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INVITED ARTICLE

The changing face of additive manufacturing

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Abstract

Purpose – The purpose of this paper is to discuss the current state-of-the-art in additive manufacturing, more commonly known as 3D printing, from the business perspectives. The primary drivers behind the development of the associated technologies are considered along with features that limit growth.

Design/methodology/approach – The approach is a personal perspective, based on approximately 25-years study of the development of the associated technologies and applications.

Findings – The discussion has found that the technology is still growing healthily, but with an understanding that there are numerous application areas that should be considered separately. Some areas are significantly more mature than others and success in some areas does not guarantee success in others.

Originality/value – This viewpoint has been prepared for the current state-of-the-art and can be compared with earlier viewpoints to see how things may have changed in the past. This should be of value to those interested to explore how the technology has developed in recent times and how it may move into the future.

Keywords 3D printing, Additive manufacturing, Business processes

Paper type Viewpoint

1. Introduction

Additive manufacturing (AM), probably better known by many people as 3D printing, has been attracting increasing amounts of public attention in recent years. AM technology has been shown to benefit applications an aerospace, automotive, medical and many other industry sectors with an increasing number of successful case studies. Furthermore, this technology is continuing to develop, broadening the scope even further and making it difficult to track down its full potential.

I became involved in AM when it was known by yet another name of rapid prototyping when I was working as a young lecturer at the Nottingham University some 25-years ago. At that time, there were only a small handful of machines in the whole of the UK. Machines were (comparatively) slow, inaccurate, difficult to use and expensive. This is the case with all emerging technologies but there was always sufficient interest and enough early adopters to maintain a steady growth until we have what we see now as a completely new branch of manufacturing.

This paper aims to explore this potential by first capturing the essence of what AM actually is, which will serve to explain why it is so important to product developers and manufacturers. This will then be supported by an analysis of the major industry sectors and go on to consider where the technology is leading us. The discussion will end by considering where the major research pushes are and what the future may have in store for this exciting field. There are no references in this paper. I will leave it up to you, the reader, to investigate the supporting evidence to back up this viewpoint.

2. What is AM?

AM follows the popularisation of 3D solid modelling Computer Aided Design (CAD). 3D CAD has enabled designers to work freely within a digital design environment so that they can express their design thinking and share across platforms. It became increasingly clear that as 3D CAD becomes more prevalent and easy to use, many of these designs are

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becoming so complex that it has become difficult to consider how manufacturing technology could turn them into a physical reality.

AM solved this by turning this complex 3D manufacturing problem into a series of simpler 2D ones, forming the physical part as a series of thin layers of material. The digital models that have already been created in the CAD system are also used to drive the AM machine. A horizontal plane that represents the build platform area of the machine is projected into the model to identify the intersecting surfaces. These intersections lead to the building of the corresponding layers and so can be indexed upwards through the layers until all have been combined together and the part is complete.

For this to result in a usable part, there are a number of assumptions must be taken care of by the technology. First, there is an assumption that the technology can control the build process so that the layer thicknesses can in turn be controlled. Most AM machines are open loop and rely on precise layer thickness control to maintain the overall accuracy of the final part. Second, it is assumed that there is a mechanism that allows individual layers to be bonded to preceding and subsequent layers. Often the strength of the final part is determined by the success of these bonds. Third, there is a general assumption that the design is of a homogeneous material and that we wish to obtain as uniform a result as possible. I will discuss this further as this is currently a particular area of development. In some processes this interface between layers can result in a weakness in the build (Z) direction that can be significantly lower than the corresponding build (XY) plane. A final assumption is that the part to be built can be done so in a layer-wise manner. For some processes this means that a support structure mechanism must be put in place to ensure all regions of the parts are connected together and will stay in their location before they may form with the rest of the part. Machines that rely on a liquid to solid phase change using photopolymer resins for example must use these supports else parts of the build will float away or fall to the bottom of the build chamber.

2.1 AM and 3D printing

As mentioned earlier, there is a tendency to use AM and 3D printing interchangeably. There is, however, an argument in favour of making a distinction between the two terms. 3D printing may be best used in conjunction with the self-contained, 3D printers that many of us are familiar with. The result from these machines are 3D printed parts that would then be used straight off the machine or after post-processing.

