = <300$ $Y = <200$ $Z = <200$	Stratasys, USA 3D Systems, USA PolyPico, Ireland 3Dinks, USA WASP, Italy
PBF	Thermal energy fuses a small region of the powder bed of the build material	• Electron beam melting (EBM) • Direct Metal Laser Sintering (DMLS) • Selective Laser Sintering/Melting (SLS/SLM)	• Relatively inexpensive • Small footprint • Powder bed acts as an integrated support structure • Large range of material options	• Relatively slow • Lack of structural integrity • Size limitations • High power required • Finish depends on precursor powder size	• Metals • Ceramics • Polymers • Composites • Hybrid	Small $X = 200–300$ $Y = 200–300$ $Z = 200–350$	ARCAM, Sweden; EOS, Germany; Concept Laser Cusing, Germany; MTT, Germany; Phoenix System Group, France; Renishaw, UK;Realizer, Germany; Matsuura, Japan, Voxeljet, 3Dsystems, USA
SL	Sheets/foils of materials are bonded	• Laminated Object Manufacturing (LOM) • Ultrasound consolidation/Ultrasound Additive Manufacturing (UC/UAM)	• High speed, • Low cost, • Ease of material handling	• Strength and integrity of parts depend on adhesive used • Finishes may require post processing • Limited material use	• Polymers • Metals • Ceramics • Hybrids	Small $X = 150–250$ $Y = 200$ $Z = 100–150$	3D systems, USA MCor, Ireland
VP	Liquid polymer in a vat is light-cured	• Stereo Lithography (SLA) • Digital Light Processing (DLP)	• Large parts • Excellent accuracy • Excellent surface finish and details	• Limited to photopolymers only • Low shelf life, poor mechanical properties of photopolymers • Expensive precursors/Slow build process	• Polymers • Ceramics	Medium $X < 2100$ $Y < 700$ $Z < 800$	Lithoz, Austria 3D Ceram, France

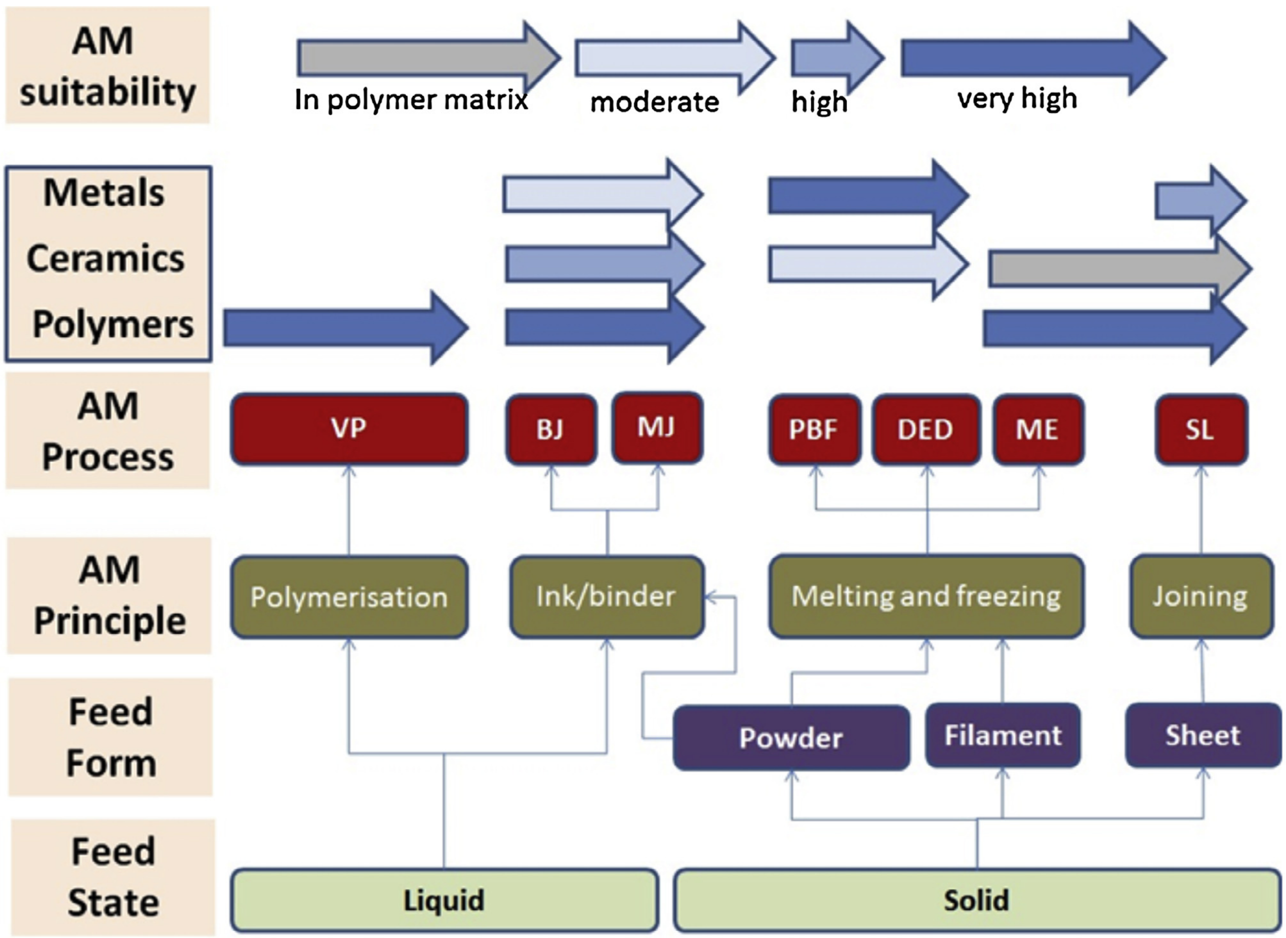

FIGURE 2

A schematic diagram of the relative suitability of additive manufacturing of three major types of materials (polymers, ceramics and metals) in various feed-forms and states using ASTM processes: Binder jetting (BJ); directed energy deposition (DED); material extrusion (ME); (4) material jetting (MJ); powder bed fusion (PBF); sheet lamination (SL); and vat photopolymerization (VP).

alloy nor be able to manufacture plastic parts. AM of parts with complex materials compositions and property gradients thus need a thorough considerations of the materials that to be manufactured into the final object [36].

Even for a single material AM, materials considerations are important. For example, a simple switch from a polymer 3D printer to a metal 3D printer to create the desired shape and structure may lead to disastrous end-results. Conventional manufacturing has mastered the science and engineering of materials over the span of a few centuries to ensure that the manufactured object is useful to the desired extent for an intended application for an intended/demanded lifetime. Yet, it is often difficult in conventional manufacturing to implement extraordinary properties of advanced functional materials especially when these properties originate from the size and shape of the material. For example, nanomaterials community has been facing the risk that interesting academic research is often irrelevant [37] in the development of future technologies and products. While AM can aid in solving many scalability issues in nano-enabled product manufacturing there is no one-size-fits-all type solution in AM. Precursor feedstock materials must be carefully designed to suit a given AM process. The manufactured object must hold together for its useful life to avoid a house of cards type situation. The good news is that research in developing specifically designed, upscalable precursor stocks is gaining importance. There are now attempts to understand and overcome materials challenges associated with application-specific AM.

