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3D metal printing technology: the need to re-invent design practice

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Abstract

3D printing or additive manufacturing is a novel method of manufacturing parts directly from digital model using layer-by-layer material build-up approach. This tool-less manufacturing method can produce fully dense metallic parts in short time, with high precision. Features of additive manufacturing like freedom of part design, part complexity, light weighting, part consolidation, and design for function are garnering particular interests in metal additive manufacturing for aerospace, oil and gas, marine, and automobile applications. Powder bed fusion, in which each powder bed layer is selectively fused using energy source like laser, is the most promising additive manufacturing technology that can be used for manufacturing small, low-volume, complex metallic parts. This review presents overview of 3D Printing technologies, materials, applications, advantages, disadvantages, challenges, economics, and applications of 3D metal printing technology, the DMLS process in detail, and also 3D metal printing perspectives in developing countries.

Keywords Additive manufacturing · 3D metal print · Powder bed fusion · Economics · Complexity for free

1 Introduction

Additive manufacturing (AM), also known as 3D printing, is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. This tool-less manufacturing approach can give industry new design flexibility, reduce energy use, and shorten time to market. Main applications of additive manufacturing include rapid prototyping, rapid tooling, direct part production, and part repairing of plastic, metal, ceramic, and composite materials. The two main parameters of any metal AM process are type of input raw material and energy source used to form the part (Bhavar et al. 2014). Input raw material can be used in the form of metal powder or wire, whereas laser/electron beam or arc can be used as energy source (Fig. 1).

Metal AM processes can be broadly classified into two major groups—powder bed fusion-based technologies (PBF) and directed energy deposition (DED) based technologies. Both of these technologies can be further classified based on the type of energy source used (Bhavar et al. 2014).

1.1 Powder-based fusion (PBF)

In PBF-based technologies, thermal energy selectively fuses regions of powder bed. Selective laser sintering/melting (SLS/SLM), Direct Metal Laser Sintering (DMLS) laser cusing, and electron beam melting (EBM) are main representative processes of PBF-based technologies (Bhavar et al. 2014). Under PBF process, DMLS is an additive manufacturing (AM) or rapid prototyping (RP) process that uses metal powder and a high power laser to sinter together a useable part. This method is capable of producing very dense parts, but to achieve gas or pressure tightness, post-treatment is often required. Most tradenames such as laser sintering, cusing, etc. are describing the same process but not different technologies. The process is very similar to an existing AM process called selective laser sintering (SLS), both SLS and DMLS are conceptually the same process, but instead of using polymers or coated metal powders in the case of SLS, DMLS uses uncoated pre-alloyed metal powders as the sintering material (Gratton 2012). The electron beam melting (EBM) technology uses a heated powder bed of metal in a vacuum that is then melted and formed layer by layer using

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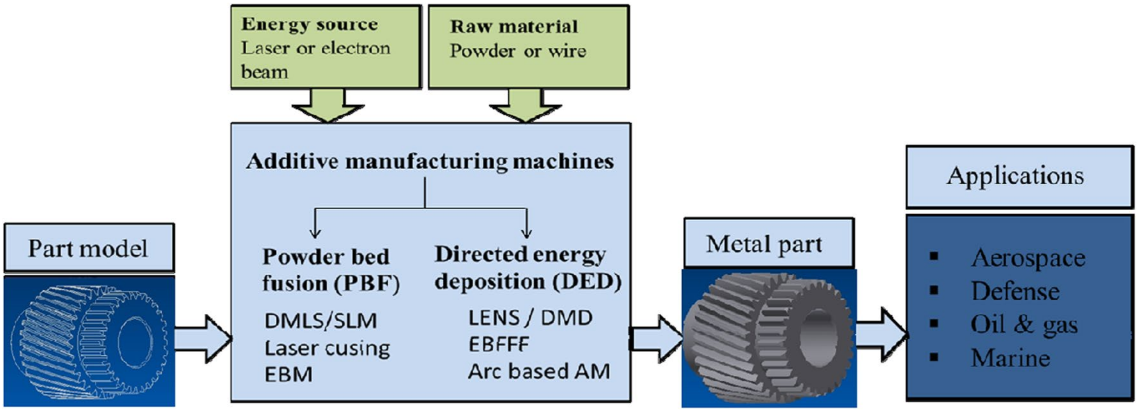


Fig. 1 Common metal additive manufacturing process

an electron beam energy source similar to that of an electron beam welding/electron microscope (Herderick 2011).

1.2 Direct energy deposition (DED)

In DED-based technologies, focused thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited. Laser engineered net shaping (LENS), direct metal deposition (DMD), electron beam free form fabrication (EBFFF), and arc-based AM are some of the popular DED-based technologies (Bhavar et al. 2014). DMD is based on a powder injection system that is coupled with a fiber laser on a robotic arm. DMD is well suited for repair of existing tooling, adding features to large parts, or for the manufacture of new parts (Herderick 2011). Electron beam freeform fabrication (EBFFF) uses a focused electron beam in a vacuum environment to create a molten pool on a metallic substrate (Electron Beam 2016). Rapid plasma deposition (RPD) makes use of an argon plasma, in which a metal wire is melted and the argon gas is propelling the molten droplets towards the substrate or base plate, where the part is created layer by layer (Paul 2015; Norsk 2016). Directed energy deposition for metal AM is less widespread for the additive manufacturing of a whole part (whereas exception exists, RPD), primarily due to lower accuracy and required post-processing. In contrary, DED has a long-standing history in repair application. The most widespread technologies in this area are the Cold Gas Spraying (as shown in Fig. 2 below), high-velocity oxygen fuel spraying, and laser metal deposition. Figure 3 gives a comparison between AM processes—PBF and DED (Berger 2013).

1.3 Application of 3D printing technology

The 3d printing technology covering wide range of alloys used in a variety of industries (including aerospace, automotive, dental, jewellery, oil and gas, orthopedics printed electronics, and tooling). Some of the potential applications such as oil and gas control valve (part of a control valve, manufactured at the Kariwa plant, Niigata Prefecture, Japan, hardware: Lumex avance 25) and Engine/Leap 1, Leap 56 Fuel Nozzle/Housing, LEAP FETT parts developed by GE,