AM can perhaps be best viewed as a process, which in turn could be combined with other processes to create more complex combinations. An example of this would be the Mori-Seiki machine that uses a metal deposition (additive) process in combination with a machining (subtractive) process to create complex geometry metal parts quicker, with better accuracy and surface finish than if done using either of these processes in isolation. As we come to understand these processes better, one can expect to see AM combined with other subtractive, formative or assembly processes to create a wide variety of new products. This has often been referred to as a potential future-factory concept.

2.2 Associated technologies

There is a tendency to view AM as an isolated technology that has somehow taken the world by storm. It has, however, already been stated that AM would not be of any benefit if it were not for 3D solid modelling CAD. It is perhaps worthwhile to indicate here that there has in fact been some form of technology convergence principle at play here. Many application areas appear to treat AM as a core technology but in conjunction with other technologies. For example, there are many applications that also make use of 3D scanning technology, mobile or cloud-based applications, entry-level microcontroller or other forms of electronics, e-business solutions, etc.

The key to much of this liberalisation is that the technologies have converged in such way that they are all widely accessible, easy to use and apply, are low-cost, often make use of digital 3D model data and can be integrated in conjunction with the internet. This is much in the same way that computer gaming, drones, VR/AR systems are also becoming popular. One of the things that makes AM something of a nexus is that it not only forms the basis for many new applications and business models, it is also an enabling technology for creating new products in a quick and easy manner.

3. Major application areas

Another reason why AM technology attracts so much scrutiny is because it provides different solutions to different user groups. Let's take a look at some examples of these different groups to identify which aspects of AM provide them with benefit.

3.1 Aerospace

Aerospace manufacturers benefit from the ability of AM to handle complex geometry. Any technology that can reduce weight in existing designs or somehow enhance the functionality for new designs would be particularly beneficial for highly regulated, high-performance industries like in aerospace. Whilst cost is always a constraint in product development and manufacturing, savings in weight or improvements in performance can be equally or more important.

Many aerospace components are defined by mathematically derived equations that relate to physical factors like fluid flow or heat transfer. AM provides that capability to reproduce these components from such equations without being compromised by the manufacturing technology. If conventional manufacturing technology is used, it may be necessary to break a design into numerous sub-components, which must be assembled and which in turn may add mass to the final product and with greater potential for failure or compromise in performance. Through techniques like topology optimisation and the use of hollow-core structures, AM can achieve such results.

There is still much that needs to be investigated in these hi-tech areas in relation to AM. For example, although internal features are feasible, it is difficult to maintain an acceptable accuracy or surface finish. Furthermore, metal AM results in mechanical properties that are too variable for many aerospace applications and so post-build inspection and processing like machining and heat treatment are likely to be required. Having said that, there are already parts finding their way into commercial products, like the fuel nozzles created for the GE LEAP engine.

3.2 Automotive

As mentioned earlier, AM used to be referred to as rapid prototyping. This was because the first major application area was for industries like the automotive sector, who saw the benefit of AM in speeding up product development. Time-critical components, like those related to styling of new vehicles (assuming engines and platforms have longer life-cycles), can slow the whole process and even delay new product launch. It is easy to use AM produced parts to perform form, fit and functional tests with a rapid turnaround should the design fail some of these assessments. AM can also be used to develop tooling solutions so that parts can be validated with serial material and even to help in short production runs for pre-release products or even to facilitate bridge-tooling for early production.

Since this approach is now used by all major car manufacturers, AM is almost an essential tool. Such application is driving the need for stronger materials, faster and bigger builds, greater precision and versatility. This in turn will open up new application sectors. Of course, complexity of form is hugely important to the automotive industry, just as time to market is essential to the aerospace industry, but the emphasis is somewhat different in each case.

3.3 Medical

The medical industry has always shown interest in AM because of the requirement for patient-specific solutions. It is becoming increasingly easy to produce 3D data sets from medical scan technology, whether it is CT, MRI or ultrasound or external body scans using technology like laser ranging or photogrammetry. With such data, doctors and surgeons can produce customised implants, surgical guides, prosthetics, orthotics, splints and rehab solutions. Such individual treatments should speed up recovery rates, make it possible to achieve a more complete recovery and reduce the need for follow-up operations. This should in turn reduce the cost of treatment. It does, however, require more attention to pre-operative planning than is currently the case.

