3D Printing: When and where does it make sense?

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Abstract

Twenty years ago, when Captain Jean-Luc Picard ordered: 'Tea, Earl Grey, hot' it emerged in a pot from the Star Trek replicator, a machine which made everything and anything from seemingly nothing. An image was created which is so ingrained in our perception of the possible future that 3D printing is perceived by many to be todays' equivalent of the replicator. Does it make sense to print everything and anything on a 3D printer? The media and countless amateur videos suggest that the possibilities are boundless, from a cake to a door handle, from designer shoes to a washer and 3D printing will replace traditional assembly line manufacturing in the near future. Traditional manufacturing has its drawbacks, especially mass production, but it can produce high quality for an amazingly low cost. 3D printing, on the other hand, generates items within a few hours which can be customized each time they are made. However, only in a very few cases can the quality of a mass produced item be attained via 3D printing. In this paper, we discuss glass manufacturing in the UK as an example.

Dreamtime

In the recently published book entitled: 'Fabricated: The New world of 3D printing' by Lipson and Kurman [1] ten principles of 3D printing are given which summarize the utopian future expectations of 3D printing enthusiasts. The ten principles are as follows:

1. Manufacturing complexity is free
2. Variety is free
3. No assembly required
4. Zero lead time
5. Unlimited design space
6. Zero skill manufacturing
7. Compact, portable manufacturing
8. Less waste by-product
9. Infinite shades of materials
10. Precise physical replication

Anyone who has dabbled in 3D printing will appreciate that these principles are unrealistic and some of them will probably never come true. Take for example principle 6: Zero skill manufacturing. Good engineering and good design has to be learned. Not every material is suitable for every task. There is no 'one approach fits all'. Somewhere in the manufacturing process, highly skilled engineers or designers have to generate via software the design files for the desired object. The products' end use and functionality will influence the engineering and design. The product is often only finalized after several iterative loops through the printer to generate feedback on the design/functionality of the object. This observation undermines principles 1 and 2 as well. The printer itself does not mind complexity or variety, however the user will. The more complex the object, the more trial and error is required to generate a satisfactory result. Even with a robust blueprint, different materials and different printers will always need specific modifications to ensure the object is printable. The lead-time to implement these requirements can become substantial, days if not weeks depending on the size and complexity of the object. The advantages over traditional manufacturing -- and let's not forget that modern manufacturing is often performed on demand -- shrink and consequently 3D printing loses its attraction when seen as a replacement for traditional methods. However, when considered as an adjunct to traditional manufacturing the perception changes. How 3D printing can add value to existing production processes will be discussed in the remainder of this paper using the example of glass container production in the UK.

The glass industry in the UK

In the UK an estimated 4 million tons of glass are manufactured each year [2]. Containers for the food and drinks industry and flat glass for glazing in buildings and cars account for 90% of the production. The remaining 10% are split between special glass, a diverse group containing lighting, hobs, ovens, medical, optical and scientific, domestic and fibreglass for insulation, fire protection, reinforcement of plastics and rubber and electronics. Currently the UK has no volume producers for domestic glass, but several small companies specialize in the high end market.

Sand, limestone and soda ash are the three main raw materials for glass making. Recycled glass is another ingredient, widely used to reduce the melting temperature and therefore decrease overall energy costs. The amount of glass recycled in 2010 in the UK was 1.6 million tons of which the container industry used 0.66 million tons [2]. Remelting glass uses 25% less energy than making glass from raw materials. Energy costs drop 2-3% for every 10% cullet (crushed glass) used in the manufacturing process.

Glass is heavy. Flat and container glass production is still undertaken in the UK, located close to its customers since transportation of those glass products over long distances is not feasible.

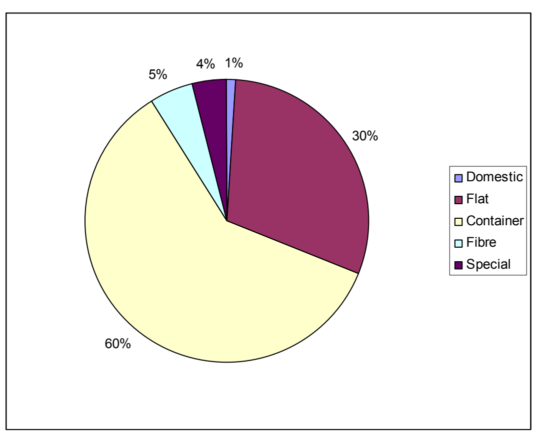

Figure 1: *Glass production in the UK*

Large scale manufacturing process

Large scale manufacturing of glass containers follows roughly 6 steps:

1. Batch preparation: The mixing of raw materials and recycled glass.
2. Melting
3. Forming
4. Annealing
5. Inspecting and Packaging
6. Storing and dispatching.