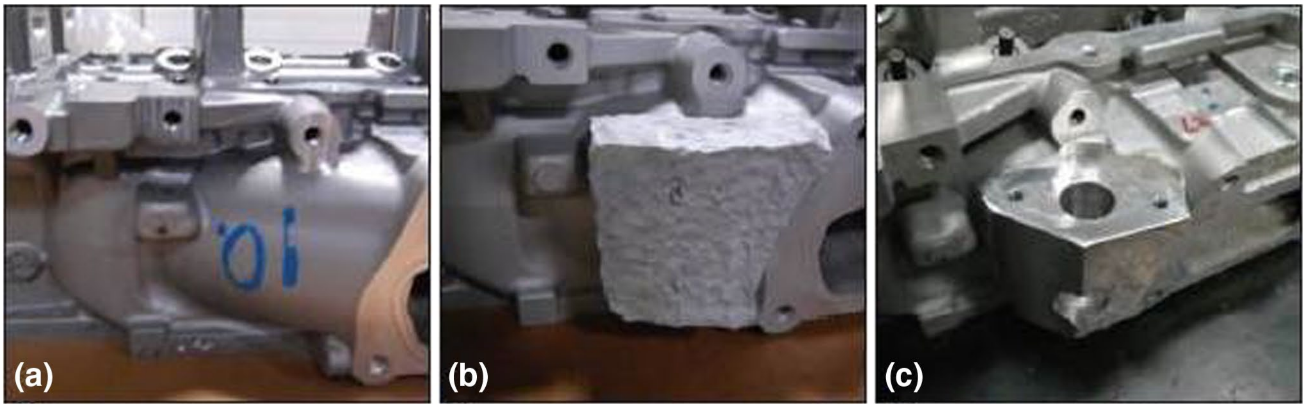
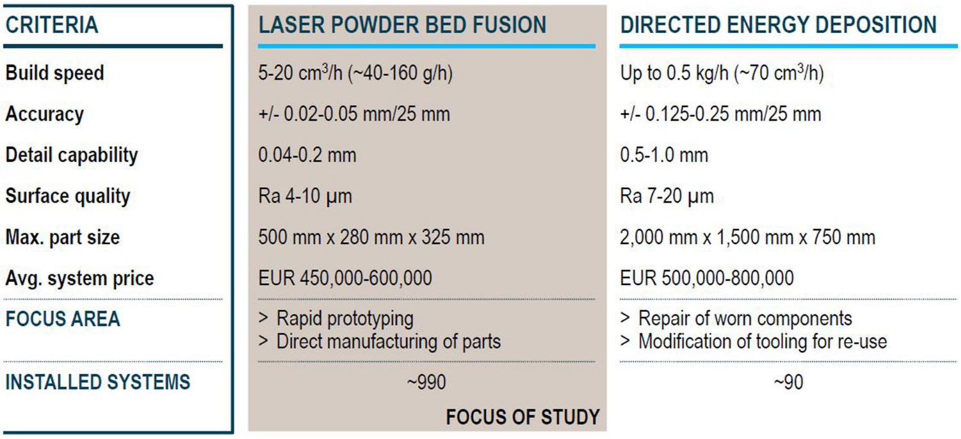


Fig. 2 Repair by cold gas spraying. **a** Prior to spraying, **b** as sprayed, and **c** finished



CRITERIA	LASER POWDER BED FUSION	DIRECTED ENERGY DEPOSITION
Build speed	5-20 cm^3/h (~40-160 g/h)	Up to 0.5 kg/h (~70 cm^3/h)
Accuracy	+/- 0.02-0.05 mm/25 mm	+/- 0.125-0.25 mm/25 mm
Detail capability	0.04-0.2 mm	0.5-1.0 mm
Surface quality	Ra 4-10 µm	Ra 7-20 µm
Max. part size	500 mm x 280 mm x 325 mm	2,000 mm x 1,500 mm x 750 mm
Avg. system price	EUR 450,000-600,000	EUR 500,000-800,000
FOCUS AREA	> Rapid prototyping > Direct manufacturing of parts	> Repair of worn components > Modification of tooling for re-use
INSTALLED SYSTEMS	~990	~90
	FOCUS OF STUDY	

Fig. 3 Comparison of PBF vs. DED

servo-controlled valves, impellers/pumps applications, and stainless steel brackets components, as shown in Fig. 4a, b (Webpages 2016; GE Newsroom 2015; Morris 2014). It needs to be pointed out that only very little information about serial production and usage of complex parts exists. Many examples, especially in the valve area, show prototypes or selected parts of a valve. Figure 5 summarizes the current readiness level of AM for different fields of application (Berger 2013).

1.4 Advantages and disadvantages of the AM process

Advantages are freedom of design, complexity for free, potential elimination of tooling, lightweight design, part consolidation by reducing assembly requirements, and elimination of production steps. One example of the advantages of AM is represented in the 2013 GE aircraft engine bracket design challenge, as shown in Fig. 6. By making use of the

Fig. 4 Examples of 3D printed products. **a** Norsk titanium RPD aero-part (Paul 2015; Norsk 2016). **b** Hydraulic valve block (height 5 cm), VTT Finland, 66% smaller than original design (VTT 2015)

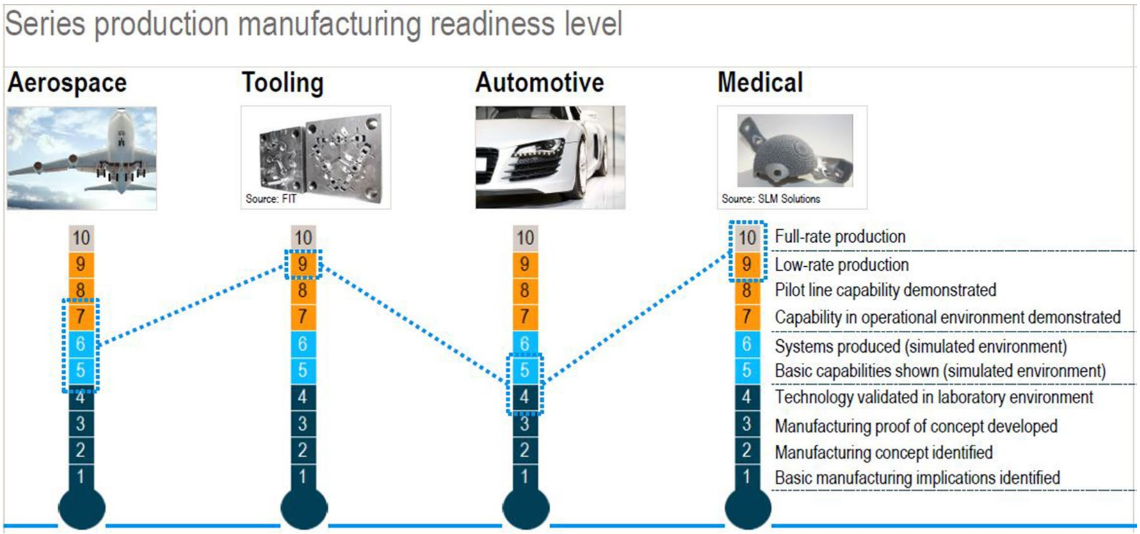
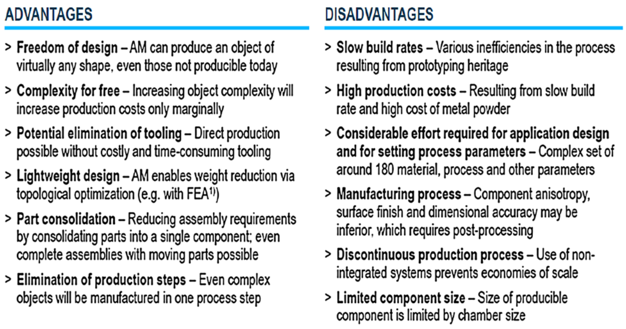


Fig. 5 AM readiness level

Fig. 6 3D printed GE aircraft engine bracket

complexity for free, it was possible to come up with a new design which was 70% lighter than the existing one (Alec 2016).