Many industries see a similar benefit in using these approaches. Many products can be enhanced by customisable elements that are designed to fit the human anatomy. Recent developments in photogrammetry technology, which in turn has been enhanced by advanced camera technology, have simplified the process of acquiring high quality 3D surface and measurement data. This is turn has led to products like the Normal^{tm} earphones or from companies like 3D Orthotics.

This ability to generate anatomical data has led to potential problems related to medical validation and liability. Most medical devices must be validated using a laborious and intensive process designated by organisations like the Food and Drug Administration. When products can be customised and bypassed using technologies that are easily available and workable without medical qualifications, the potential for incorrect and misuse is extremely high. Although FDA approval may be appropriate for the machines and materials used, AM for medical applications may also benefit from process validation, like ISO13485.

3.4 Disruptive innovation

The previous examples are set to significantly impact the medical industry. Whilst regulation of medical practices is vital, the effect on implant manufacturers for example will be profound. The use of AM in hospitals to create custom implants to order is inevitable, which will eventually obviate the need for the current implant supply chain. New business models will therefore come into existence.

AM, in the form of 3D printing, has already spawned a large number of new businesses. As previously mentioned this has come about through the principle of technology convergence. Affordable, easy to use and prolific technologies based on computing, the internet and sensor-based technology have enabled entrepreneurs to explore business opportunities without significant capital outlay. Many of these businesses will fail but it is clear that AM somehow enables the creative processes to take place and allow designers to develop their ideas in a quick and easy fashion.

4. How AM is affecting industry today

It is clear that AM is evolving into at least two significant groups. There is an industry that revolves around accessible, low-cost, low-end technologies whilst there remains a demand for high-end technology.

4.1 Low-end technologies

Around the year 2009, a number of key patents lapsed for the Fused Deposition Modelling technology owned by Stratasys that enabled a number of similar machines, including many developed using an open-source approach, to be developed. This created a pricing war that reduced machine costs by orders of magnitude. Machines are now so affordable that many people even have their own machines at home. Aside from the obvious cost advantage, it is important to note that the machines in this bracket are no better than equivalent capacity devices from 15 or more years ago. However, putting them in the hands of many more people has opened the doors to many more applications and business opportunities. Furthermore, with low-cost comes the inevitable reductions in reliability and customer support for such machines, which in general a consumer market is prepared to tolerate. As more patents become obsolete, these impacts are anticipated to continue with the added benefits of increased diversity and performance.

4.2 High-end technologies

Manufacturing industry was obviously the first application field for AM. There have always been significant benefits here and there will continue to be so. Low-end machines are extensively used in industry for idea generation and support but there is an increasing demand for improvements in material properties, build speed, work envelope and accuracy. These can only be fully achieved using more expensive and complex technology. In fact, high-end AM still accounts for at least two thirds of the AM economy.

An example is the Connex process, which was developed for the Polyjet technology to make it possible to create parts with hard and softer regions similar to parts that can be fabricated using injection over-moulding techniques. This has evolved around the concept of "digital materials" where it is possible to predefine the material properties before the part is built so that different regions or even different printed elements (voxels) can be tagged with mechanical (hard/soft) or optical (e.g. colour or translucency) properties.

Furthermore, since it is now common for AM to be used for direct manufacture of low-volume production parts, part strength, durability, accuracy and variability are all important issues. Many technologies are working with composite materials to address this.

Probably the most important aspect of high-end machines is that they are specifically targeted for industrial use. In general, industry has higher demands on reliability and performance than consumers. As such, much of the cost in high-end AM machines is connected to this, either in terms of the use of higher grade components, operating systems with self-diagnostics, additional sensor technology for condition monitoring, or extensive warranty and maintenance agreements. Since time is money, downtime relates to loss of income and industry demands greater reliability and customer support.

5. The future

So what does the future hold for AM? One of the things to note is that AM is not a single technology at a single stage of development. There are a host of AM technologies, some of which are at a relatively early stage and some at an almost mature stage. Note the comments about this being almost 30-years as a commercial technology with many users gaining almost immediate benefit from reduction of time to market for products developed using AM. I have already indicated that AM technology has diverged into high-end industrial and low-end general use. If we look at some of the research areas, we can see how AM may in fact become even more diverse and indeed pervasive.

