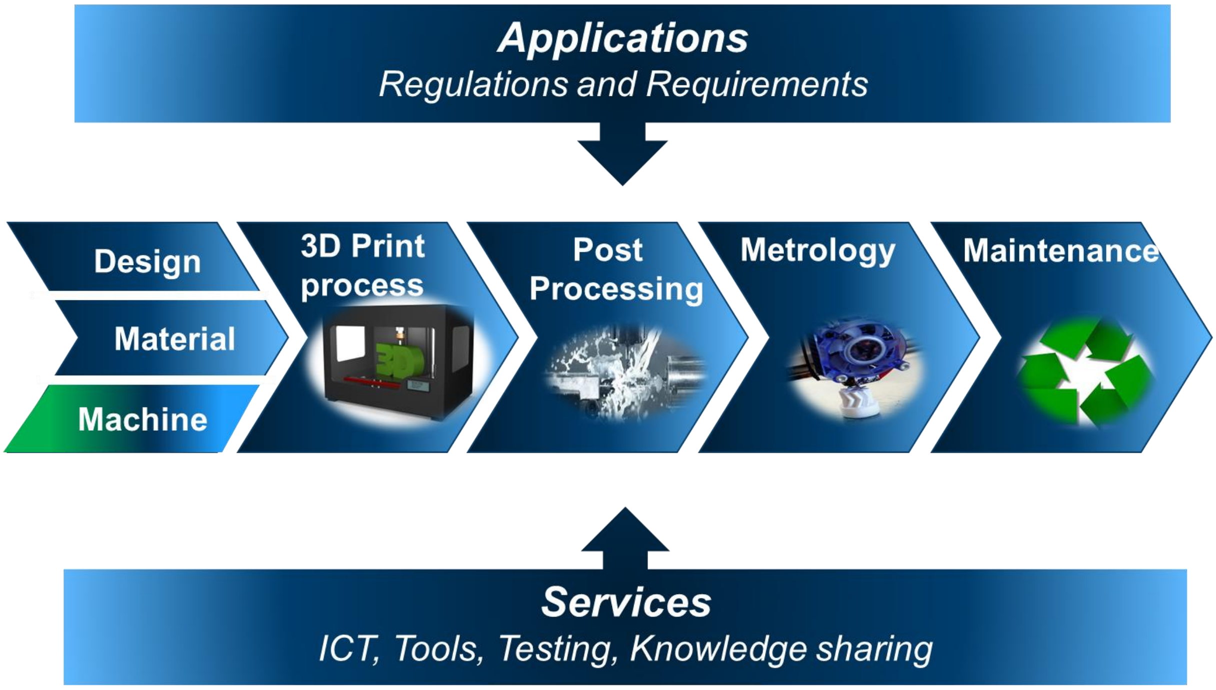
Quality assurance and Quality control in metal AM: Machine



Keywords: SLM vs EBM, process description, power source, build platform, recoater mechanism, laser

Content

1. Introduction

Additive Manufacturing includes a range of production technologies, which are differentiated by four main characteristics (table 1), namely;

- Material
- Material - feedstock
- Material - Deposition Method
- Energy Source

Table 1 An overview of the main characteristics of AM production technologies

Material	Metals, polymers, ceramics, organic, (tissue, food and structural
Material – feedstock	Powder, wire, resin
Material – Deposition Method	Bed, basin, feed
Energy – Phase Transformation Method	Laser Sintering, Laser Melting, Electron Beam Melting, Ultra Violet Curing, Heated Nozzle, Binder Fluid[1]

Additive Manufacturing is a layer by layer process. In each layer a base material (1) in a specific form (2) is selectively deposition (3) to create a two dimensional cross section of the 3D part (see Process - build profile). The energy source (4) – rather the method of phase transformation - describes the method with which the phase of the base material is transformed, to create the two dimensional cross section. This may be done by sintering, melting or by (temporarily) attaching particles with a binder fluid.

In this chapter the machines used for two powder-bed fusion technologies are discussed; Selective Laser Melting (SLM) and Electron Beam Melting (EBM). Although SLM is a trademark term for SLM solutions, we use the term as generic for all Leaser Beam Melting (LBM) technologies. In section 2 a general overview of the two production technologies is given. In the following section, the main element of the machines are described in more detail, namely power source (Section 3), build-platform (Section 4), recoater (Section 5), Inert chamber environment (Section 6). Additional important machine aspects related to quality include; build preparation (see Process), and in-situ process monitoring and control systems (see Metrology).

