

Making the Impossible: The Additive Manufacturing Revolution

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Abstract

When one hears the word 'manufacturing', they might think of factories with elaborate cutting tools and large machines churning out large numbers of parts each minute. For many years this has been the norm, but recent developments in additive manufacturing (commonly referred to as 3D printing) have led to a revolution in the way parts can be designed and produced across a wide range of industry sectors. For example, in the world of prototyping and product design, it can often be a time and money intensive process to make incremental changes to potential products. With a 3D printer, however, changes can be made easily, cheaply, and often right in the office where the designers work. Other significant users of additive manufacturing technologies are the automotive and aeronautical sectors where intricate parts, once impossible to produce by traditional methods, can lead to significant material-usage and weight reductions. This review looks to provide an overview of the different additive manufacturing technologies, from desktop Fused Deposition Modelling (FDM) printers to large Selective Laser Sintering (SLS) machines that can produce larger and higher resolution metallic parts. Further to this, some of the current uses of these technologies will be highlighted to show the breadth and depth of their potential applications, followed by a brief outlook to how the world of manufacturing might change in the near future.

1. Introduction

When we hear the word 'manufacturing' we might think of factories with elaborate cutting tools and large machines churning out hundreds of parts each minute. For many years this has been the norm, but recent developments in Additive Manufacturing (AM), commonly referred to as 3D printing, have led to a revolution in the way parts can be designed and produced. Two industries that have embraced the AM revolution are the automotive and aeronautical sectors, resulting in significant reductions in manufacturing costs and weight reduction for modern cars and aircraft.

As the name suggests, Additive Manufacturing involves adding layers of material sequentially to form the desired part. This is particularly useful for complicated designs that were once thought to be impossible. One design element that is particularly troublesome for

33 traditional machining techniques is the production of cavities within an object, but thanks to
34 AM this is no longer a problem. Another significant advantage of this technology is the way
35 the design process is digitized, meaning that digital designs can be converted to the printer-
36 readable file format easily.

37 The first 3D manufacturing technology was patented back in 1986 [1] and since then
38 there has been rapid advancement in the capabilities of 3D printers, especially since the turn
39 of the millennium. In recent years, 3D printers have even become available to consumers in
40 the form of desktop machines. As in industry, the user can quickly go from designing to
41 printing an object, and there are even online repositories (e.g. Thingiverse [2]) with files that
42 can be downloaded and sent to the printer in a matter of minutes. There are also decentralized
43 3D printing services, such as 3D Hubs [3], which can get parts printed for you and save you
44 the cost of buying a printer yourself.

45 Additive Manufacturing encompasses a variety of techniques, based on a variety of
46 technological advancements, as outlined in Figure 1. These include material extrusion, vat
47 polymerization and powder bed fusion methods. These methods use different materials, and
48 result in parts that are suitable for different applications, depending on things like the
49 resolution, mechanical properties (such as strength) and surface finish. We will explain the
50 technology behind many of these techniques and we will discuss their advantages,
51 disadvantages and applications.