Even though glass itself is a very environmental friendly material and there is no shortage of raw materials required to produce glass, glass production is a highly energy consuming process which represents a significant proportion of the overall cost of manufacture. Over the last 30 years, the melting furnaces have been optimized so that the energy consumption per ton of glass has halved [2]. They are now working at an optimum which cannot be further improved without changing the glass-making process completely. The current big push within the glass container industry is to increase the number of items per ton of glass to counteract increasing energy costs, for example light weight containers are replacing more and more traditional containers.

Figure 2: *Layer by layer printed little glass vessel. During firing the structure was embedded in plaster. The vessel is about 4 cm high and took 20 min to print it.*

3D printed glass is based on the so called kiln method, the oldest glass making method. It is a process where the shape of the object is generated before it is fired. Traditionally moulds are used, but the shape can also be printed either by a powder bed printer [4] or by an extrusion printer using pastes. 3D printers use glass frit with particle sizes of about 60µm. After printing, the objects have to be fired to transform them from so called 'greenware' into glass. However, because of the small particle size the melting temperature decreases from 1600 ºC to 720 ºC which represents, overall, a huge energy saving. The number of steps remains the same as in traditional glass production, but the order changes. Since melting happens after forming, the objects have to be supported during the melting step in order for them not to lose their shape.

Does the reduction of melting temperature make 3D printing an attractive alternative to traditional manufacturing? The short answer is no, at least not with the present commercially available technologies.

A major obstacle is the duration of the production process. Whereas forming from molten glass in a mass production environment takes only seconds, forming by 3D printing can take up to hours as shown in Table 1. As an example we have chosen a 200ml drinking glass. What defines a drinking glass? One should be able to drink from it and it should be made of glass. The condition that one should be able to drink from it restricts its shape. The shape of the container which will hold the liquid will not look too different from any glass that can be bought in a shop.

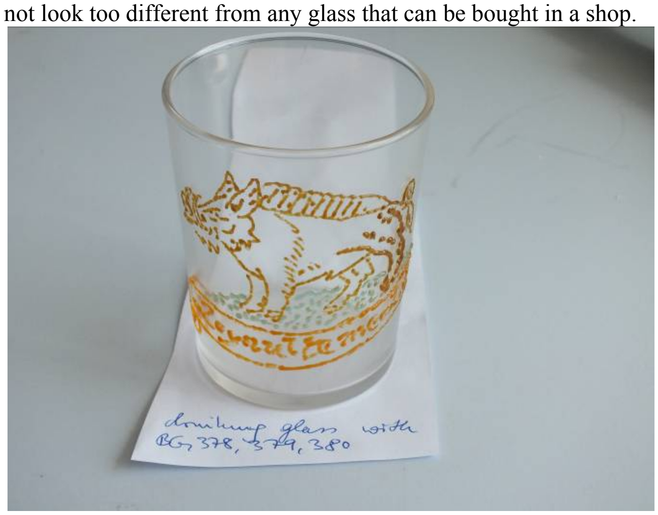

Figure 3: *Embellishment printed on a glass. Only a single layer was applied. The printing time for the 3 colour print was about 10 min.*

Table 1

Technology	Typical layer thickness in µm	Build rate cm^3/h	Printing time	Maximal object dimensions cm^3
Fused deposition molding	127 to 330	12-18	4 to 6 h	91 x 61 x 91
Electron beam melting	50 to 200	25-80	53min to 2h48min	20 x 20 x 35
Selective laser sintering	80 to 150	90- 500	8 to 47 min	55 x 55 x 75
Powder bed printing	89 to 102	Vertical build speed 5-15 mm/h	6h40min to 20h	51 x 38 x 23
Stereo-lithography	50 to 150	Maximum part draw-ing speed 2.5 to 10 m/s (225 cm^3/h)	5 to 20 min	210 x 70 x 80