Conventional manufacturing uses pre-fabricated or pre-formed materials supplied in some standardized size and shapes that form the starting point for further manufacturing. For example, to make a wire mesh, one would order steel wires of a certain gauge size and sufficient length which would then be cut and weaved into the final product. The supplier of steel wire would have it in stock, or procure it, from a few layers of resellers which would ultimately lead to a wire drawing vendor which had bought steel ingots from a rolling or re-rolling mill. A steel smelter would have to have the steel smelt according to certain application oriented standard compositions from the original raw materials that is pig iron, additives (e.g. ferrosilicon) and fluxes (e.g. lime). The smelt steel would have to be cast, hot worked to break the cast structure and shape into a billet form which would then be hot and cold rolled with intermittent heat treatments to remove internal stress. The desired tensile, fatigue and creep properties of a steel wire result as a consequence of significant amount of thermal and mechanical treatments at each states of processing. Every step of these processes has impact

Table 2

General characteristics of AM of metals and manufacturers of AM machines (adapted from Ref. [38]).

AM system and manufacturer		Build volume (mm × mm × mm)	Heat source and process	Country of manufacturing
Powder bed	ARCAM (A2)	$X = 200–300$	Electron beam melting (EBM)	Sweden
	EOS (M280)	$Y = 200–300$	Direct Metal Laser Sintering (DMLS)	Germany
	Concept Laser Cusing (M3)	$Z = 200–350$	Selective Laser Sintering/Melting (SLS/SLM)	Germany
	MTT (SLM 250)			Germany
	Phoenix system group (PXL)			France
	Renishaw (AM 250)			UK
	Realizer (SLM 250)			Germany
	Matsuura (Lunnex Advanced 25)			Japan
Powder feed	Optomec (LENS 850-R)	$X = 600–3200$	Laser engineered net shaping (LENS)	USA
	POM DMD (66R)	$Y = 1500–3500$	Direct Metal Deposition (DMD)	USA
	Accufusion Laser consolidation	$Z = 350–1000$	Laser consolidation (LC)	Canada
	Irepa laser (LF 6000)		Laser Deposition (LD)	France
	Trumpf			Germany
	Huffman (HC-205)			USA
Wire feed	Sciaky (NG1)	$X = 600–750$	Electron beam melting (EBM)	USA
	MER plasma FFF	$Y = 500–600$	Plasma arc melting	USA
	Honeywell ion fusion formation	$Z = 500–5000$	Plasma arc melting	USA

on the density and imperfections such as dislocations in the structure which can play a critical role towards safe and reliable function of the end-use application of the wire in the wire mesh. A simple melt extrusion of steel powders or filaments in to a AM built wire mesh may not necessarily produce the same end-results as that would have been obtained from conventional manufacturing. Yet, AM has been successfully employed for metals. Table 2 lists representative metal AM technology sources and specifications along with the country of the manufacturers [38].

If we compare the chain of events in conventional manufacturing with that in AM, the latter starts with its feedstock, which can be a solid powder, filament/wire, sheet or even a liquid or gaseous precursor (e.g. in laser jet chemical vapour deposition). Steel powders used for AM have been prepared through a vendor, for example, either from a blown re-melt of the steel that was originally obtained from a smelter or a rolling mill, or through a reductionist approach such as pulverization of a 'finished' or 'semi-finished' rolled bar or wire using from. Literature is abundant with examples of why special care is required in this step because these powders from finished/semi-finished steel feedstocks are in fact secondary raw materials for AM, which would render them into a near-finished product. At the moment, the design of AM feed stock is carried out through trial and error methods in experiments, which is system specific, expensive and time consuming. First principle materials design can significantly cut down such number of trials using educated targeting of key property attributes in the feedstock. Modelling enabled computational optimization to solve the so called 'inverse-problem' has the potential in achieving voxel-by-voxel control in additive manufacturing. The computation cost of process modelling can be significant and may require high performance computing [18]. A generalized, mesoscale materials-manufacturing modelling framework or platform may be required from which product specific knowledge can be extracted conveniently.

Feedstock preparation would require customization to suite the intended AM technology as a slight variation in properties of the feedstock can have significant impact on the consolidation of the object being manufactured (the job) and the performance of the final product. In many cases, homogeneity of the property may be required throughout the job to ensure adequate compaction and cohesion of the feedstock into the AM product. Surface properties, especially the surface chemistry and wettability, would play a critical role in the adherence of particles within the green compact, which can then be led to a cohesive structure through binding or fusion. As the heating source moves to the longer wavelength, sources such as mid and far IR, and microwave sources, the process would become more selective as the absorption of these longer wave radiations is highly dependent on the materials chemical constituents.

As AM focuses on getting the final shape and structure as nearly to the finished products as possible, it may limit the extent of post-processing. Many conventional post-processing techniques can be improvised however, and can potentially be integrated into the AM suite. It may still be possible that current materials selection strategy is inadequate and new or alternative materials selection strategies have to be sought to suit AM of a certain product. For example, a monolithic metal component used in making a product does not necessarily mean that the component could not be used in the product if made from a metal matrix composite that may meet the specifications required for the intended purpose of the product. The application requirements must be emphasized and the selected material may need to be 'designed' for AM.

Heating and cooling are essential steps in many AM. Figure 3 compares the specific energy required in typical AM process categories along with the fabrication speed and resolution that can be achieved. Many AM approaches such as BJ utilize binders to enable manufacturing using relatively lower heat. It is a good

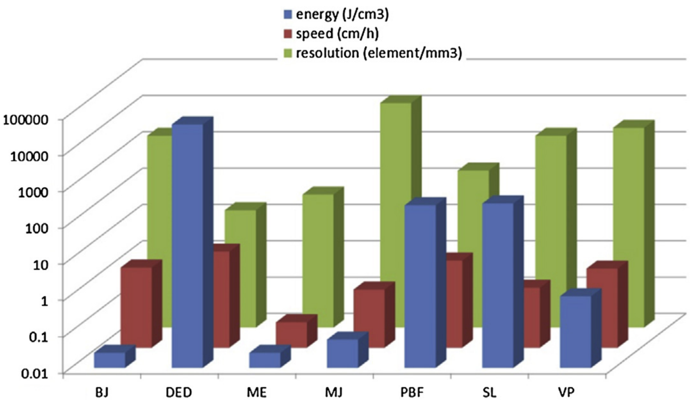

FIGURE 3

Relative energy use vis a vis the speed and resolution of fabrication in different AM techniques. Adapted from Ref. [30]. Binder jetting (BJ); directed energy deposition (DED); material extrusion (ME); material jetting (MJ); powder bed fusion (PBF); sheet lamination (SL); and vat photopolymerization (VP).

move but the binder selection, application and durability may be critical. In fact, many binders can actually be adequate to prepare a composite, hybrid or FGM product that can potentially replace their monolithic counterpart. It again emphasizes a move to the 'Designer's Materials' to paraphrase with Richard Feynman' famous 'Designer's solid' concept. The importance of hot and cold working, heat treatment and the surface finish can be critical for metallic parts and are of a major concern in load-bearing and/or high repetitive cycle applications. AM is a process that relies on non-equilibrium solidification. Most conventional processing approaches are based on equilibrium solidification. Therefore, it is important to understand a material's suitability for process under the constraint of AM working conditions. Despite the use of similar heat and mass input microstructural differences can result due to the non-equilibrium heat transfer during cooling [39].