The current disadvantages (AM still being a new technology) are slow build rates, limited component size (restricted by the size of the build chamber), considerable effort required for application design and for setting process parameters, dimensional accuracy, required post-treatment methods like surface finishing, and the stability and quality of the used powder. Figure 7 summarizes the current advantages and disadvantages (Berger 2013). Figure 8 is giving an overview about the manufacturing readiness level of AM for different application (Berger 2013).



ADVANTAGES

- > **Freedom of design –** AM can produce an object of virtually any shape, even those not producible today
- > **Complexity for free –** Increasing object complexity will increase production costs only marginally
- > **Potential elimination of tooling –** Direct production possible without costly and time-consuming tooling
- > **Lightweight design –** AM enables weight reduction via topological optimization (e.g. with FEA$^{1)}$)
- > **Part consolidation –** Reducing assembly requirements by consolidating parts into a single component; even complete assemblies with moving parts possible
- > **Elimination of production steps –** Even complex objects will be manufactured in one process step

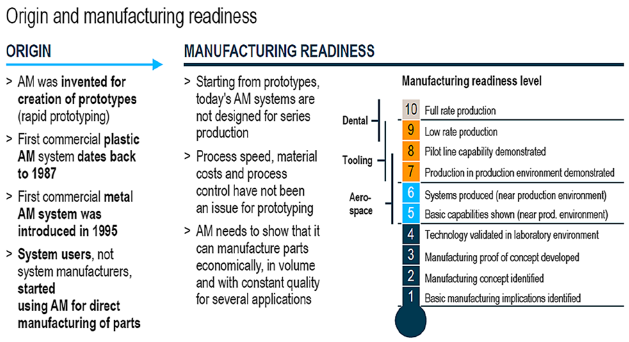
DISADVANTAGES

- > **Slow build rates –** Various inefficiencies in the process resulting from prototyping heritage
- > **High production costs –** Resulting from slow build rate and high cost of metal powder
- > **Considerable effort required for application design and for setting process parameters –** Complex set of around 180 material, process and other parameters
- > **Manufacturing process –** Component anisotropy, surface finish and dimensional accuracy may be inferior, which requires post-processing
- > **Discontinuous production process –** Use of non-integrated systems prevents economies of scale
- > **Limited component size –** Size of producible component is limited by chamber size

Fig. 7 AM advantages and disadvantages

1.5 Economics of 3D printing technology

The components considered for driving the additive manufacturing cost are material cost, labor cost, machine cost, and energy consumption. Material cost constitutes major proportion of additive manufacturing cost for laser sintering process. Labor cost would be 2–3% and energy consumption is less than 1%. (Thomas and Gilbert 2014). Metal AM started to gain attention in aerospace, oil and gas, marine, automobile, manufacturing tools, and medical applications because of the advantages offered by this process. First, it can reduce buy-to-fly ratio considerably which is the ratio


Origin and manufacturing readiness

ORIGIN

- AM was **invented for creation of prototypes** (rapid prototyping)
- First commercial **plastic AM** system **dates back to 1987**
- First commercial **metal AM system was introduced in 1995**
- **System users**, not system manufacturers, **started using AM for direct manufacturing of parts**

MANUFACTURING READINESS

- Starting from prototypes, today's AM systems are not designed for series production
- Process speed, material costs and process control have not been an issue for prototyping
- AM needs to show that it can manufacture parts economically, in volume and with constant quality for several applications

Manufacturing readiness level

10 Full rate production
9 Low rate production
8 Pilot line capability demonstrated
7 Production in production environment demonstrated
6 Systems produced (near production environment)
5 Basic capabilities shown (near prod. environment)
4 Technology validated in laboratory environment
3 Manufacturing proof of concept developed
2 Manufacturing concept identified
1 Basic manufacturing implications identified

Fig. 8 AM origin and manufacturing readiness level

of input material weight to final part weight. For the conventional manufacturing processes, buy-to-fly ratio for aerospace engine and structural components can be as high as 10:1 and 20:1, respectively. AM can produce near net shape using layer-by-layer addition of materials as per requirement which can reduce buy-to-fly ratio up to 1:1. Conventionally manufactured part may require a number of different manufacturing processes like casting, rolling, forging, machining, drilling, and welding etc., whereas the same part can be produced using AM which eliminates required tooling and produces part in single processing step. Several post-treatment processes, at least the cutting off the product from the base plate by wire edm is required and most of part need also the removal of the support structures. Every part manufactured by AM can be unique and produced in very short time, which enables mass customization. AM also reduces assembly requirements by integrating number of parts required in assembly into a single part. It reduces overall weight, decreases manufacturing time, reduces number of manufacturing processes required, reduces cost and material requirements, and optimizes required mechanical properties (Bhavar et al. 2014). The use of AM techniques is shown to be advantageous for parts which have a high buy:fly ratio, have a complex shape, have a high cost of raw material used for machining from solid, have slow machining rates, and are difficult and expensive to machine. The specific cost of material deposited by additive manufacturing systems required to give a 30% saving over the conventional machine from solid techniques is estimated for a typical aerospace-titanium alloy over a range of buy:fly ratios, as shown in Fig. 9 (Allen 2015). In view of above information and below graph shown in Fig. 10, using AM, geometrically complex shapes with increased functional performance can be manufactured at virtually no additional cost (Berger 2013).

However, it needs to be noted, that in most cases, a simple copying of the existing design made by conventional methods to AM will lead not to a significant cost reduction. AM will be beneficial when the product performance is also enhanced, as shown in Fig. 11 (Berger 2013).