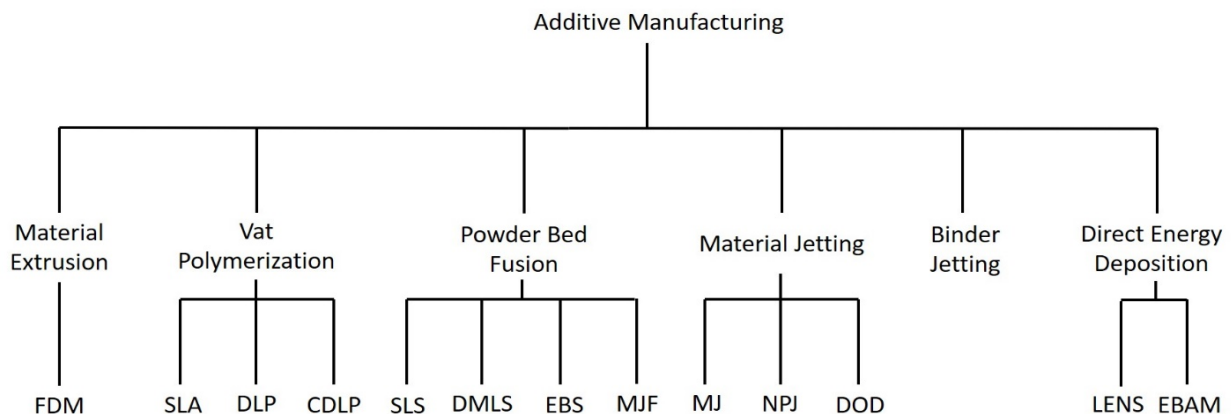


Figure 1: The different additive manufacturing technologies

53 2. Fused Deposition Modelling

54 Fused Deposition Modelling (FDM) is
55 perhaps the best known AM method and it is
56 generally what most people have in mind when
57 they refer to 3D printing. The underlying
58 technology is relatively simple compared to the
59 others methods that will be outlined later in this

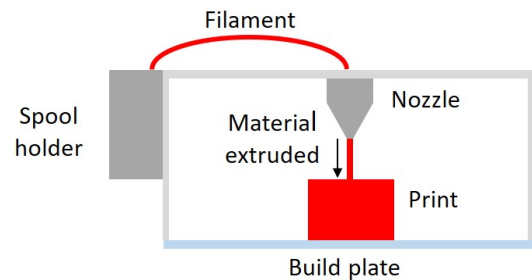


Figure 2: Schematic of FDM printer

60 article, but this turns out to be one of its major advantages. The process involves extruding a
61 thermoplastic filament through a heated nozzle, which moves relative to a build plate. As the
62 nozzle moves it deposits a thin line (typically around 0.1-0.2 mm high, 0.4 mm wide,
63 depending on the printer) of molten plastic in precise locations, where it cools and solidifies
64 (see Figure 2). Each successive layer of material undergoes the same process, building up an
65 object. If a design with overhangs is needed, supports can be printed at the same time as the
66 design and are removed by the user once the piece is finished.

67 Due to the method of feeding in material as a filament, FDM is limited to using
68 polymers with a melting temperature of around 280°C or below, with the common printing
69 materials including polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and Nylon,
70 although other polymers are available. The desired properties of the printed part will
71 determine the choice of material. For example, if an object that needs to be a strong structural
72 part, polycarbonate filament would be a good choice, despite being more expensive than the
73 other materials mentioned. There also some issues with toxic fumes (e.g. with ABS) given off
74 by some of the melted plastics, which may need to be taken into account.

75 FDM was originally developed by Scott Crump, who later founded the additive
76 manufacturing firm Stratasys, and patented the technology in 1992 [4]. When the patents
77 expired in 2009, it resulted in a large increase in the number of FDM printer manufacturers,
78 with some the big names in the industry currently including Ultimaker [5], Flashforge [6] and
79 Makerbot [7]. This helped to drive the costs of printers down from several thousands of
80 pounds to just a few hundred.

81 Print times can be a matter of hours and the material costs are generally low (typically
82 around £10/kg, depending on the material), making this technology very useful for
83 prototyping designs. The ease of altering digital models to try several different designs is
84 another reason why AM in general is suitable for prototyping. FDM is used widely, but one
85 particularly exciting application is in the construction of tools and other objects in space. The
86 International Space Station's Additive Manufacturing Facility [8] is currently home to a large
87 FDM printer produced by the company Made In Space Inc [9]. This printer is not too different
88 to the printers available to consumers and it allows astronauts to build tools, spare parts etc.
89 on board rather than relying on expensive resupply missions. Overall, the simplicity of the
90 FDM technology and low cost of the machines mean that they are a popular option for 3D
91 printing hobbyists and experts alike.

92

93 **3. Vat Polymerization**

94 Unlike FDM, where polymer material is melted and deposited sequentially, Vat
95 Polymerization methods use light of a specific wavelength (typically ultraviolet) to solidify
96 photopolymers one layer at a time. There are a few different methods that use this principle,
97 namely Stereolithography and Direct Light Processing.