It is generally expected in AM that the heat affected zone is limited due to more localized and rapid heating. Rapid and non-linear cooling is often believed to produce fine equiaxed grain structure, which is, generally speaking, reduce the susceptibility of cracking during deposition due to its better ability to hinder crack propagation. Fine grained structure is also known to improve ductility and fracture toughness. Such generalizations must be taken with caution as there are abundant examples where rapid cooling can defy these expectations as for example by forming a hard and brittle martensitic phase when steel is quenched. A more case by case approach must be taken when using high temperature manufacturing followed by rapid cooling.

Ceramics, especially oxide based ceramics, are generally less susceptible to oxidation, and their powder chemistry is less susceptible to degradation over time during storage and transport. Controlling stoichiometry of non-oxide ceramics to a close tolerance can be critical for functional properties, however. Ceramics processing is a mature technique and AM benefits from the huge knowledge of ceramic powder manufacturing and process. In fact, ceramics can be manufactured by any of the seven ASTM classified AM processes as well as other yet to be classified techniques such as electrophoresis and electrophotographic printing in a single step or direct process or a multi-step indirect process [40]. In the direct process both the shape and functional property are achieved at the same time. Single-step processes to shape ceramics include direct energy deposition and single-step powder bed fusion such as selective laser melting (SLM) and selective laser sintering (SLS) processes. Binding between ceramic particles are achieved through chemical binding, solid state sintering, partial and full melting of particles.

Although single step techniques offer a rapid turnover in the production of ceramic parts a significant proportion of AM processes used for ceramics are multi-step (indirect) processes, where the shape setting step is followed by one or multiple shape and function consolidation steps. A binder material is typically used to keep the powder consolidate together in to a shape. The binder is then removed through one or more 'debinding' steps [41,42]. The selection of binder is important in these processes for both flow and agglomeration of particles during AM process. If the AM process parameters are optimized, cracks and large pores can be avoided in making ceramic components. This leads to mechanical properties of AM manufactured ceramics comparable to those of conventional ceramics. In many cases extra densification steps may be required to obtain satisfactory mechanical properties. Anisotropic shrinkage during post-AM consolidation needs to be controlled to avoid negative influence on the dimensional accuracies of final parts [43].

Polymers have been very popular as materials for additive manufacturing of plastics, polymer matrix composites and functionally graded materials targeting a variety of applications [44–46]. This is due to the relatively lower melting and curing temperature, excellent ability to flow when molten or softened, and chemical stability of polymers. They can be AM processed in the feed form of liquid, powders, filaments or sheets. Material jetting and photopolymerization techniques are more common [47] although all known AM processes can be applied if the right formulations of polymers are available or can be developed. This can be a limiting factor for laser sintering based AM for which, currently, only polyamide (PA) based formulations PA12 and PA11 have been used [48]. There is a drive towards using high performance polymers because of the need to have parts and prototypes that can have outstanding mechanical, dimensional, and chemical stability at high temperature and pressure even after exposure to very harsh conditions including those encountered for example in AM processes. Such polymers can be amorphous (e.g. polysulfone, polyetherimide) or semi-crystalline polymers (polyphenylene sulfide, polyetheretherketone). Various liquid crystalline polymers can also be used. In many cases, the performance of conventional polymers can be enhanced for additive manufacturing by the addition of special fillers such as graphene, carbon nanotubes, nanocellulose, nanoclay, and nanosilica.

The size of the material feedstock can range from nanometers to micrometre to millimetre. Colloidal and rheological properties of particles, droplets, additives, fillers and binders in the feedstock, however, need to be considered carefully. Metal particles are most susceptible to environmental degradation for example due to moisture and oxygen. They can also be pyrophoric and needs special care in storage and handling. The process of metal powder manufacturing may cause severe plastic deformation and internal strain, which can age. The time from the production of these powders to their use can affect the AM process and the final properties of the AM product. Special attention must be given while recycling unused materials irrespective of whether they are metals, ceramics or polymers. The thermal history may degrade the feed material especially when such materials have been specially prepared for a target AM process to have a desired functional property.

The feedstock materials in AM thus require much more intense design thinking than conventional manufacturing. Raw materials used in AM are considered to be secondary in nature as they usually require careful pre-processing before used in industrial production. In addition to the inherent chemical constitution thermal (specific heat, crystallization and recrystallisation, surface and bulk melting, equilibrium and non-equilibrium solidification, phase solubility and precipitation, latent heat, thermal expansion and conduction, glass transition in case of polymers), optical/electronic (absorption, reflection, transmission if photon or radiation process used) and rheological properties (melt viscosity, surface tension) of such secondary raw materials are intrinsic considerations. Extrinsic properties that require special considerations are the process of manufacturing of feed (precipitation, erosion, etching, grinding/ball milling, cryo-milling, electrodischarge melting), Shape and surface of the feed (irregular, sharp corners, smooth, spherical, plane, rough, textured, coated), colloidal properties (size, distribution, dispersion, agglomeration) and flow through the feeding system (e.g. a nozzle) at the feeding conditions. Table 3 summarizes the materials related issues that are to be considered in AM.

The measurements: towards real time, in line, quality assurance

While inspection and quality assurance have been the corner stones of both ancient and modern manufacturing, this narrative for AM is relatively new. The field is, however, rapidly growing as the success of AM is critically dependent on robust quality assurance. In a PwC survey nearly half of the manufacturers surveyed indicated that uncertain quality of the final product was a barrier

Table 3

Intrinsic and extrinsic properties of feedstock materials, relevant metrological approach and metrology techniques for AM. XPS: X-ray photoelectron spectroscopy; ToF-SIMS: Time of Flight Secondary Ion Mass Spectroscopy; PSA: Particle Size Analyser; DSC: Differential Scanning Calorimeter; DTA: Differential Thermal Analysis; TGA: Thermogravimetric analysis; DMA: Dynamic Mechanical Analyser; SEM: Scanning Electron Microscopy; TEM: transmission electron microscope; EDX: Energy Dispersive X-Ray Spectroscopy; FT-IR: Fourier Transform Infra-Red spectroscopy; Raman: Raman Spectroscopy; IR-M: Infra-Red Microscopy; CARS: Coherent anti-stokes Raman Spectroscopy; c-OBF: Confocal Optical Birefringence; TSDC: Thermally Stimulated Depolarisation Current; XRD: X-ray Diffraction; EBSD: electron back scattered diffraction; TEM: Transmission Electron Microscopy; LM: visible light microscopy; PM: polarization microscopy; X-CT: X-ray computed tomography; IR-T: Infrared thermography; ZP: zeta potential measurement; EK: electrokinetic measurements; DLS: dynamic light scattering; AAS: atomic absorption spectroscopy; UV–Vis: ultraviolet–visible light absorption spectroscopy; IR: infra-red; GM: gravimetry; MW: microwave; CA: contact angle measurements; AFM: Atomic Force Microscopy; SFG: Sum Frequency Generation spectro/microscopy.