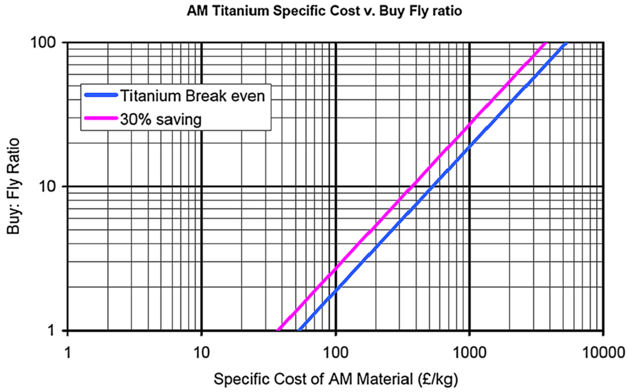


Fig. 9 Specific cost of AM material for a range of buy:fly ratios

2 Technology selection for metal additive manufacturing

Several technologies have been developed for additive manufacturing—powder bed fusion is the leading technology and also most relevant for metal objects, as observed in Fig. 12. Direct metal laser sintering—DMLS is the most preferred powder bed fusion technology in view of short manufacturing time, cost-effective assembly, and wide variety of metal parts, as shown in Fig. 13 (Berger 2013). Complex geometries and assemblies with multiple components can be simplified to fewer parts with a more cost-effective assembly. DMLS does not require special tooling like castings, so it is convenient for short production runs (Met 2016). It needs to be noted that SLS, SLM, and DMLS are often used in conjunction to describe the same basic technology.

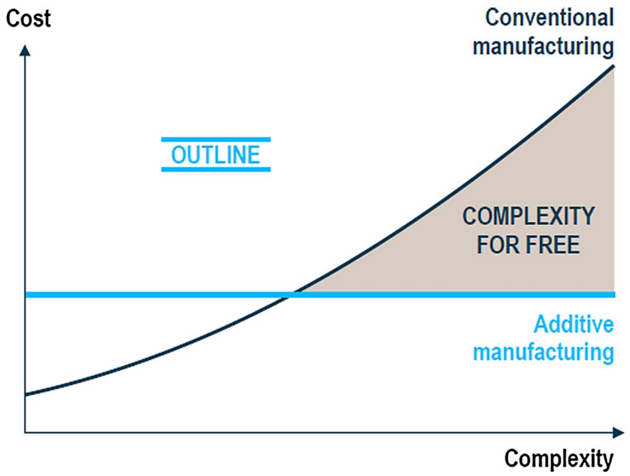
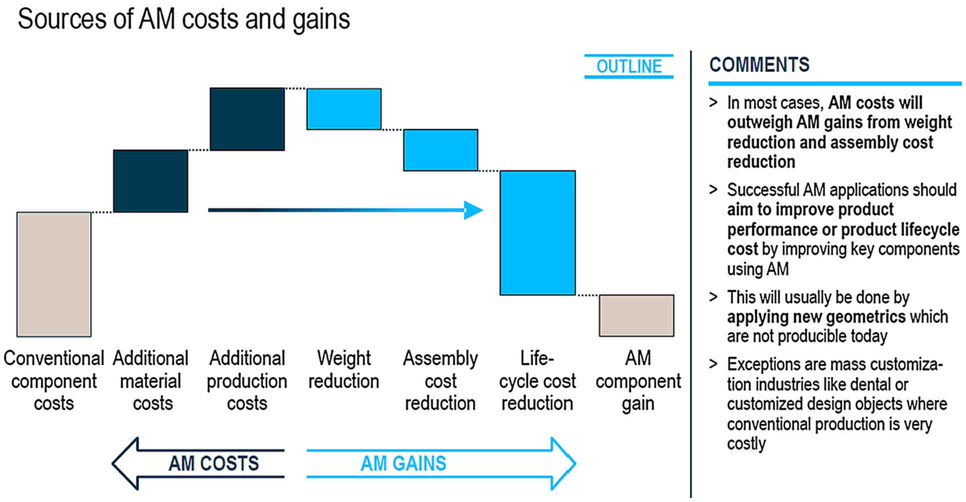


Fig. 10 Cost vs. complexity between AM and conventional manufacturing methods

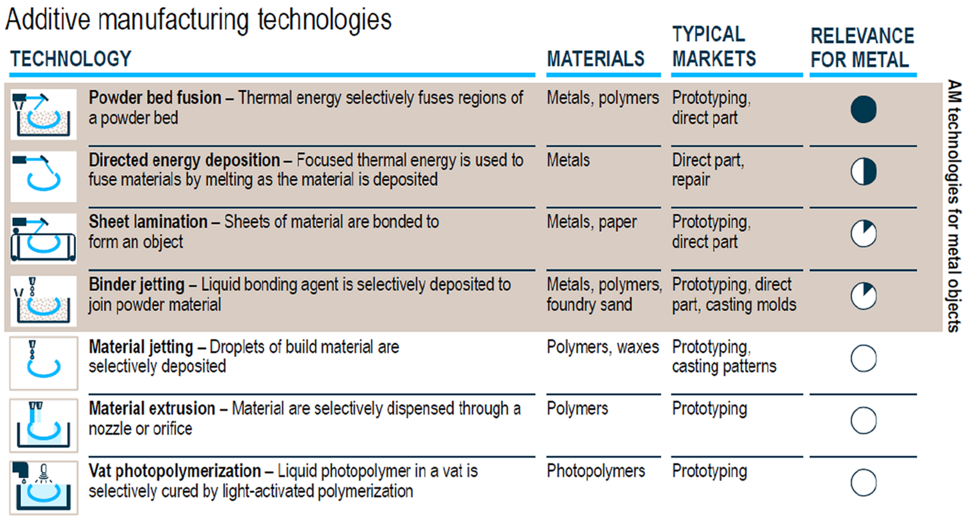
Fig. 11 AM: cost and gains



COMMENTS

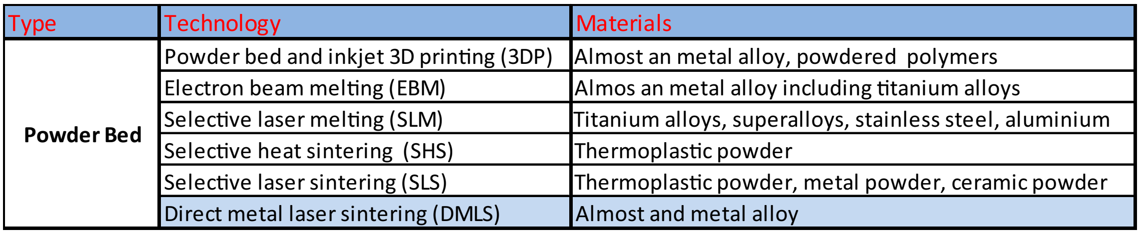
- > In most cases, **AM costs will outweigh AM gains from weight reduction and assembly cost reduction**
- > Successful AM applications should **aim to improve product performance or product lifecycle cost** by improving key components using AM
- > This will usually be done by **applying new geometrics** which are not producible today
- > Exceptions are mass customization industries like dental or customized design objects where conventional production is very costly