5.1 Materials

Materials research will continue to drive AM development. The various AM technologies that are available determine what materials can be used in the machines. For example, extrusion-based technology must require a liquid to solid phase change that can be handled within the extrusion head. Similarly photopolymer curing systems must obviously cure on exposure to specific wavelengths of light. However, even with these constraints it is possible to develop a much larger range of materials than is currently available. The use of composite fillers is a relatively simple means of extending this range without having to make significant changes to the technology.

Probably the most exciting branch of AM from a materials perspective is currently in metals. The most widely used metals in AM are also some of the most widely used in industry, namely steel, titanium alloys and cobalt chromium. Probably the most exciting is titanium since it is heavily used in both medical and aerospace industries. Aluminium would be an obvious addition to this and is in fact now available along with Inconel, platinum, gold, silver, copper and brass. Many of these materials may, however, require additives that aid the fusion process or the resultant parts may require further post-treatments to enhance their functionality. Machining of key surfaces to ensure accuracy and assembly fit would also be a desirable post-process.

A key benefit of AM is the ability to create multiple material components in a single process, like the digital material process mentioned earlier. This would provide functional differences within a single structure. These functionally gradient materials could create a structure that includes a material with high-heat conductivity, like copper, in certain regions. The same structure could also contain steel to enhance the part strength. The use of a gradient between these materials could feasibly prevent interfacial weaknesses. Many laser engineered net-shaping machines have multiple feed channels that can enable mixing of metals in variable ratios to try to achieve this. The same process can also blend alloys in-situ, which can be difficult for certain materials. It is becoming popular to blend titanium and tantalum in this way to generate medical implants with greater biocompatibility.

One material that has yet to be successfully added to AM technology is ceramics. Whilst there has been a widely publicised glass printer, the results will never be useful for many optical applications. Furthermore, there have been numerous ceramic-filled composite approaches that can result in useful ceramic parts. However, these are complex AM processes that require significant post-processing using furnaces, for example.

5.2 Design for AM

With the increasing emphasis on the use of AM for direct manufacturing of low volume, patient specific, or customised products, there is an equally increasing need to ensure these parts are fabricated right first time. Predictive mechanisms for these parts, using finite element techniques, for example, are important to ensure that the parts can be properly built inside the AM machine and will withstand the forces and other environmental conditions that they were designed for. This is fuelling the need for a branch of design for X aimed at AM. Since many AM technologies result in parts that are heterogeneous in their mechanical properties, this may not be a simple process. Design support must include attributes relating to layer thickness, wall thickness, support structures, finishing parameters, build times, and other factors that relate to final part quality. In addition to this, as mentioned previously, some AM technologies can include more than one material or can locally modify the properties within a part.

One of the benefits of AM is the so-called "design freedom" or "complexity for free" attached to the build. Although this is not completely true, since there are always compromises in any manufacturing process, there are certainly many process constraints that can be avoided. AM is therefore becoming the process of choice for those wishing to explore topology optimisation, which allows designers to focus on ensuring the geometry of the part will not require additional material and therefore extra mass.

Until recently, the file format of choice was the STL surface model that uses a simple triangular approximation. As designs became more complex, corresponding files also became too large and wieldy. Furthermore, this represented a risk that file format errors may go unchecked. With multiple material constructs, mechanistic features (like gears, living hinges, etc.), colour, and other information that described the parts being built, it has become increasingly clear that a more versatile file format is going to be required moving forward. Whilst the AMF format is attracting some interest, it is not clear whether another, more universal approach may become evident in the future.

5.3 Biomanufacturing

A huge amount of effort is being directed towards the possibility of AM allowing the fabrication of spare human organs. Based around tissue engineering and regenerative medicine, there are many efforts to recreate the 3D features of these organs with most success revolving around bone engineering. Since bones have relatively high mechanical strength and rigidity, there is a strong similarity to polymer-based AM output. Scaffold structures are often created using bioactive materials, like ceramics, surrounded by biodegradable polymers. Tissue cells are introduced into these scaffolds along with proteins and other agents that encourage healthy differentiation and proliferation. In many respects, current AM technology is unsuitable for this process, lacking the accuracy, complexity and functionality to achieve a desirable result. Nevertheless, there is much that already has been learned in trying to achieve this. For example, 3D tissue samples have been used in drug discovery trials.