98 One advantage of these techniques is the speed at which prints can be made: for
99 example, large functional parts of several tens of cm in length can be produced within a day
100 [10]. Another advantage is that they can achieve a much better resolution (i.e. better detail)
101 and surface finish than FDM. One disadvantage, however, is higher printer costs. As with
102 FDM, Vat Polymerization methods can be used for prototyping, however, another regular
103 application is in the medical industry. For example, data from MRI scans can be used to create
104 a digital model, and then an anatomically accurate printed model of parts of the human body,
105 such as limbs and the skull. These are useful for study and diagnosis [11]. Custom prosthetics
106 and dental implants can also be made using a similar process. Another application is the
107 production of moulds for injection moulding when low numbers of each part need to be made,
108 as this would otherwise be financially unsuitable using normal injection moulding dies [12].

109 3.1 Stereolithography

110 During Stereolithography (SLA), the print
111 build plate is submerged by approximately 0.1 mm
112 in a bath of liquid photopolymer resin. A laser
113 tuned in the ultraviolet (UV) selectively cures
114 regions in the polymer to form a single layer of the
115 build. Once a layer is finished, the build plate drops
116 further into the polymer bath so that a new layer

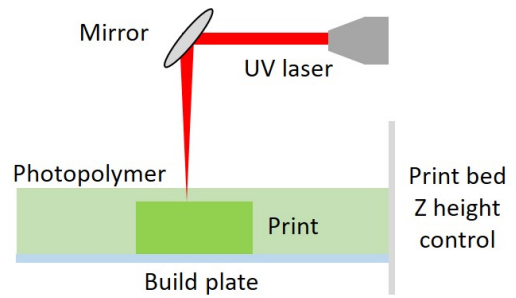


Figure 3: Schematic of a SLA printer

117 can be cured. A schematic is shown in Figure 3. Due to the nature of the curing process, SLA
118 is limited to photopolymers, i.e. polymers that solidify or crosslink when exposed to UV light.

119 The term stereolithography was first used by Chuck Hall, who then went on to patent
120 the SLA technology in 1986 [1], several years before FDM was initially patented. In a similar
121 way to Crump and the founding of Stratasys, Hall went on to cofound the company 3D
122 Systems, which at the time was the first 3D printing company of its kind [13]. In the current
123 market situation, printers of this type that are able to produce parts of the quality and size
124 required for industry typically cost hundreds of thousands of pounds. As with all aspects of
125 3D printing technologies, however, the costs are dropping rapidly, meaning that there are
126 now smaller versions of SLA machines that are around 100 times cheaper, such as the
127 Formlabs Form 2 [14]. For even less money, very compact desktop machines are available for
128 as little as £250 [15].

129 3.2 Direct Light Processing & Continuous Direct Light Processing

130 The Direct Light Processing (DLP) technique is similar to SLA but it relies on a light
131 screen instead of a laser to cure all parts of the layer simultaneously. This reduces print times
132 but it has the disadvantage that the print will be made up of small cubes, called voxels,
133 corresponding to the pixels on the screen, which reduces the surface finish.

134 Another similar technique is Continuous DLP, which has the curing light in constant
135 operation, such that the build plate must be constantly in motion. This further reduces print

136 times compared to DLP and SLA, although there is still an issue with reduced resolution due
137 to the pixels in the light screen.

138

139 4. Powder Bed Fusion

140 Powder Bed Fusion (PBF) methods use a thermal process to sinter and solidify
141 powders of polymers or metals. Because there is no liquid involved (unlike in Vat
142 Polymerization) the powder must be evenly spread over the build to achieve accurate layers.
143 This typically means that there is a mechanism to achieve this built into the printer.

144 4.1 Selective Laser Sintering

145 In a similar way to SLA, Selective Laser Sintering (SLS) solidifies a thin layer of the
146 material using a focussed laser. However, unlike SLA, the material tends to be a polymeric
147 powder rather than a liquid resin. This form of additive manufacturing was developed by
148 Carl R. Deckard in the 1980s, with a patent for the technology granted in 1989 [16].