Fig. 12 AM technologies/materials selection



Additive manufacturing technologies

TECHNOLOGY	MATERIALS	TYPICAL MARKETS	RELEVANCE FOR METAL
Powder bed fusion – Thermal energy selectively fuses regions of a powder bed	Metals, polymers	Prototyping, direct part	●
Directed energy deposition – Focused thermal energy is used to fuse materials by melting as the material is deposited	Metals	Direct part, repair	◐
Sheet lamination – Sheets of material are bonded to form an object	Metals, paper	Prototyping, direct part	◔
Binder jetting – Liquid bonding agent is selectively deposited to join powder material	Metals, polymers, foundry sand	Prototyping, direct part, casting molds	◔
Material jetting – Droplets of build material are selectively deposited	Polymers, waxes	Prototyping, casting patterns	○
Material extrusion – Material are selectively dispensed through a nozzle or orifice	Polymers	Prototyping	○
Vat photopolymerization – Liquid photopolymer in a vat is selectively cured by light-activated polymerization	Photopolymers	Prototyping	○



Type	Technology	Materials
Powder Bed	Powder bed and inkjet 3D printing (3DP)	Almost an metal alloy, powdered polymers
	Electron beam melting (EBM)	Almos an metal alloy including titanium alloys
	Selective laser melting (SLM)	Titanium alloys, superalloys, stainless steel, aluminium
	Selective heat sintering (SHS)	Thermoplastic powder
	Selective laser sintering (SLS)	Thermoplastic powder, metal powder, ceramic powder
	Direct metal laser sintering (DMLS)	Almost and metal alloy

Fig. 13 Powder bed fusion technologies and materials

3 Direct metal laser sintering: DMLS

3.1 Principle

Direct metal laser sintering (DMLS) is a laser-based rapid prototyping and tooling process by means of which net shape parts are fabricated in a single process. Complex parts can be produced directly from 3D-CAD models by layer-wise solidification of metal powder layers in portions of the layer corresponding to the cross-section of the three-dimensional part in the respective layer (Syvänen et al. 2008). Figure 14 below shows the basic components used in the DMLS process. The basic principle of the DMLS Technology is to melt down thin layers (20–60 μm) of Metal Powder with an electronically driven

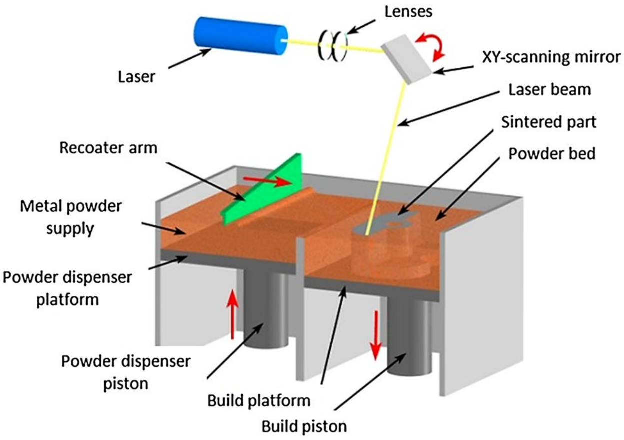


Fig. 14 DMLS setup

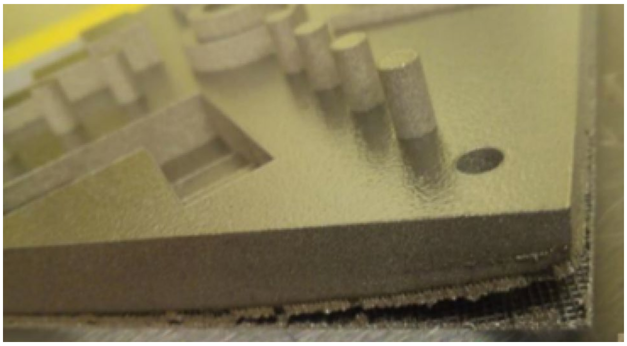


Fig. 15 Effect of large thermal stresses

laser beam (200 W) (Met 2016). The important parts of DMLS machine are: the building platform, dispenser unit, recoater unit, the laser system, precision optics such as *F*- theta lens or varioscan, a high speed scanner, and a computer with process software (EOS 2016; Surel 2008; Udroiu 2012). Metal powder is stored in dispenser unit and the recoater is used for coating of metal powder of uniform layer thickness on steel base plates. It needs to be noted that SLM, SLS, and DMLS are describing basically the same process, main difference being the nature of the powder.

3.2 DMLS additive manufacturing process

A steel base plate is mounted on building platform. Prototype part/mould is built on building platform. A layer of metal powder of grain size smaller and smallest fraction below 6 µm is spread on a steel base plate. The laser beam sinters the first layer. The building platform moves down by 20 µm. If powder layer thickness is 20 micron, powder needs to be much smaller in size. The build rate depends upon accuracy and roughness. The recoater moves towards the dispenser. The dispenser moves up, so that sufficient powder is taken by the recoater to spread a new layer of powder on the already sintered layer. The laser sinters the second layer, and thus, the process continues till part gets completed (Gratton 2012). Different parts can be built in one setup on a single base plate. Layer by layer, it is possible to build any kind of shape and geometry, even those which are impossible to obtain with any other kind of technology. The accuracy is ± 0.05 mm. The resulting DMLS 3D printed parts have different material structure/mechanical properties of those obtained through conventional techniques depending upon the materials. The steps involved in building a prototype part/ mould on AM machine are as follows:

- Creation of 3D CAD model of prototype part/mould.
- Converting the CAD model to .STL format.
- Support structure definition and smoothing of corners/ edges is required.
- Slicing the .STL model in to thin layers.
- The layer file .SLI is fed to DMLS–AM/rapid prototyping machine.

3.3 DMLS technology and design boundaries

When applying AM, several boundary conditions compared to the traditional design and processes are changing. Below listed are the main differences, which need to be accounted for planning to use AM technologies.

- Best fit model vs. 6point hard nest reference system.
- Roughness (Rz) factor of deposition layer thickness.
- Support structures during build required, which need to be removed later.
- Wire EDM required to cut part from base plate.
- Roughness is internal and external, which could influence the flow behavior of internal channels, in addition, the reduction of internal roughness requires (sometimes) very complicated methods (roughness is more waviness; therefore, it is not removing burrs).
- Parts are normally NOT dense enough for (high) pressure application without HIP process afterwards.
- Material structure differs from casting/forging (sometimes better LCF, tensile values) (Slotwinski 2013).
- Material has preferred direction due build method (random laser and path control to mitigate to a certain extent).
- Design of part to avoid large thermal stresses (Refer Fig. 15 below) (Kruth et al. 2010).