[1] In some technologies the feedstock is a mix between metal powder particles with some binder, such as ExOne technology. On that case, the binder is not exactly polymer but other low melting point alloy. See: http://www.exone.com/Resources/Materials

2. SLM & EBM Hardware Review

A schematic overview of both SLM and EBM technology is given in the paragraphs below.

SLM technology

Selective laser melting (SLM) is a technique that uses 3D CAD data as a source and forms 3D objects by means of a high-power laser beam that fuses and melts metallic powders together. In many sources SLM is considered to be a subcategory of selective laser sintering (SLS). But this is not so true as SLM process fully melts the metal material into solid 3D-dimentional part unlike selective laser sintering. The history of SLM started with German research project held by group of Fraunhofer Institute ILT in 1995.

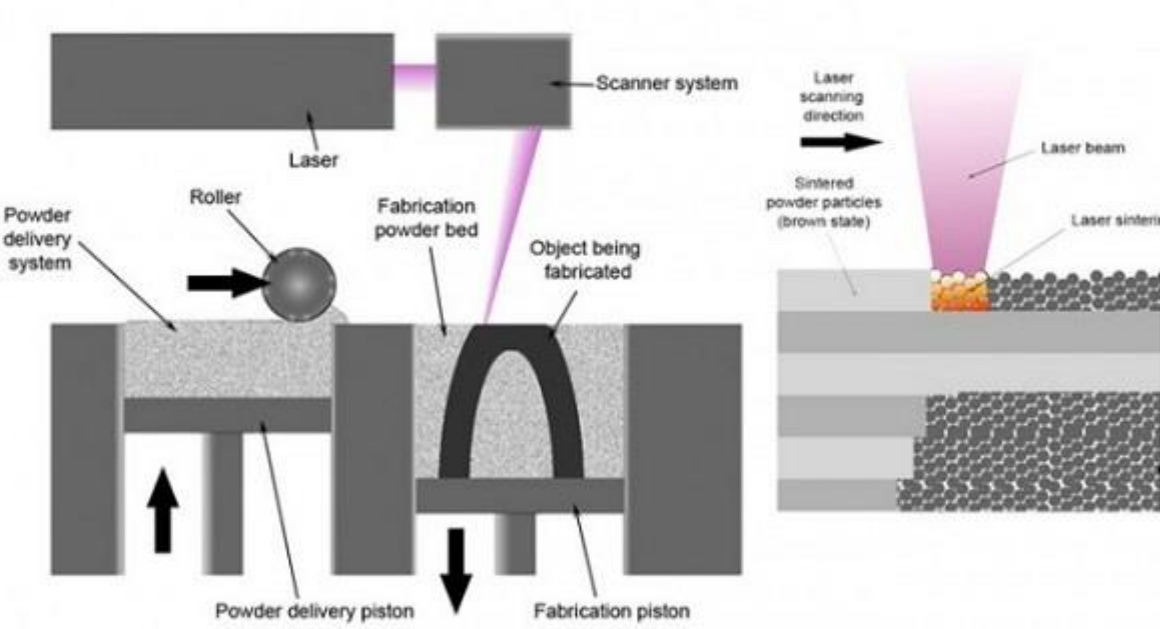


Figure 1 Schematic overview of the SLM technology (http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview/#slm)

Similarly to other 3d printing methods CAD file needs to be processed by special software to slice the CAD file information into 2D layers. The file format used by printing machine is also a standard .stl file. Right after the file is loaded the printing machine's software assigns parameters and values for construction of the path.

The fine metal powder is evenly distributed onto a plate, then each slice of 2D layer image is intensively fused by applying high laser energy that is directed to the powdered plate. The energy of laser is so intense that metal powder melts fully and forms a solid object. After the layer is completed the process starts over again for the next layer. Metals that can be used for SLM include stainless steel, titanium, cobalt chrome and aluminium (3dprintingfromscratch, web page accessed 16 March 2016).

EBM technology

The same as SLM, EBM is a powder bed fusion technique. While SLM uses high-power laser beam as its power source, EBM uses an electron beam instead. In case of EBM as the process is under vacuum and the temperature inside of the chamber is close to the melting temperature, the behaviour of the material is quite different. The solidification process is slower than in SLM, that causes a better grain growth with less anisotropy than SLM. There is not residual stresses nor distortions. Then, it is not required some post-process such stress relief. At the end, the metallographic microstructure is different and hence, the mechanical properties (figure 2).