149 4.2 Selective Laser Melting & Direct Metal Laser Sintering

150 Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are two
151 methods that can be used to produce metallic
152 parts from powder precursors. SLM involves
153 fully melting the metallic powder which cools to
154 forms a solid object. DMLS heats the powder
155 enough to cause a chemical reaction between the
156 powder particles (see Figure 4).

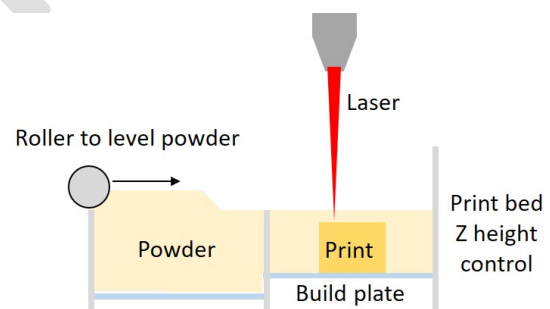


Figure 4: Schematic of an SLS, SLM or DMLS printer

157 SLM can be used for both alloy and single-component powders while DMLS is usually
158 only done with alloys (for example, Ti-6-4 and nickel alloys which are commonly used
159 engineering materials). The major disadvantage of these two processes is the high costs;
160 traditional manufacturing methods may still be more cost effective for simple designs.

161 Regardless of this, there is a wide range of manufacturers producing SLM and DMLS
162 machines including 3D Systems [17], Renishaw [18] and EOS [19].

163 These two methods play an important role in the manufacture of components for use
164 in the automotive and aerospace [20] industries. Boeing [20] and Bugatti [21] are two such
165 companies, with Boeing introducing 3D printed titanium structural components into some of
166 their new aircraft [20], while Bugatti are the first car company in the world to develop titanium
167 brake calipers via 3D printing [21]. The combination of strong metallic materials and the
168 possibility of producing components that are impossible to produce via standard
169 casting/machining methods means that these high-performance parts can be produced with
170 lower weights and less waste material. Another cutting-edge example in aerospace is the fully
171 3D printed SuperDraco engine chamber built by SpaceX, which will be used for crew-carrying
172 flights into low orbit [22], [23] . These engine chambers were made using Inconel (a nickel-
173 based alloy) and printed using a DLMS machine produced by EOS [19]. SpaceX have also
174 flown 3D printed parts on their Falcon 9 rockets [22].

175 **4.3 Electron Beam Melting**

176 In a similar process to the other PBF methods, Electron Beam Melting (EBM) employs
177 an electron beam rather than a laser to melt the powder. The electron beam requires less
178 energy than the laser which means that the running costs can be reduced. The process is also
179 faster and the final print has less residual stress due to cooling. However, it generally has a
180 lower resolution and a worse surface finish than SLS and DMLS and is used less frequently
181 as a result.

182 **4.4 Multi Jet Fusion**

183 Multi Jet Fusion (MJF) relies on a combination between SLS and Material Jetting
184 technologies, which will be introduced below, as a method to produce plastic parts.
185 Developed by Hewlett-Packard, these machines deposit a fusing agent on a thin layer of
186 polymer powder, while a detailing agent is applied near to the edges of the design to prevent

187 sintering [24]. A high energy infrared source is used to activate the fusing agent and it causes
188 the powder to solidify only in the presence of the fusing agent.

189

190 **5. Material Jetting**

191 Material jetting (also known as PolyJet printing [25]) depends on the same type of
192 technology as regular 2D inkjet printing, that is, liquid material is jetted onto the build plate
193 and is cured using UV light or high temperatures (depending on the material used). The
194 technologies available include regular material jetting, which uses photopolymeric resins like
195 those used in SLA, and there are more specialist machines that function with metals or wax.