3.4 Main process problems

AM still being a young technology exhibits a number of process problems, which needs to be known when developing a part to be produced by AM, especially SLM/DMLS

- Different thermal boundaries expected during build-up (heating up or cooling down during build of the single layers).
- Technology transfer between different systems (hardware supplier) not/very limited possible (R&D equipment should be the same as production equipment).
- Depending on optics, test results cannot be transferred (*F*-theta lens vs. varioscan).
- Argon cross flow stability.
- Stability of brush/recoater.
- (Random) laser path and directional material pattern,
- Breakdown of melt pool, Re-fusing for densifying layer. Accuracy of overlapping laser paths (in case of multiple lasers).
- Powder handling (EHS issue)and delivery to system
- Purity of powder (supply chain- higher requirements compared to thermal spray application).
- Re-use of powder (sieving, sizing, etc.).
- Parts cleaning.
- Overhang surfaces and support structures, see Fig. 16 below (Alvarez 2014).

3.5 Main determining factors for productivity and cost

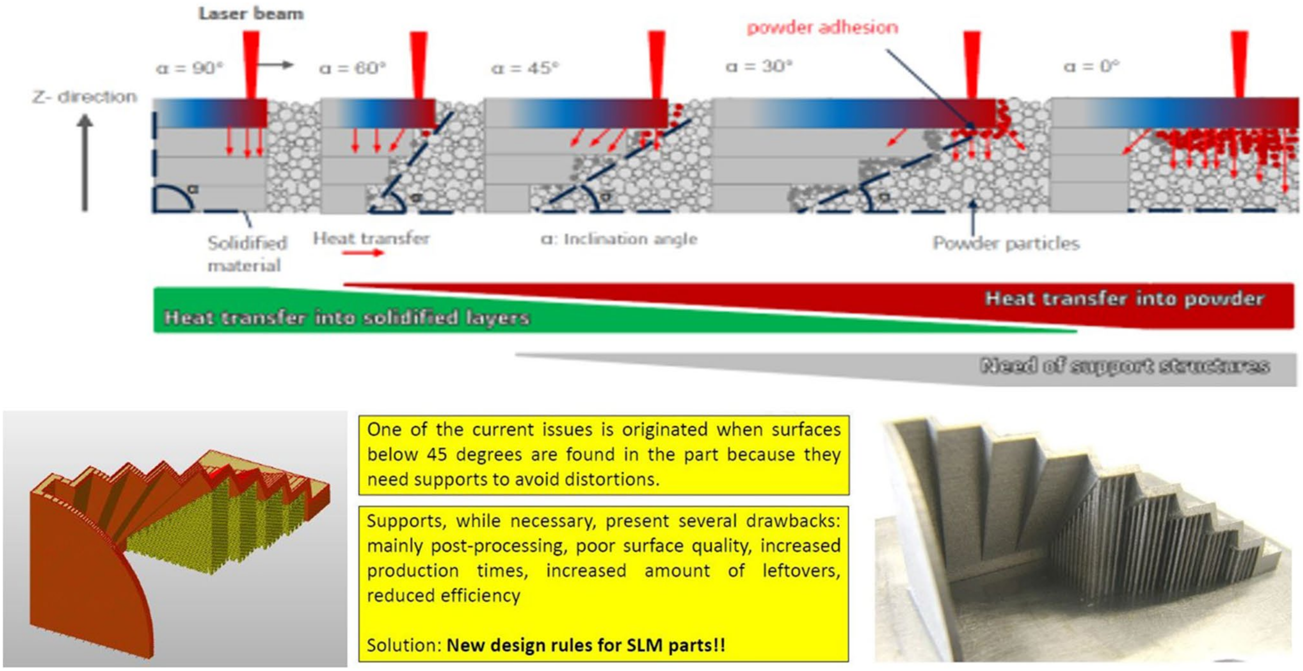
The cost of additive manufacturing is quite high, mainly to the very slow build rate. Typical factors influencing this parameter are as follows:

- laser scanning speed,
- laser power,
- number of laser and scanners,
- overlap area of multiple lasers,
- required roughness (layer thickness),
- base plate preheating capability.

In addition, the productivity of the complete system is influenced by the powder handling and exchange in combination with the required cleaning of the built part to remove the remaining powder. Most of the companies delivering AM equipment have addressed this problem and can deliver quick exchange system to minimize downtime of the production equipment.

Figure 17 describes the future trend for the key parameters (Berger 2013).

The powder is identified as one of the major cost (and problem) contributor to the AM process. Especially, for (high temperature) metal powder, several challenges exist as described in below Fig. 18 (Alvarez 2014).

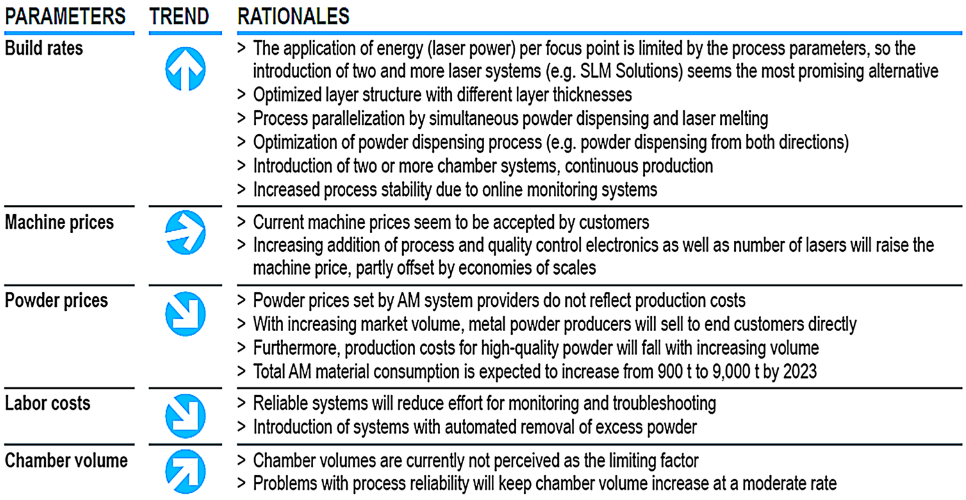


One of the current issues is originated when surfaces below 45 degrees are found in the part because they need supports to avoid distortions.