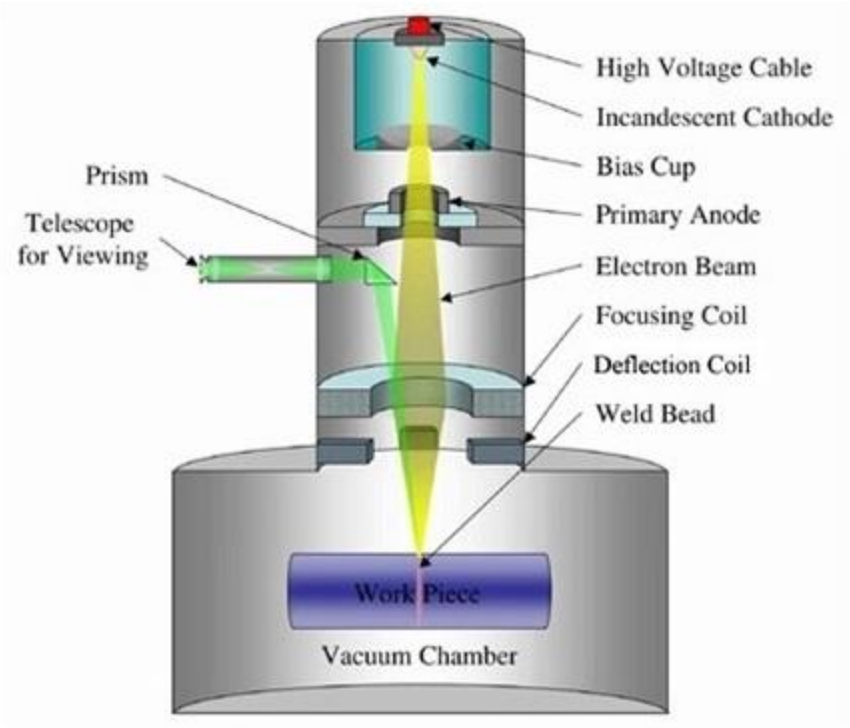


Figure 2 A schematic overview of the EBM technology (http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview/#ebm).

In recent years one of the challenges for the adoption of metal AM technology is a need to develop the hardware. There is a high demand for the improvement in the overall productivity of AM hardware, which can be subdivided into power source, increased build volume, higher build rate, efficient material handling, and in-process monitoring which are currently under development.

Table 1 below gives an overview of SLM and EBM equipment's available in the market with their main features such as power source, build platform, focus diameter, scan speeds and build rates.

Table 1 - List of SLM and EBM hardware with main features

OEM & Product Name's	Power Source	Process	Build Platform Dimensions XxYxZ in mm^3	Focus Diameter in µm	Scan Speed n m/s
EOS GmbH EOS M400 EOS M 290 , 280 EOS M 080 (Precious Metals- Gold, Silver, platinum &palladium alloys)	Yb-fibre laser 1 KW 400W 100W	DMLS	400x400x400 250x250x325 Ø80 mm x 90 mm	90 100 30	7
SLM Solutions Germany SLM 500HL SLM 280HL SLM125	Yb- fibre laser 4x 400 W or 2x (400 & 1000 W) 200W	SLM	500x280x320 280x280x350 125x125x125	70-120/700	10-20 Build Rate: 70ccm/h
Concept Laser GmbH X Line 1000R M2, M1 MLab	Yb-fibre laser 1 kW 200W – 400W 50W-100W	SLM SLM	630x400x500 250x250x380 90x90x80	100 – 500 50 - 200 20 - 80	7 Build Rate 20 - 100 cm3/h 1 - 5 cm3/h
Realiser GmbH SLM300 SLM100 SLM50 (Precious Metals and Dental)	Max 1KW Fibre 50-200W 20 -120W	SLM	300x300x300 125x125x200 Dia 70x40 in z	Not available	Not available
Renishaw SLM 250 Renishaw EVO Project	200W – 400W 500W	SLM	245x245x300	70	Build Rate 5 cm^3 - 20 cm^3 per hour
3D Systems ProX 400 ProX 300 ProX 200 ProX100 (Dental)	2x 500W fibre lasers (1KW Opt) 500W 300W 50W	SLM	500x500x500 250x250x300 140x140x100 100x100x80	100	Not Available
Arcam AB Q20 Q10 A2X	3KW Electron Beam	EBM	350Dia X380 Z 200x200x180 200x200x380	100-180	Build Rate 55[1] - 80[2] cm^3/h (Ti-6Al-4V) ([1]fine surface quality, [2]high build speed)

3. Power source

General

Recent development in laser services has assisted AM hardware to improve the speed and feature resolution. SLM systems used for metal parts have a laser as the power source; this can be up to 1KW however it is more common to be between 200-500W. The high powered lasers help to increase the deposition rate of SLM process. There are several SLM equipment OEM's in the market and only one EBM equipment provider which is made by Swedish company ArcamAB, the electron beam gun can generate up to 3000W power.