Property	Material factors	Specific property of interest	Metrology approach	Specific/potential metrology technique
Intrinsic	Bulk chemistry	Elemental	Off line/At-line	AAS, UV-Vis, IR, EDX, GM, ToF-SIMS
		Molecular/bonding	Off line/At-line	Raman, FTIR, CD
	Surface chemistry	Elemental	Off line/At-line	XPS, AAS, UV-Vis, FTIR, EDX
		Molecular/bonding	Off line/At-line	XPS, ToF-SIMS, Raman, FTIR, SFG
	Size	Average size and size distribution	Off line/At-line	
	Thermal	Specific heat, latent heat, melting/freezing, (Re)-crystallization, softening, glass transition temperatures	Off line/At-line On line/In-line	DSC, DTA, TGA, Optical pyrometry IR thermography
		Expansion	Off-line	Dilatometry
		Phase solubility, precipitation	Off-line/At-line On-line/In-Line	TGA, FTIR, Raman LM, IRM
		Equilibrium and non-equilibrium solidification	Off Line	DTA
	Optical	Absorption/ reflection/transmission/ polarization/birefringence	Off-line/At-line/ Online/In line	UV-Vis, IR, MW
	Rheological	Melt viscosity	Off-line	Rheometry
		Surface tension	Off-line	CA
		Viscoelasticity	Off-line	DMA
Extrinsic	Process history	Precipitation, erosion, etching, grinding, ball milling, cryomilling, EDM	Off-line	Supplier specification and datasheet
	Shape/surface/Morphology	Irregularity, sharp corner, spherical/planar morph, coating	Off-line	LM, PM, SEM, TEM, Raman, IRM
		Roughness or smoothness	Off-line/At-line On-line/In-Line	AFM, profilometry Optical profilometry
		Texture	Off-line/At-line Online/In line	XRD, EBSD, SEM, TEM, LM, PM, IRM xCT, IRT
	Colloidal	Size, distribution, dispersion, agglomeration	Off-line/At-line	ZP, EK, DLS

to the adoption of AM [49]. Measurements underpin process optimization, inspection and monitoring, and product quality assurance. While we can make some very complex and unconventional shapes and structures by additive manufacturing, we are yet to put in place a robust quality assurance scheme mainly due to lack of appropriate and enough metrological tools and methodologies available for different AM techniques.

Metrology, the science and act of measuring, is required for AM not only from a technological confidence point of view but also due to the market pull for consistent and reliable performance of AM-built parts. It would soon become a legal and financial requirement for AM products that would be sold in the market. Similar to risk perception related to nanomaterials [50,51] the underwriting community would require adequate and standardized measures to ascertain functional properties, shape and dimensional tolerance and performance of AM products for insurance. On the other hand, metrology is equally important to control and optimize AM so that the production remains at low cost by better utilization of expensive feed materials, increasing production yield, reducing part rejection, increasing energy efficiency and decreasing post-build processing requirements.

Metrology in AM can be carried out inside the build chamber (*in situ*) or outside the chamber (*ex situ* or off line). The schema in Fig. 4 explains these approaches in metrological analysis. In the *in situ* approach, metrology tools integrated with the movable nozzle or heat source of AM can provide a convenient way of conducting real-time investigation of deposition, fusion, freezing and consolidation at the same spot (the donut in Fig. 4). Fast imaging techniques using for example optical, X-ray, e-beam, ultrasound or scanning probe can be used for such measurements. The beam approach can also be used remotely by scanning a focal point that would move along with the depositing nozzle/heat source in tandem. The latter approach has been used in metal AM where a visible light charged coupled device (CCD) camera or an infrared (IR) camera mounted externally have provided *in situ*, non-contact, non-destructive analysis of the melt pool analysis [52]. The built part can also be analyzed *in situ* but while the job is still on the production line (On line metrology in Fig. 4) at a sample point that has already been deposited and either undergoing or has completed fusion, freezing and consolidation. This approach allows the convenience of locating the sample spot sufficiently far away from the deposition spot while still providing *in situ* information. Both beam and probe based approach can be suitable for such analysis. In *ex situ*, at-line metrological approach, a sample can be extracted from an arbitrarily chosen point (the donut in Fig. 4). The extracted sample can then be transferred outside the chamber for measurement and analysis. This technique is minimally destructive as the sampling damage in the part can be repaired in the next sequence of layer deposition. Finally, the completed job or a part of the job can be sent for *ex situ*, off line metrological analysis. This approach does not provide real time process information and may require destructive process in sample preparation but provides a wealth of information regarding process variables that may have deterred desired performance or adequate quality. Off-site techniques also allow a much more detailed forensic of the materials' issues that can be linked to the performance of the AM-built part.

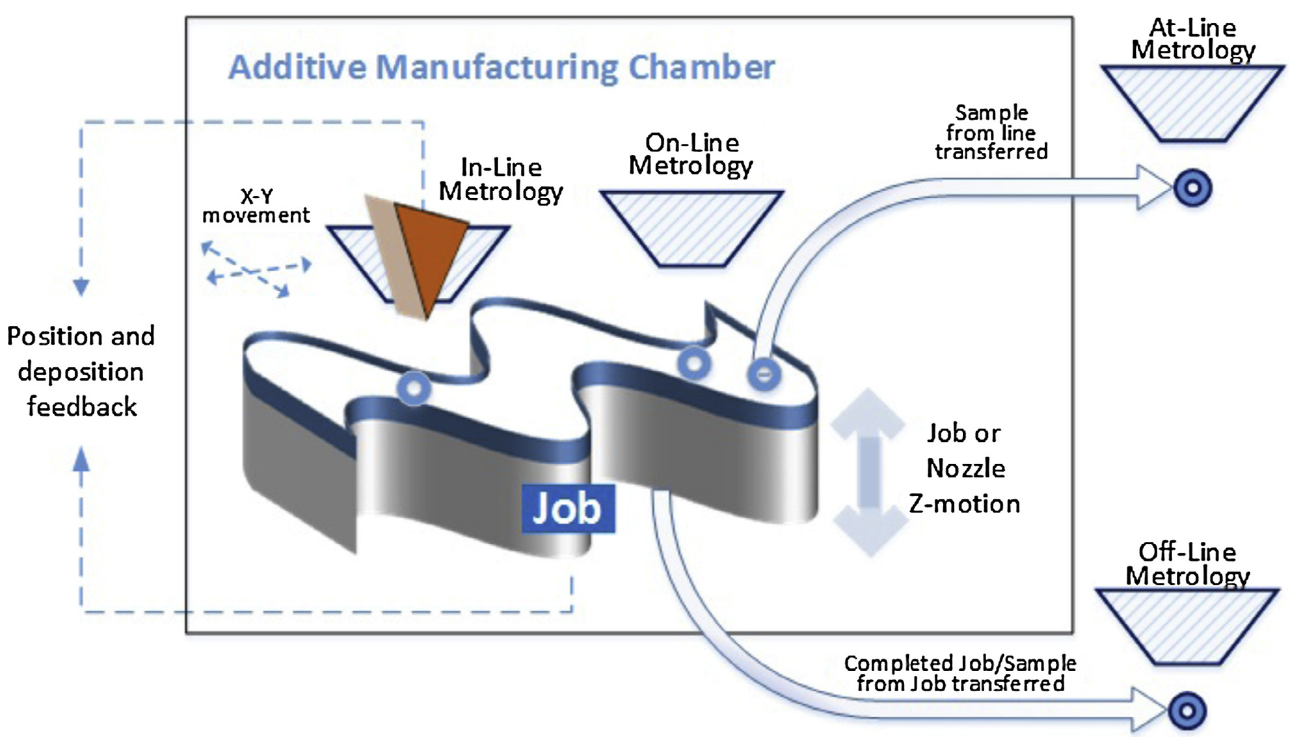

FIGURE 4

A schema of metrological approaches in AM.