Supports, while necessary, present several drawbacks: mainly post-processing, poor surface quality, increased production times, increased amount of leftovers, reduced efficiency

Solution: **New design rules for SLM parts!!**

Fig. 16 Need and challenges regarding support structures



PARAMETERS	TREND	RATIONALES
Build rates	↑	> The application of energy (laser power) per focus point is limited by the process parameters, so the introduction of two and more laser systems (e.g. SLM Solutions) seems the most promising alternative > Optimized layer structure with different layer thicknesses > Process parallelization by simultaneous powder dispensing and laser melting > Optimization of powder dispensing process (e.g. powder dispensing from both directions) > Introduction of two or more chamber systems, continuous production > Increased process stability due to online monitoring systems
Machine prices	→	> Current machine prices seem to be accepted by customers > Increasing addition of process and quality control electronics as well as number of lasers will raise the machine price, partly offset by economies of scales
Powder prices	↘	> Powder prices set by AM system providers do not reflect production costs > With increasing market volume, metal powder producers will sell to end customers directly > Furthermore, production costs for high-quality powder will fall with increasing volume > Total AM material consumption is expected to increase from 900 t to 9,000 t by 2023
Labor costs	↘	> Reliable systems will reduce effort for monitoring and troubleshooting > Introduction of systems with automated removal of excess powder
Chamber volume	↗	> Chamber volumes are currently not perceived as the limiting factor > Problems with process reliability will keep chamber volume increase at a moderate rate

Fig. 17 Future trend for key parameters

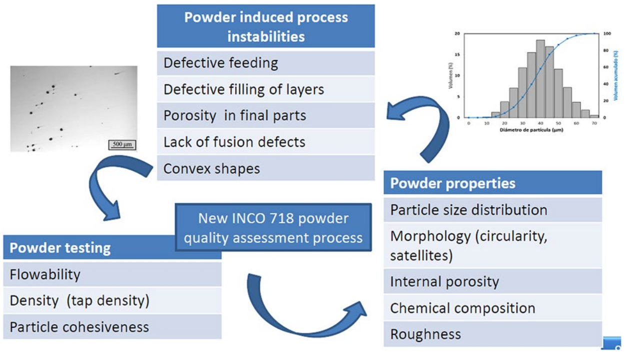
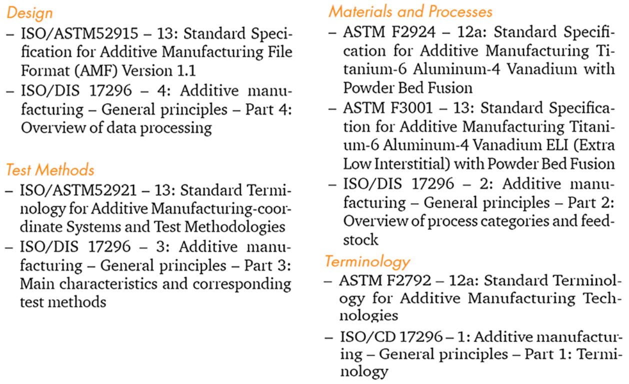


Fig. 18 Problems related to powder quality



Design
- ISO/ASTM52915 – 13: Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1
- ISO/DIS 17296 – 4: Additive manufacturing – General principles – Part 4: Overview of data processing

Test Methods
- ISO/ASTM52921 – 13: Standard Terminology for Additive Manufacturing-coordinate Systems and Test Methodologies
- ISO/DIS 17296 – 3: Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods

Materials and Processes
- ASTM F2924 – 12a: Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
- ASTM F3001 – 13: Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
- ISO/DIS 17296 – 2: Additive manufacturing – General principles – Part 2: Overview of process categories and feedstock

Terminology
- ASTM F2792 – 12a: Standard Terminology for Additive Manufacturing Technologies
- ISO/CD 17296 – 1: Additive manufacturing – General principles – Part 1: Terminology

Fig. 19 List of available standards for AM

3.6 Human skills and availability of standards

DMLS is automated process, but skilled labor is required. Direct labor costs are low but skilled labor required at all times (Vazquez et al. 2016; Swift and Booker 2013). It needs to be noted that there is still a lack of education and training of design engineers in AM processes, leading to the situation, that the full potential of AM is only slowly released. One contributing factor might be that the range of standards covering AM is still very limited, as shown in Fig. 19(VGB 2015).

4 Powder bed fusion equipment

EOS is a German company founded in 1989 that manufactures equipment for metal AM focused on their Direct Metal Laser Sintering (DMLS) technology. Typical DMLS machines developed by EOS are EOSINT M 280, EOS M290, and EOS M400, and developed by 3D Systems are ProX 100, ProX 200. It produces components by means of additive manufacturing—fully automatically, without tools and based directly on three-dimensional CAD design data; typical build volume by EOS: 250 mm × 250 mm × 325 mm (9.85 in. × 9.85 in. × 12.8 in .), 400 mm × 400 mm × 400 mm (15.8 × 15.8 × 15.8 in.) and 3D Systems: 250 mm × 250 mm × 330 mm (9.85 in. × 9.85 in. × 12.9 in.). Machines are user-friendliness, low-dust, ergonomic working conditions, and data can be processed conveniently at the workplace. The technology is used both for rapid prototyping, as it decreases development time for new products, and production manufacturing as a cost-saving method to simplify assemblies and complex geometries (EOS 2016). The Fig. 20 gives an overview about the different manufactures and a historical breakdown of sold equipment (Berger 2013).

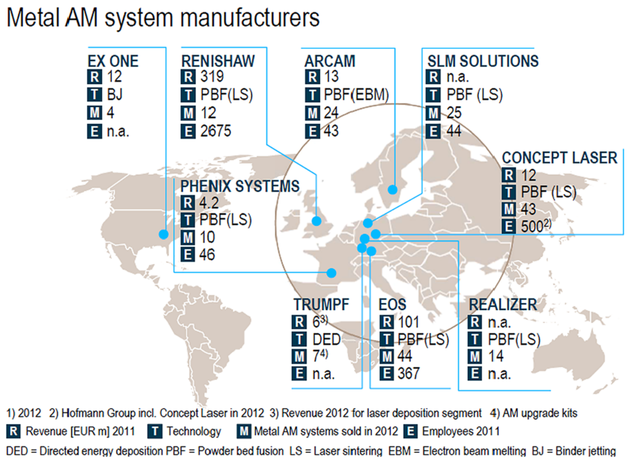


Fig. 20 Additive manufacturing hardware market overview

5 Metal 3D printing and developing countries

5.1 Metal 3D printing and the supply chain myth

People trying to use 3D printing to solve poverty in developing world by bypassing the supply chain problem—assuming that 3D printing needs nothing more than the powder or the printing material. In reality, the supply chain problem is still not eliminated due to (a) printers can only make (to the most extent) only parts, not whole products which are also requiring different material and (b) the 3D printer have complex electronics embedded, which needs a supply chain for maintenance and repair, which is even more prominent with metal 3D printing compared to the relatively easy and cheap polymer printers. Designing for developing countries is called designing for "the base of the pyramid", because it is designing for a lot of people with little money. This is actually the opposite of what 3D printers are good at—making a small number of parts at relatively high cost but making them unique (Faludi 2015) or creating completely new features, not possible with other manufacturing techniques which are also not the number one needed product group in developing countries.