Table 1 clearly demonstrates that a simple drinking glass is not a suitable object for additive manufacturing using 3D printing. However, there is a case for considering using a 3D printer as an adjunct to facilitate mass customization of such simple objects. For example, in order to 'decommodify' the simple drinking glass it can be embellished with a personal 2.5D pattern selected (or even supplied) by the end user. In Table 2, we compare the cost of three printing methods to make a customized embellished drinking glass: printing from scratch (Figure 2), printing on a glass blank (Figure 3) and printing the embellishment as an impact print with the print plate being 3D printed (Figure 4). In all three cases we assume the glass body to be a standard tumbler, 13 cm high, top diameter 8 cm and bottom diameter 6 cm. The weight is assumed to be 300 g. For the sake of simplicity, we assume a single colour embellishment which weighs 50 g. The part will not be post-processed after the object has left the kiln. We base our estimate for on the price of industrial clear cullet of £33 per ton [3] (for comparison the price per ton for steel is £461, for stainless steel £1818 [5], for aluminum £1197 [6] and for multigrade paper £115-120 [7]). If the embellishment is done in green or amber glass, the price per ton lies between £15 (green) and £25 (amber). But for 3D printing the industrial cullet has to be further processed. The particle size has to be reduced from several mm to several µm in size, which requires several milling stages. We estimate that the milling stages and consequent quality control tests could increase the price per ton by at least a factor of 200. The support material is plaster of Paris and the price per ton is assumed as £60. The rubber price per ton is about £3000 at present.

Figure 4: *The sunflower was generated by using two different prints for petals and centre. The hollow shape was generated by slumping the glass flat.*

Table 2: all cost based on industrial prices

	Printing from scratch	Printing on glass blank (drinking glass made by traditional methods)	Printing with printed rubber printing plate
Material cost	Glass frit for container and embellishment: £2.2 Support material for firing: £0.01	Glass blank: £0.1 Glass frit for embellishment: £0.3 Support material for firing: £0.01	Material for rubber printing plate: £0.15 Glass frit for embellishment: £0.3 Support material for firing: £0.01
Printing time	3 to 8 hours depending on the printing process	0.01 to 2 hours depending on the complexity of the embellishment	2 hours for printing of the printing plate, 1s for actual print of embellishment.
Firing time including annealing	9 hours	9 hours	9 hours
Energy cost of printing and annealing	£0.01 to 1	£0.01 to 1	£0.01 to 1
Total cost for first item	£3.31	£1.41	£1.46
Cost of a repeat	£3.31	£1.41	£1.31 + 0.15/n where n is the number of repeats.

The energy cost in Table 2 is hard to estimate. The upper limit represents the cost for one single object fired in a small kiln. The lower limit is calculated by using the energy cost for melting glass at industrial levels (combining numbers given in [2] and [8]). The cost for the glass blanks already contains the energy costs for their production including annealing. If the embellishment is applied just before the glass blank is annealed during its production, then no additional firing is required. The temperatures are still high enough to fuse the glass particles together and to the still hot glass blank. 3D printers which could function under such conditions would not look like the ones we know today, but they would allow customization of mass produced containers, whether it was for advertising, security tags or a relatively simple structure which would give additional strength to light weight containers.

Inspection and transport cost are again not easy to estimate. If printing was performed as an add on, the cost for inspection and transport would not be different to the unembellished product. Talking to glass makers in a studio glass workshop, inspection is not a separate step for small runs that is smaller than 100 items. The item is basically inspected during all stages of production. For high end products, courier transport is a relatively negligible cost and is subsequently not really accounted for.

Conclusions

For 3D printing to be employed more widely and not only as a means of prototyping, the following obstacles have to be overcome:

- The choice of materials has to be expanded
- Printing times have to be drastically reduced.

Rapid prototyping is often based on plastic materials, but for specialized engine parts metal sintering has been combined with 3D printing techniques. User groups have modified existing 3D printers for paste printing and have successfully demonstrated that sugar, chocolate, clay and to a limited extent glass can be printed.

All printing techniques whether powder bed, stereolithography, electron beam melting, laser sintering or fused deposition moulding are relatively slow which makes the printing of large objects unfeasible for production runs even as small as 100 items. In the case of 3D printing, small is definitely beautiful. Instead of printing the whole object we suggest using 3D printing as a way to add features and therefore to add value to otherwise mass produced objects. Printing of a single layer, an interface for example, could be possible at speeds comparable to traditional inkjet printing. The printers would look different depending on the task. For example printing a bar code on a still hot glass container demands a different printer design to printing a cartilage layer into a damaged hip joint. The possibilities are numerous. Whether it is for the interface between a medical implant and the human body or the heat sink for the CPU and GPU in a laptop computer, 3D material printing could span all industries.

References

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Author Biography

Susanne Klein received a diploma in theoretical physics and a PhD in medical physics from the University of Saarland in Germany. After working as a Telekom research fellow at the Johann Wolfgang Goethe University in Frankfurt, Germany, and as a Royal Society research assistant at the University of Bristol , UK, she joined HP Labs. Her present research interest centers on inorganic materials for 3D printing applications. Fraser Dickin has a BSc in Biomedical Electronics from Salford University, an MSc in Microprocessor Engineering and a PhD in Instrumentation from Manchester University. His current work includes embedded systems for 3D printing and also systems for forensic image processing.