Regardless of the specific AM process or technology employed, AM parts generally present similar metrological challenges and issues [53]. This makes possible a generic discussion on metrological issues relevant to AM without delving into the details of specific process and technique related problems. For example inspection processes for powder metallurgy fabricated parts can be educational in understanding parts formed using metal AM [54–56]. Currently available non-destructive testing (NDT) can be a good starting point to detect and characterize defects considered to be significant, although the definition of a defect and its size will depend on the feed materials type (metals, polymers, ceramics, composites, hybrid), AM process and technique involved, the intended application and the fundamental materials science of structure-property relationship. Table 4 lists a number of generic issues related to AM and suggest metrological approaches that can be taken to tackle these issues.

Currently, AM tool manufacturers emphasis *in situ* measurements of the dimensions of the job that is being built (dimensional metrology). Dimensional tolerances of the AM part is important but due to the emphasis of AM towards its ability to create shapes and features in the component, it is important to establish that these too are within the tolerance limit of intended dimension and designed shapes. This would in turn allow assembly of complex components if all of them are manufactured within certain expected and agreed upon tolerances. Such an approach will enable a high confidence in product, improve energy efficiency, and reduce scrap material, redundant processing time, and cost.

In AM the use of a layer-by-layer building of a 3D space tessellation ends up with a 2D building strategy, which may result in discontinuities in all directions of building As a consequence, AM products often suffer from dimensional inaccuracy, unacceptable surface finish state, structural and mechanical anisotropies [57–61]. The dimensional resolution of AM is limited by available tooling, the dimension of which is finite. This can lead to differences between the virtual and the real design in AM [62]. As a result, internal structural features may not be well captured during AM; internal discontinuities (porosities) may appear; and the state of surface finish may not be limited due to rough profiles. In addition to these defects the AM product can have trapped unwanted material which change the local density of the structure, modify the local stress distributions and serve as an internal crack initiator thus affecting the performance expected from the virtual design. Strategies exist to overcome these defects during AM process but characterization of such defects is integral to such process optimization in AM [63]. A number of characterization techniques have been used for real-time control of structural and microstructural defects in AM parts to provide information on the process-generated internal network of pores, surface roughness, part volume, and the amount

Table 4

Generic materials issues and suitable metrology for AM. XPS: X-ray photoelectron spectroscopy; ToF-SIMS: Time of Flight Secondary Ion Mass Spectroscopy; PSA: Particle Size Analyser; DSC: Differential Scanning Calorimeter; DTA: Differential Thermal Analysis; TGA: Thermogravimetric analysis; DMA: Dynamic Mechanical Analyser; SEM: Scanning Electron Microscopy; TEM: transmission electron microscope; EDX: Energy Dispersive X-Ray Spectroscopy; FT-IR: Fourier Transform Infra-Red spectroscopy; Raman: Raman Spectroscopy; IR-M: Infra-Red Microscopy; CARS: Coherent anti-stokes Raman Spectroscopy; c-OBF: Confocal Optical Birefringence; TSDC: Thermally Stimulated Depolarisation Current; XRD: X-ray Diffraction; EBSD: electron back scattered diffraction; TEM: Transmission Electron Microscopy; LM: visible light microscopy; PM: polarization microscopy; X-CT: X-ray computed tomography; IR-T: infrared thermography; ZP: zeta potential measurement; EK: electrokinetic measurements; DLS: dynamic light scattering; AAS: atomic absorption spectroscopy; UV–Vis: ultraviolet–visible light absorption spectroscopy; IR: Infra-Red; GM: gravimetry; MW: microwave; CA: contact angle measurements; AFM: Atomic Force Microscopy; SFG: Sum Frequency Generation spectro/microscopy.

Material factors	Specific property of interest	Metrology approach	Specific/potential metrology technique
Solid (powder, wire, sheet) or liquid feedstock preparation/engineering/modification			
Surface chemistry/chemistry of binder, filler, adhesive and fluxes	Elemental	Off-line/At line	XPS, AAS, UV-Vis, IR, EDX
	Molecular/bonding	Off-line/At line	XPS, ToF-SIMS, Raman, FTIR, SFG
Wettability	Surface energy Surface charge	Off-line/At line	CA
Finish	Roughness	Off-line/At line	AFM, Profilometry
Anisotropy	Texture	Off-line/At line	XRD, EM, LM, PM
Built-part monitoring			
Shape, size and build volume	Dimensions	On-line/In-Line	Contact metrology Optical metrology
Surface chemistry	Molecular bonding	On-line/In-Line	Raman, FTIR, SFG
Macrostructure and porosity	Droplet/melt pool size	On-line/In-Line	IR-T, LM, PM, EM
Microstructure,	Grains, grain boundaries, cracks and defects	On-line/In-Line/At line/Off-Line	IR-M, Raman, PM, LM, EM. Raman, FTIR, IRM, SFG
Thermal management	Heat distribution and dispersion, thermal stress	On-line/In-Line	IR-T
Post-Build processing			
Thermal	Internal stress	Off-Line	XRD
Hot and cold working	Grains, grain boundaries, cracks and defects including dislocations	Off-Line	EM, LM, PM
Heat treatment	Stress-release, grain refinement	Off-Line	XRD, EM, LM, PM
Surface finish	Roughness	Off-Line	AFM, Profilometry

of support material trapped. These techniques include optical tomography, X-ray tomography, thermographic analysis or ultrasonic monitoring [64–69].

Most manufacturing relies some form of dimensional metrology for example contact/optical coordinate measurements during making of the object. Contact techniques are slow but accurate for regular geometric objects. However, these are largely inadequate for AM products where the shapes deviate significantly from being geometrically simple. Besides, many AM processes create 3D structures, the inside of which cannot be measured by contact metrological systems. Measuring texture and in-process defects largely depends on both destructive and non-destructive off-line characterization techniques such as X-ray computed tomography (X-CT) and electron microscopy (EM). Non-destructive techniques such as IR thermal imaging, while excellent for monitoring thermal management, can produce only limited tolerance information. X-CT and some relatively higher pressure scanning electron microscopes can be integrated in the build chamber for in-line and on line metrology.

Additive manufacturing provides infinite design freedom to create a complex labyrinth of structures, shapes and forms of huge range of materials – all to be manufactured at a very high speed. It makes finding an in line metrology tool from the current pool of techniques extremely difficult. Contact measurement becomes ineffective due to the presence of enormous amount of surfaces within a 3D structure most of which are inaccessible by a contact probe. A switch to non-contact method such as those based on optical, electrical or magnetic measurements will be required. In particular, the scope of optical metrology is quite large for both in line and on line metrology [70]. One of the contributing factors to this potential of optical metrology is that optical techniques are already part of precision engineering in optical lithography and laser machining. Visible light imaging usually provides poor image contrast in polymers, biological materials and transparent ceramics. This can be improved by switching to non-linear optics where the contrast is generated from the materials inherent chemical and structural properties. Examples include the use of polarization microscopy, Raman and infra-red spectromicroscopy [71].