196 Objet, who are now a part of Stratsys, were the pioneers of the material jetting
197 technology, where several small nozzles are used to deposit liquid polymeric material onto
198 the build plate, which is cured using a UV lamp. Multiple materials can be used
199 simultaneously and this allows the mixing of polymers to achieve different mechanical
200 properties. This also permits the deposition of separate scaffolding material that can be
201 dissolved away once the print has finished. Due to their good surface finishing and the
202 potential of mixing multiple materials for a variety of mechanical properties, these printers
203 are excellent for prototyping; using this technology a prototype can have the same look and
204 feel in hand as a real product would. This is why they are used by product design companies
205 such as Oxford Rapid Prototyping [26]. In addition to prototyping, MJ can also be used to
206 produce moulds for injection moulding, like with SLA.

207 While the visual quality of the parts is often excellent, the thermoplastic polymer resins
208 that are used for this type of printing often have poor mechanical properties, such as
209 brittleness. Also, the liquid resins are expensive at several hundred pounds per kilogram,
210 meaning that for many applications this method of producing parts is not cost effective.

211 **5.1 Nanoparticle Jetting and Drop-On-Demand**

212 Nanoparticle jetting, trademarked by the company XJet [27], uses a liquid containing
213 nanoparticles of metal or support material. Once each layer is deposited the liquid is

214 evaporated using high temperatures and it leaving behind the metal or support material.
215 Drop-On-Demand (DOD) printers are used to produce wax parts which are most often used
216 for investment casting purposes. Here the material is again in liquid form and is deposited in
217 a point-like fashion.

218

219 **6. Binder Jetting**

220 As the name suggests, Binder Jetting uses a binder to solidify layers of powder
221 together. The powder, either ceramic, metallic or sand, is spread in a thin layer and the binder
222 is jetted over the desired areas to solidify it. Once the build is finished, post processing is
223 usually required and extra chemicals are often added to improve the material's mechanical
224 properties. Ceramic parts produced by this method have excellent surface finish, making it a
225 suitable method for producing objects that require very exact dimensions, such as packaging
226 and even sculptures. Metallic parts made using this method can be functional and tend to
227 have lower production costs than those produced with SLM and DMLS. Often though, their
228 mechanical properties can be worse.

229 One very useful application of Binder Jetting is the production of sand-casting moulds.
230 During the sand casting process molten metal is poured into a mould made of sand to produce
231 a part. The mould is traditionally created by packing sand around a high-resolution model of
232 the part, which is usually machined, requiring lots of time and resources. Using Binder Jetting,
233 however, the mould can instead be made quickly and cheaply, and can even have more
234 complicated geometries than can usually be machined [28].

235

236 **7. Direct Energy Deposition (DED)**

237 This type of manufacturing process concerns melting a metal powder or wire material
238 as it is being deposited. In particular, these methods are well suited to adding metal to existing
239 parts or performing repairs. There are two types of DED: LENS and EBAM. Laser Engineered
240 Net Shape (LENS) uses a laser to heat the print bed as the material is deposited, whereas

241 Electron Beam Additive Manufacturing (EBAM) uses an electron beam to heat the metal
242 powder or wire, welding it to the rest of the build material. One advantage to these methods
243 is the great extent to which the microstructure of the metal material can be controlled –
244 something which is often more difficult in other methods of metal additive manufacturing,
245 and is greatly important with regards to ensuring good mechanical properties [29].

246

247 **8. Conclusions**

248 Additive manufacturing has proven to be a significant step forward in manufacturing
249 technologies, allowing product development to be much faster and cheaper in many cases. It
250 also allows entirely new designs that were not achievable by standard methods (machining
251 or casting) to be possible. As we have discussed, there are several different technologies
252 available, each with their own advantages and disadvantages. The most economical printers
253 available are desktop FDM printers, but these are limited to using a relatively small selection
254 of polymer materials. For more structural applications, metal printers based on SLM
255 technology are available, although at a much higher cost. A common application of many of
256 these AM types is prototyping, due the ease of changing designs and rapid production of the
257 models. However, across the full range of technologies there are uses in aerospace, medicine,
258 and tool and mould production, to name a few.