It may be that foodstuffs can be created using AM, including the growing of artificial tissue samples to replace meat. Once created, they can be recombined into shapes that are aesthetically pleasing and edible. Whilst it is generally unnecessary, it is my belief that the first large-scale consumer-based AM technology is likely to be located in the kitchen. There have already been a number of chocolate AM machines commercially released and AM has been applied in high-end molecular gastronomic restaurants.

5.4 Integrated systems for Niche applications

As previously mentioned, AM is about processes as well as just 3D printing. Looking at it this way, one can easily see how it can become pervasive throughout many manufacturing sectors. Align Technologies Invisalign orthodontic process is a great example here. AM is just a small component of the whole process, but it is what defines it. It is also quite interesting to note that the process makes use of some of the largest stereolithography machines currently available, even though each individual part is relatively small in order to make batch processing easier. If align were able to define what machine they really need, it may be something with a build platform 30 m long by only 150 mm wide and 50 mm high.

In the future we may find that specific Niche applications will demand dedicated AM-based technology. There has recently been a lot of interest in use of AM for building and construction. Whilst it is difficult to see the sense in entire buildings being made this way, it may be appropriate to use AM technology to make sub-systems, benefiting from the design freedom and customisation advantages. Since buildings are an assembly of structural components combined with service and aesthetic elements, AM is likely to be part of a complex assembly-based manufacturing system. Whatever this may look like, it will be considerably larger than current conventional AM systems. This will be true if we are to see developments for mining, oil & gas and structural aerospace production. All of these sectors would benefit from the capacity for AM to be flexible but we will need to see machines constructed very differently from what we see today.

5.5 Micron-scale systems

Whilst some machines operate around the 10-20 micron range, it is not a resolution that many of them are comfortable with. Physical properties of materials make higher resolutions difficult to deal with. Photopolymers would need to have very low viscosity. Particle sizes would need to be very fine for powder-bed systems, which would lead to agglomeration issues due to electrostatic forces. Extrusion nozzles would need to be very fine, requiring very high pressures.

All of the above issues would require special attention to both the materials and the machinery. Furthermore, resulting build times would likely be much slower than we may tolerate. High-resolution systems do exist in the sub-10 micron range. However, these machines can normally only make very small parts out of a small range of materials for specialist applications. A bright future is in store for a machine that can create a 200 mm cubed part with better than 10 micron resolution, in a wide range of materials in a day or less.

5.6 And?

The implications of AM are far reaching. We have covered the majority of the key issues already but the biggest impact is in the democratisation and social impact that this technology represents. AM and 3D printing has given rise to new business models and even new terminologies. AM has made product development so fast that it is possible to design, build and commercialise a completely new idea in a matter of days if not hours. With this speed it is not possible to keep track of the intellectual property in the conventional manner. AM lends itself very well to an open-source approach, which supports those who get their products to market quickest rather than those who seek to slow progress down through patent protection. This is in itself very ironic since AM technology has benefited significantly from protection of key patents, allowing technology to mature in good time rather than being pressurised by competition.

A final thought. There has been no mention of 4D printing thus far in this editorial. It is my understanding that this term has gained popularity due to the design of parts that have a time component associated with them. This may be in form of 3D printed fabrics or parts with mechanistic properties, for example, which will somehow change their form after they come off the machine. Alternatively, we may consider that sensors and/or actuators may be embedded within the parts so that they may have more active functionality. A further approach may be that 3D printed scaffolds created for tissue regeneration may grow into something else. These are all possible of course, but to call it something else appears to me to demean the technology by saying that 3D printing is not good enough.

6. Conclusions

The future is bright for AM. There are many opportunities that are left to explore. As we do, the technology will itself grow into something else. As such, we must understand therefore that AM and 3D printing are not a single technology or a single application. There are in fact many technologies and applications and they all continue to develop. Some of these are emerging and some have already developed into mature, profitable and widely accepted applications.

Please note that this is a personalised view that is by no means comprehensive. It is aimed at provoking thought and I encourage you to challenge these views and work towards some of the goals to prove either right or wrong. I have enjoyed the last 25-years of AM and look forward to seeing how it will evolve in the future.

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