Many prominent AM machine manufacturers now provide *in situ* monitoring and closed-loop feedback modules, which can be added onto the basic AM machine used in powder bed fusion and direct energy deposition. Most of these modules involve image based melt pool monitoring camera rather than any significant defect analysis. In many cases, however, the data generated is stored but not analyzed in real-time for closed-loop feedback [72]. Metrology in AM is still a challenging issue as it appears that adequate non-destructive techniques are not yet fully available to evaluate properly AM part performance [73]. *In situ* measurements of AM processes, such as metals-based powder bed fusion processes, requires high speed measurements of localized, rapid melting and cooling. The movement of the heat source at high velocities and accelerations poses another challenge of constant refocusing of imaging apparatus in tandem with the movement. The location of the imaging sensor system in the AM chamber must not interfere with the machine's normal operations (e.g. spreading or laying down powders, melting, cooling), environmental conditions (e.g. inert atmospheres or vacuum) and safety systems (e.g. laser protections). Above all, the sensor system must be immune from the contamination from the process debris and by-products.

Materials characterization of AM parts is also challenged by AM machine and process variability requiring high level of customization of the techniques for *in situ* measurements. Use of laser based imaging can be very useful in meeting the metrological need of AM. Fast real-time imaging with laser scanning of real surfaces has been demonstrated in surface texture analysis [74]. Imaging techniques such as confocal imaging, optical coherence tomography (OCT) and IR tomography can provide subsurface information. In many cases laser based spectroscopic imaging can also reveal the chemistry of the surface and inside the structure. One of the biggest challenges of image based approaches is that it also generates big data from which rapid, online decision making would need to make use of image processing, pattern recognition and automatic decision making algorithms with respect to suitable benchmarks. The dream of distance digital manufacturing (DDM) would then be one step closer through transmission and sharing of these data to an end user, who can then customize from his/her workplace the production of his/her own product at a distant foundry.

Completely new approaches to instrument design based on a combination of expertise and innovation will help to overcome the barriers towards current instrumentation needs for the required accuracy and measurement speed for AM operations. Fundamental research will be needed to develop the next-generation of techniques for dimensional, texture, mechanical and chemical measurements of additively manufactured components. These new techniques should offer higher accuracy and faster measurement speed in an AM operational environment. Non-contact methods such as optical and X-ray techniques must be customized to enable rapid, real time ambient measurements. These measurements would have to be properly benchmarked with respect to off-line techniques, which have higher accuracy but are slow and difficult to incorporate in a manufacturing environment. Calibration methods and samples [75] will have to be developed for these new metrological approaches, techniques and methodologies.

The market: a drive from 'lab' to 'fab'

Since the first patent granted in 1986 [76] and the first 3D printing machine (stereo-lithography based) built in the late 1980s by 3D Systems, the market for AM industry has grown significantly within the first decade ($\sim$\$1 billion US – 1997). Concurrently, AM has transitioned from rapid prototyping to functional prototyping. Today, AM is used in all sectors of industries from space to toy to food, and represent a multi-billion dollar industry. Cheaper machines makes AM more accessible item today than ever before, partly due to the FFF patent. A new AM machine can be purchased today for as little as \$500 compared to > \$100,000 in the 1990s. The future of AM will be driven more towards design and materials innovation for manufacturing of real products. Some of the key applications of AM are listed below:

Car Industry	• Integration of many parts in a unified composite part • Construction of production means • Production of spare parts and accessories • Fast standardization
Aerospace/ Aeronautics	• Production of accessories of complex geometry • Control of density, mechanical properties • Production of lighter accessories
Medicine/ Pharmaceutical Industry	• Planning of surgical operation with the use of accurate anatomic models that are based on the Computed Tomography (CT) or the Magnetic Resonance Imaging (MRI) • Development of adjustable orthopaedic implants and prosthetics • Use of printed simulated corpse for medical training in anatomy • Printing of biodegradable living tissues for tests during the development phase of the medicinal product
Sports Industry	• Production of accessories of complex geometry • Creation of adjusted protective equipment for better application and use • Creation of prototypes of multiple colours and composite materials for products testing
Construction industry	• Additive manufacturing of concretes for conventional building • Novel design of functional concretes such as self-cleaning concrete, high performance concrete • Building construction using materials found in the vicinity • Cement free building • Low cost, low energy building

Currently, AM is more suitable to high value low volume products as it pays no heed to unit labour costs or traditional economies of scale. The technology enables flexible production and mass customization as designs can be changed quickly. The capital investment in AM is quite high even for the manufacturing of an object of the size of a small boat [77,78]. Additionally, the multiplicity of skills required by an operator to operate AM will require high skill labour on a building site. It will also take some time before decision making can be totally replaced by full automation through digital decision making. This makes way for the realistic expectation that AM is not about replacing conventional mass manufacturing, which can produce, if required, thousands of identical parts at low cost. It is about making shapes and products which are not either possible or cost-effective to manufacture through conventional manufacturing. This is where AM is showing high promises and has been greeted enthusiastically by some of the world's biggest manufacturers, such as Airbus, Boeing, GE, Ford and Siemens [79] in an attempt to a leap towards Manufacturing 4.0.

Additive manufacturing is the cornerstone of realizing Factory 4.0 or Manufacturing 4.0 and has placed manufacturing competitiveness and higher productivity in both national and supranational agenda worldwide. Both industrialized and newly-industrialized nations are taking part in this pursuit. For example, manufacturing in the European Union contributes to 30 million jobs directly and twice as many jobs indirectly [80]. It contributes to 80% of total EU export and 80% of private R&D expenditure. Advanced manufacturing currently contributes to 1.6 million jobs and 11% of the total EU production. Almost half of European manufacturing companies have not used advanced manufacturing technologies in the past and do not plan to use them in the next years. AM is seen as a key to secure robust industrial base, with a value creation of 1.6 million jobs and to amount 11% of total EU production [80]. There is a strong drive to change this. In Europe, 'Digital Innovation Hubs' in every region based on World class specialized competence centre are able to provide industry with access to knowledge, technology development means and testing facilities. It will reach an investment level of €12 billion in the next 7 years.

In the United States (US) of America, where AM concept started about three decades ago, AM is now used in almost every manufacturing sectors by leading industries including sectors such as space, automotive, semiconductor, aerospace and biomedical. Similar to its European counterpart, the US manufacturing industry has been under pressure from Asia especially China in terms of competitiveness. AM has provided a significant opportunity for emerging US manufacturing while maintaining and progressing US innovation. The US is currently one of the primary producer of AM systems (see Tables 1 and 2) and one of the major users of AM technology [81,82]. However, in an increasingly competitive world, taking advantage of the opportunities that AM offers may prove to be difficult. Some fear that AM may turn the US into a more competitive place for manufacturing resulting in more goods being produced in place while with a concomitant reduction of manufacturing employment [83]. Even if AM leads to a significant increase in productivity that may attracts jobs from overseas and facilitate a net increase in employment through new products, it may not bring in a net increase in manufacturing employment due to transfer of employment to other employment sectors [84].