3D printing's greatest promise for developing nations is likely the same as in rich nations: empowering small businesses by lowering the barrier to manufacturing. 3D print small quantities of different parts for several companies, once a product is successful in the market, switch to a mass production system. The company can use the earnings from the small, diverse sale to finance the expansion. In this way, it either can replace the venture capitalists or at least allows a proof of concept with connected sales to be presented to potential investors.

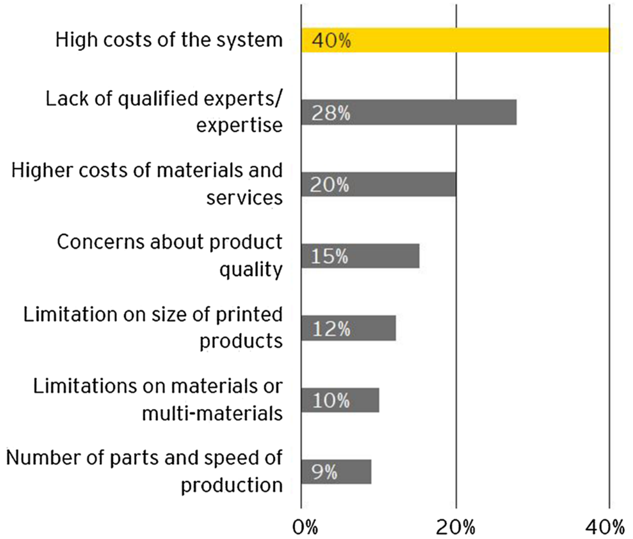


Fig. 21 EY global 3DP study with 900 companies (Mueller and Karevska 2016)

5.2 Low-cost hardware

One of the biggest obstacles in starting a business with metal 3D printing are the relatively high investment costs for the printing equipment, usually starting in the range of 350 k US$ (Fig. 21). Most of the powder bed fusion technologies employing complex laser and electronics and, therefore, difficult to scale down to a significantly lower price. Direct energy deposition technologies can be much simpler and, therefore, much cheaper. One initiative developed an open-source metal 3-D Printer which cost less than 2000 US$.

The metal 3-D printer (Fig. 22) is controlled with an open-source micro-controller and is a combination of a low-cost commercial gas–metal arc welder and a derivative of the Rostock, a deltabot RepRap (Anzalone et al. 2013).

This low-cost 3D metal printer is only the first step and can be seen as proof of concept. First part out of carbon steel ER70S-6, using a Lincoln Power MIG with a mixture of 75% Argon and 25% CO2, was a cup specimen which showed water tightness. Another example is customized sprocket, utilising a low-cost Miller MIG system (Fig. 23). The results are promising and have proven the concept, but considerable future work is necessary to develop this technology to make it appropriate for widespread deployment.

5.3 Availability of 3DP qualified experts

To fully deploy the use of 3D printing, developing countries need to have enough number of experts who can design, model, and manufacture different products. So far, there is a shortage of experts who can design and manufacture different products using 3D printing technology

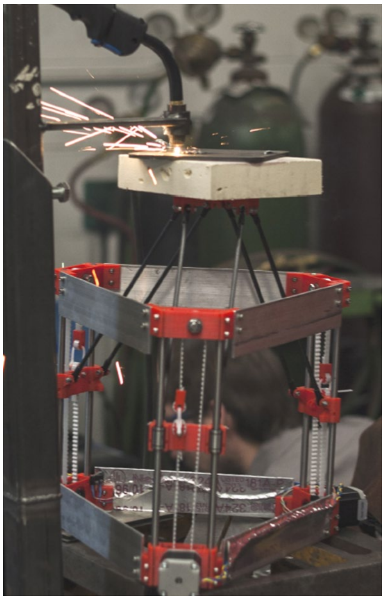


Fig. 22 Open-source metal 3D printer during deposition

Fig. 23 Model and 3D printed customized sprocket

(Fig. 21). More training is needed—not only—in developing countries so as to increase the availability experts of 3D printing technology (Fredrick et al. 2014).

This training can be and must be multi-sided. It needs to start in school, where kids are learning to design parts for relatively inexpensive polymer 3D printer. With this early exposure to this technology, it will be possible to raise a new generation of designers, who will not be "tainted" by current design limits due to the traditional manufacturing. From their early experience with non-metal, this new generation of designers will have a jumpstart for new and innovative products for 3D metal printing. This also poses an opportunity for developing countries, due to the fact that the gap in knowledge and experience is not as wide as in other technologies.

5.4 Limited and fixed materials

Currently, the 3D printers create products by making use of plastics, resin, ceramic, and metals. The common 3D Printers are still not capable of mixing different materials required for printing. As a result, for a product that needs a mixture of more than one material as constituents, its quality or strength is affected. For example, printing models that contains both rubber and metals is still challenging. Meanwhile, the large commercial 3D printers that support mixed materials are very expensive for majority of users from developing countries (Fredrick et al. 2014).

5.5 Opportunities for developing countries with 3D metal printing

The opportunities for developing countries with 3D metal printing compared to 3D printing of other materials are rather limited today due to the described high entrance barrier of initial printing investment cost as well as the so far limited local market for such metal products.

Nethertheless, 3D printing, especially with polymer or concrete, is guaranteed to give everybody in the developing countries the power to manufacture or just create virtually whatsoever for their own uses. For example, developing countries can use 3D printing technology to manufacture local equipment such as toys, farming tools, domestic tool, etc. This will help to create new jobs and empower people economically.

Science and technology are the important aspects of economic development in the developed countries. Developing countries also need science and technology to improve the lives of the citizens. Henceforth, with this 3D printing technology, it is anticipated that the teaching of science in developing countries will advance. In the developed countries, 3D printing is basically used by students to generate models/prototypes of things deprived of the use of costly tooling needed in subtractive methods. Students design and manufacture physical models. The classroom permits students to study and engage innovative applications for 3D printing. This can be replicated to developing countries (Fredrick et al. 2014).

6 Conclusion

Additive manufacturing (AM), also known as 3D printing, has captured the imagination of many technology observers and manufacturing professionals. The technology has been widely heralded as a means to rethink design, digitise manufacturing, produce to demand, and customise products.

There is a rich landscape of available technologies and materials for metal additive manufacturing. The range of currently available materials is already very large, ranging from titanium alloys and nickel alloys to high-grade stainless steels and is increasing rapidly. Additive manufacturing technologies offering product complexity for free but demanding a new product design tailored for AM. 3D Printing technology presents a huge prospect for developing countries. The technology offers local societies the ability to innovate, design, and create tools that support and improve their daily lives. Moreover, as technological advancement and Internet access improved in developing countries, 3D printing technology is expected to revolutionize manufacturing sector worldwide.

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