259 Currently, 3D printers are still quite rare outside of industry, and only enthusiasts are
260 likely to own one. However, with the price of additive manufacturing technologies dropping
261 all the time, it is likely that a printer could become as common a household item as an iron or
262 kettle. In the future we might not have to go to shops or look to specialists to get replacement
263 parts or custom-made items, we might instead be able to make some from the luxury of our
264 own homes.

265

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Reviewers for Making the Impossible: The Additive Manufacturing Revolution by Harry Orchard (STAAR 8 - 2018)

Review 1 - Po-Hsiang Chan – Minor revision

1. Is the subject matter of the article suitable for an interdisciplinary audience? I believe that this article is suitable for an interdisciplinary audience. The author briefly outlines the manufacturing process of each additive manufacturing technology without the use of excessive jargons, written in a way that can easily be understood by non-specialists.

2. Does the title reflect the subject matter of the article? The choice of word 'revolution' implies significant changes as a result of the introduction of this technology. Therefore, one would probably expect that this article is about how the introduction of different additive manufacturing technology changes the way we produce parts, the business model of the industry, or replacing existing technologies. A more accurate description of this article would be an overview of different existing additive manufacturing technologies.

3. Does the article make a contribution to the discussion in its field? Yes

4. Is the article clearly written? Yes, this article is written in clear English without overusing jargons.

5. Is the article well structured? Yes, this article is well structured based on the outline of Figure 1.

6. Are the references relevant and satisfactory? Yes, the references were cited accurately.

7. Do you feel the article appropriately uses figures, tables and appendices? Yes, all the figures are relevant and were correctly cited in the article.

8. What is your recommendation? Minor revision

Reviewer's comments to the author: This article is a well written and structured in a way that can be easily understood and follow. The article provides a good overview of some of the existing additive manufacturing technologies, their manufacturing processes, their applications, as well as its relative advantage and disadvantages compared to other 3D printing methods. In my opinion, this article covers much of the major 3D printing technologies, including the latest 3D printing technology such as the Multi Jet Fusion. Therefore, this article will be a good read for non-specialists who wish to learn more about the existing technologies on the market nowadays.

The main critique of this article is that not every 3D printing technology was given equal weight in terms of the information discussed. While the history, manufacturing process, and the applications of FDM, SLA, and SLS were discussed in detail, SLS, DOD and EBM were only briefly mentioned. As a result, the reader might interpret SLS, DOD, and EBM as being less important or much rarer than the other technologies. Other important technologies in 3D printing such as bio-printing and tissue 3D printing can also be mentioned briefly. It would

also be good to include figures for the Material Jetting, Binder Jetting, and Direct Energy Deposition section for consistency.

In the introduction section, another industry that has been heavily influenced by 3d printing is the jewellery making industry, medical industry, and the consumer product prototyping industry (Line 28 – 29), which should also be mentioned in the text. As for the advantage of 3D printing in general, digitization is definitely one of them (Line 35 – 36), but not specifically for the fact that the design is can be easily converted into 'machine-readable format', CNC can also do the same. Other significant advantages also include complexity-free, meaning that the increase in design complexity won't necessarily be translated into the production cost.

In the FDM section, direct pellet 3D printing should also be mentioned (Line 67 – 68), the material doesn't necessarily have to be in the form of filaments. A reference (Line 73 – 74) for the issue of toxic fumes and ultrafine particles is recommended (Azimi et al. 2016 and Stephens et al. 2013). The price of a 3D printing filament is usually in the range of 10 – 50 GBP (Line 81 – 82), it is also worth mentioning that the higher the pricemm, the better the filament quality in terms of filament size consistency and bonding between the layers during printing.

In the Vat Polymerization section, abbreviation on the Stereolithography (SLA) and Direct Light Processing should be added (Line 97) to be consistent with the other sections. The sentence starting with 'As with FDM...' (Line 101 – 103) also needs rewriting. One of the major uses for SLA and DLP is in the jewellery industry, where waxes or castable resins can be used to print molds. I would recommend adding the jewellery application to this section as well. In the SLA section, prices for the SLA machine needs to be clarified (Line 126), 100 times cheaper than what? The sentence starting from 'As with all...' (124 - 126) also needs to be rewritten in a better format.