Globally, an estimated $642.6 million in revenue was recorded for additive manufactured goods, with the US accounting for an estimated $246.1 million or 38.3% of global production in 2011 [75]. Approximately 62.8% of all commercial/ industrial units sold in 2011 were constructed by the top three producers of AM systems: Stratasys, Z Corporation, and 3D Systems. Approximately 64.4% of all systems were manufactured by companies based in the US. Between 2031 and 2038, AM is expected to reach 50% of its market potential, while reaching 100% of its expected market potential between 2058 and 2065 [85]. In monetary terms this estimate indicates that the industry would reach the size of $50 billion between 2029 and 2031 and $100 billion between 2031 and 2044 [78].

With 70% manufacturing share of global trade and 5 out of the top 10 global manufacturers, Asia is embarking on AM mostly through research investment [86–89] with the hope to translate into mainstream productions as early as 2018 [90]. The key reasons for the recent boost is the expiration of AM technique patents and also an increasingly global outreach of the AM tools by the current manufacturers from the US, Europe and Canada. Continuous support and investment from both public private sectors has also facilitated the growth. The potential for 3D printing to cut dependence on more traditional, labour-intensive manufacturing processes will enable it to play a significant role in the economies in these countries. China is no doubt the frontrunner in the adoption of AM in Asia. In 2013, the value of China's 3D printing market was estimated at 1.72 billion yuan with 9% share of the global market. Of the 200,000 printers installed in 2013 worldwide, China accounted for only 10% in comparison's to 40% in the US. Currently the status of 3D printing technology is on a par with that in advanced economies such as the US but China still lags behind in materials and software developments [91]. This scenario is going to change soon, however, given the track record of China's in surpassing the US in 2012 to become the leading manufacturer of the world [92]. If this happens, users of additive manufacturing technology, materials and software would have to buy the technology from Asia and their suppliers would compete with experienced Asian players.

AM has been considered to be a market disrupter. Instead of augmenting the current supply and value chains AM may potentially replace them. When considering the vast global network and supply chain that currently exists where raw materials are mined in one country or location, processed to stock or component level at another location or factory and assembled into an array of various products are multiple sites, it is possible to understand the high entry barrier for AM to replace this value chain in the short term. End product manufacturers using AM would have to embody the entire value chain. This means a compression of the value chain that will require in-house expertise in materials, metrology, joining, assembly, robotics, automation and computer aided design. It is therefore likely that the AM market will continue to develop in low volume production of high value-added products. Over time, particular players along the value chain may begin to incorporate individual additive manufacturing techniques on a cost effective basis into the chain. This means that continuous improvements and innovations in performance and compatibility of individual categories of additive manufacturing with particular materials systems will be of paramount importance for future uptake of AM. Other drivers that are potentially important as new manufacturing technologies and innovations progress to market include the regulatory and framework conditions within the market.

Industrial scale implementation challenges and future directions

AM in industry is currently at a turning-point, since more and more industrial units have started using it for both rapid prototyping and product manufacturing. The use of a 3D printer has nowadays surpassed standardization and printing of tools and small objects. Some 11% of the 100 manufacturing companies participating in a PwC-survey informed that they had already moved to 3D printing for mass production of individual parts or integrated products while an estimated 42% of large North American companies stated that by 2020 they would use SLS 3D printers for a large portion of their operations [93]. It can be expected that more companies will follow as the range of materials for AM continues to expand. The success in AM of thermoplastic polymers such as poly lactic acid (PLA) or acrylonitrile butadiene styrene (ABS), the photosensitive resins, ceramics, cement, glass can be expanded to many more metals, ceramics and thermoplastic composites reinforced with carbon nanotubes and fibres biologicals, food, pharmaceuticals and so on. Process optimization and selection of process parameters will be key determinants of the success (Fig. 5).

AM can provide a viable alternative to current projection-based manufacturing by introducing on-demand manufacturing. This make-on-demand manufacturing is similar to the print-on-demand strategy widely adopted in print industry where a pre-composed finished book is printed from its digital proof when a customer has placed an order. This would mean that storage of the manufactured part may not be necessary or long. Only

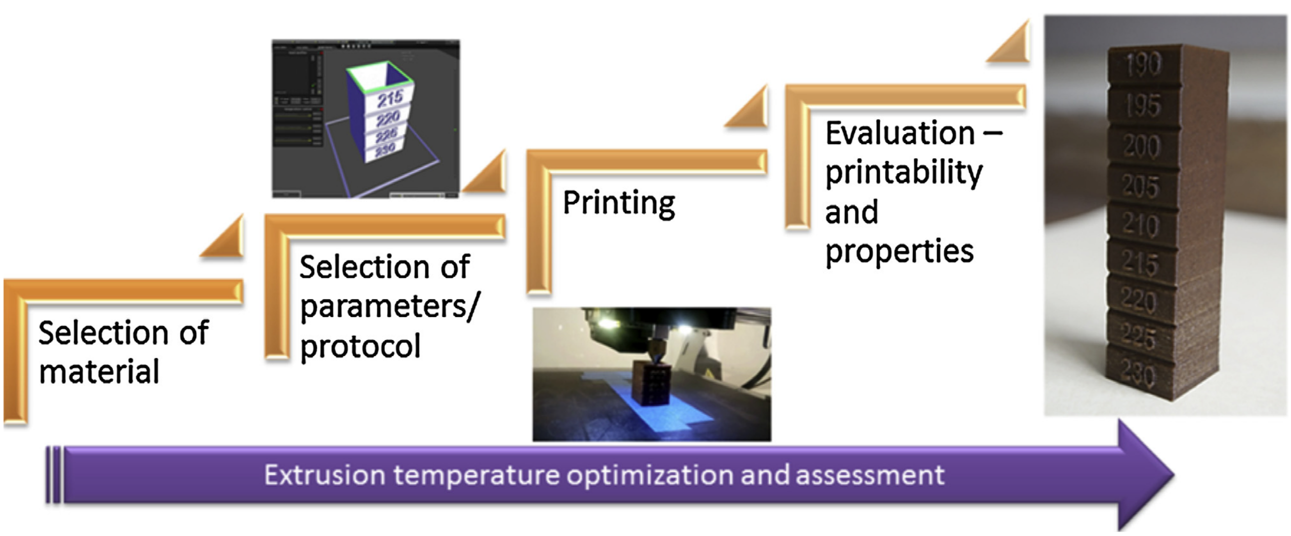

FIGURE 5

An example of materials and process selection protocol of Additive manufacturing developed for polymer fused filament fabrication (FFF). The material filament is polylactic acid (PLA) co-blended with lignin, for low cost carbon fibre precursor [94].

the digital version of the design of the part will be saved. Parts from that design will be manufactured additively on demand with immediate shipment of the finished parts. Similarly, many parts can be made only when a customer will place the order in real time.

Despite the fact that the direct costs of the production of products with new methods and the above materials are usually higher, the flexibility offered by AM means that the total cost may be substantially lower. Cost considerations can be a big factor in industrial implementation of AM. Figure 6 shows a radar chart that compares economic and noneconomic impacts of Selective laser sintering (SLS) with conventional manufacturing (old industrial method). We have selected SLS due to our familiarity with these factors in relation to implementing SLS, which has matured enough to make such comparison possible.

The ten potential benefits of additive manufacturing discussed in the introduction require overcoming some of the current problems that would need to be promptly resolved. Manufacturing time, high initial production cost, nonconsecutive production process, materials and mechanical properties and standards specifications are some examples. The construction of an object in additive manufacturing requires that a digital 'design' is forwarded to a printer. This opens the door not only for unlimited revisions, readjustments and improvements of the product but also a far more complex product design and implementation strategy. For example, the question of optimizing the production and integration of old and new procedures when the design is improved will need to be addressed in the most cost effective way. It may not be prudent to invest in a new 3D printer every time the digital design changes for improvement and the former 3D printer becomes redundant to meet the demand of new process design.

The bulk feedstock capacity, the adaptability of the size and shape of the bulk feedstock and the selection of mutually conflicting objectives of achieving higher resolutions and speed would need to be considered. The cost-benefit of adopting 3D

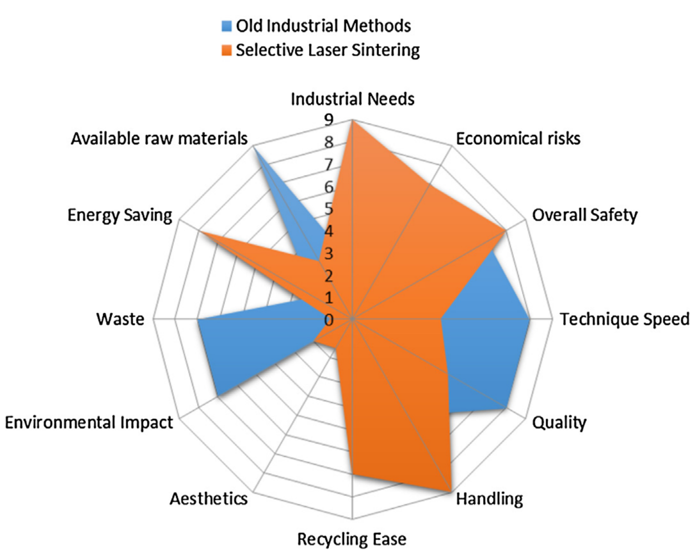

FIGURE 6

A radar chart of additive manufacturing 'past' vs. selective laser sintering (scale 0–9, with 9 being the most significant factor).

printing in particular with respect to the cost of replacing competing conventional technology in making the product must be carefully considered. The need for tailoring materials to suit specific additive manufacturing process and product may require the growth of a secondary raw materials manufacturer such as powder process service providers or an integrated powder processing unit next to the additive manufacturing facility. Such endeavours would significantly increase the cost of feedstock and capital investment for additive manufacturing. Industrial production requires expensive equipment to replace traditional production lines and the energy consumption for the case of large metallic and ceramic components (e.g. due to the laser use) has to be balanced with the prospect of materials and energy saving through zero waste and high throughput manufacturing.

Industry uptake of AM will need efforts in three primary areas: costs, the comparative benefits of AM over conventional manufacturing of the same part, and the rate at which such benefits occur. Costs have been identified as being a one of the most overburdening factors. AM machine costs range between 50% and 75% of total production cost whereas the cost of materials ranges between 20% and 40% and labour ranges between 5% and 30% [95]. Reducing these costs may have a significant effect on the adoption of AM technologies in terms of quality, performance validation, and expanding size capabilities [96]. The expectation that objects can be made anywhere and through consumer-driven on-demand mass-personalization in product design can be restricted due to material limitations, validation and certification. These considerations are of enormous importance for AM growth sectors such as aerospace, automotive and biomedical industry [97–98]. As the design data moves across borders and regions question around taxation, cross-border duty and data protection, ownership, use and fate after production would arise.

Explosive growth in the field of AM has created many new opportunities in manufacturing during the past two decades. Most organizations are considering AM based approaches for low volume parts and concept models. Educators at different colleges and schools are using AM to turn various creative ideas to physical models that can be touched and felt. However, surface finish and dimensional tolerances are still important issues that need further innovation in AM machines. One recent trend is the addition of a subtractive system in combination with AM. The purpose of the subtractive tool is to enhance surface finish, and minimize defects between the layers. Such an approach can increase the usability of AM processed parts in the as processed forms. Another issue with AM is reproducibility. Since each part is built layer-by-layer, part quality between machines or for the same machine at different times should be the same. Otherwise, parts for critical applications may not be manufactured via AM. This problem is inherently complicated due to AM approaches. Most AM processes starts with powder metals, where particle sizes and shapes will vary from batch to batch. The heat source is typically a laser or an electron beam. Both the intensity and beam diameter can vary with the usage of the machine. All of these parameters needed to be optimized for different materials to assure reproducible part quality, which is not trivial. Also, multi-materials AM is slowly gaining popularity. In the world of multi-materials AM, understanding material to material interactions and their processability are also key

RESEARCH: Review

Table 5

A summary of the issues related to the 4Ms of additive manufacturing.

	Key issues
Making	- Evolution of the layer-by-layer fabrication technology with versatility, flexibility and customization - Wide range of materials including metallic, ceramic, polymers and their combinations in the form of composites, hybrid, or functionally graded materials (FGMs) - Development of self-contained, robust, user-friendly, safe, integrated system that would provide the required power, scan motion and speed, high feature-volume resolution with concomitant energy for part fabrication and dimensional control.
Material	- Manufacturing techniques, data communications and system changes within Industry 4.0 or Manufacturing 4.0 - Homogeneity prerequisite - Surface key properties - Extent of required finishing - Nanometers to micrometre feedstock material size
Metrology	- Need for real time in line quality assurance - Monitor and control towards optimization - High level of customization of the techniques for *in situ* measurements - High accuracy and measurement speed requirement
Market	- Factory 4.0 or Manufacturing 4.0 benefit from Digital Innovation Hubs - AM industries range from space to toy to food and represent a multi-billion dollar industry - Cheaper machines makes AM more accessible

issues to successful part fabrication. As AM is revolutionizing the world of manufacturing, it is also a tool that has the potential to create manufacturing hubs even in remote corners of the world, aiding the transformation towards a 'flat world' faster. This can be achieved by ensuring a harmony between the 4Ms of AM, as it has been summarized in Table 5.

Summary

Additive Manufacturing has a market niche with an enormous growth potential if the main barriers to up-take can be addressed. It is clear and reassuring that advances in the technology related to 'making' are producing objects faster, and are able to print these objects in much greater complexities with multiple combinations of materials, colours and finishes. The challenge remains, however, transfer this 'making' into obtaining objects that are functional. A great deal of work is needed in addressing the challenges related to the two key enabling technologies namely 'materials' and 'metrology' to achieve this functionality in a predictive and reproductive ways. The good news is that there is a significant interest in industry for taking up AM as one of the main production engineering route for the next generation. It has the power to make the manufacturing world more 'flat'. Additive Manufacturing, in our opinion, is definitely at the cross-road from where this new and much-hyped but somewhat unproven manufacturing process must move towards a technology that demonstrates the ability to produce real, innovative, complex and robust products.

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