For the PBF section, the last sentence for the first paragraph also appeared to be redundant (Line 143). If the author intends to keep this Line 143, more detail on the powder spreading mechanism should be given.

For the MJF Section, better to replace 'below' with 'in the next section' (Line 184) to improve readability.

For the Material Jetting section, one of the major drawbacks is the low shelf-life of the photopolymer resins due to their UV-sensitive nature (Line 210). (Same for SLA and DLP).

In the first paragraph of the binder jetting section, a reference should be given to support the claim that mechanical properties of metallic parts produced using this method is worse than SLM and DMLS (Line 228).

In the conclusion, I would recommend replacing the word 'economical' with 'affordable' (line 252) since the word is often associated with the machine running cost, in which case the SLA and DLP printers are usually cheaper to run as it requires less movement than FDM printers. Furthermore, I would like to add that 3D printer is no longer rare (perhaps 10 years ago), you can see them in many libraries and educational institutes (Line 259).

Finally, since many companies are cited in this article, a declaration of conflicts of interest should also be included.

Review 2 – Siu Shing Wong – Accept

1. Is the subject matter of the article suitable for an interdisciplinary audience? Yes. The article is well-structured in a way that audience from diverse background can easily follow. There is not much detailed science behind each technology but give a general concept. To improve, I would also include a few real images of 3D printers. Besides, the figures of SLS and SLA are quite similar so it would be better to highlight the distinction so as to avoid confusion.

2. Does the title reflect the subject matter of the article? Yes-ish. I may oversee how 3D printing will make the impossible possible, but the title I come up in mind after reading would be "Different types of additive manufacturing and their application". It may be more comprehensive if including the way of traditional manufacturing, perhaps a table comparing subtractive manufacturing and additive manufacturing.

3. Does the article make a contribution to the discussion in its field? Yes. It provides an historical perspective to 3D printing and a well-written summary of the available 3D printing technology. It can popularize the idea of additive manufacturing to layman.

4. Is the article clearly written? Yes. Definitely. Very coherent.

5. Is the article well structured? Yes. The introduction gives a bird-eye view of 3D printing. The remaining parts are divided into sections of most relevant 3D printing technology. It is easy to follow the logic. Perhaps I would prefer putting material jetting before multi-jet fusion so that they are in order of prerequisite knowledge.

6. Are the references relevant and satisfactory? Yes.

7. Do you feel the article appropriately uses figures, tables and appendices? Yes. However, in the tree diagram, some child nodes are of different level of view. As mentioned (Vat Polymerization and the rest).

8. What is your recommendation? Accept

Reviewer's comments to the author N/A

Review 3 - Pat Warner – Minor revision

1. Is the subject matter of the article suitable for an interdisciplinary audience? The subject matter is written in a way that is relatively easy to understand, even if you had little, or perhaps no prior knowledge of 3D printing.

2. Does the title reflect the subject matter of the article? I'm not sure that a description of the various types of technology available really covers "Making the Impossible" or explains "The Additive Manufacturing Revolution". Perhaps a more in-depth look at items that can only be made using additive processes, explaining why additive is the only available solution would benefit the audience.

3. Does the article make a contribution to the discussion in its field? It could, with a little more detail.

4. Is the article clearly written? The article is relatively easy to follow, but jumps around a little, see below.

5. Is the article well structured? The article could probably do with a shuffle of some of the paragraphs, grouping the metallic and polymer technologies together for example.

6. Are the references relevant and satisfactory? The references appear to be relevant, except
Apparatus for Production of Three-Dimensional Objects by Stereolithography is a patent by C Hull, not C Hall.
Hall is mentioned a number of times throughout the article.

7. Do you feel the article appropriately uses figures, tables and appendices? I'm not convinced that figures and tables are appropriate for an article such as this, unless used to highlight the differences between the technologies for surface finish, mechanical properties and cost per part.

8. What is your recommendation? Minor revision

Reviewer's comments to the author: On the whole a well constructed article, with plenty of information to prompt further discussions on the subject.