SLM process is divided into two cycle times, one is primary and other is auxiliary process time. Primary cycle time is the duration of actual melting of powder per layer and auxiliary cycle time is the duration of recoating powder for the next layer and platform lowering. The primary cycle time is a major part of SLM process which equals to 80 % of total time per layer (2). The main factors which affect the primary cycle time are scan spacing (ÄYs), scan velocity (Vs) and layer thickness (Ds). The SLM process build rate is calculated by equation given below,

Build Rate Vp = Ds * Vs* ÄYs

The scan velocity and layer thickness are mainly dependent on the laser power. The scan spacing is dependent on the laser beam diameter, which can be a maximum up to 0.7 times of focused beam diameter (2). The high laser powers can have bigger impact on increasing the build rate as they allow the laser to scan faster and still achieve the 100 % density in the part.

In the SLM process scan spacing also shows some significance towards increasing the build rate at high powers. The respective cross sections are shown in Figure 4, where it can be seen that changing scan spacing from 0.15 to 0.25 mm can have approx. 60 % increase in the build rate at 50µm layer thickness and a scan velocity of 1700 mm/s.

For the EBM process the use of high power has demonstrated to increase the build rate. There are two different systems built by Arcam AB with the same high power beam. One has a high power beam with larger platform (platform diameter of 350 and height of 380 in mm) to build parts faster with improved surface finish for applications in aerospace and the other one gives higher resolution (i.e. small beam diameter) at same power which can be used to process complex biomedical components such as light weight structures for bone in growth application (3) (4). EBM has a higher build rate than the SLM process, as is shown in table EBM has build rate capability of 80cm^3/hr with high resolution.

Multi-laser, Multi-scanner technology with high or variable power lasers

SLM Solutions Germany implemented a multi-laser with multi-scanning mechanisms in their hardware SLM280HL and SLM500HL to improve the productivity of the SLM process to build rate of 70 cm^3/hr. These systems have the ability to work with 2 lasers (400W each) & 2 scanners Or 4 lasers & 4 scanners combinations. Figure 3 on next page shows a real time view of 4 lasers scanning a layer of a part.

Prior to this new design all SLM hardware consisted one or two lasers and with one scanner mechanism which couldn't speed up the process drastically as exposure time per layer still remained limited due to the use of only one scanner(11).

Figure 3 Real time picture of 4 lasers, 4 scanners SLM system (11)

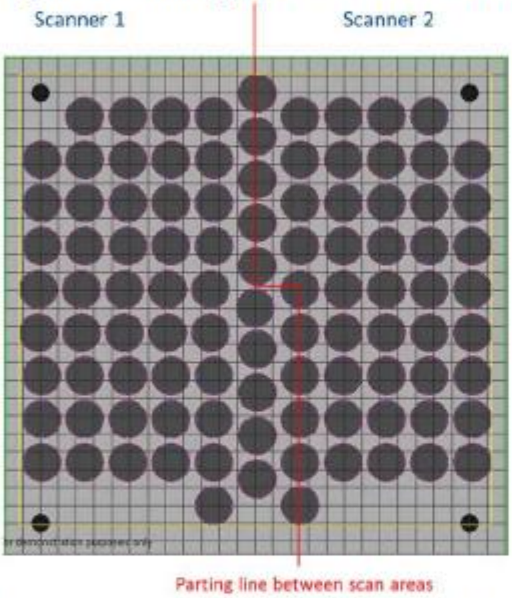


Figure 4 Schematics of designed overlap between 2 lasers – 2 scanning system (11)

Figure 4 shows a schematic of how the platform is divided so that a multi scanning system does not allow the lasers to cross each other on the platform. An overlap zone is designed to avoid any porosity and inconsistency issues in any given layer with help of precise scanner adjustments

This technology helps to achieve the deposition rate up to 70 cm^3 per hour which almost equal and comparable to existing EBM machines.

EBM systems also have a multi-beam technology capability in their hardware. EBM Multi-beam technology enables one beam to be divided in to several beams by swiftly moving the electron spot to achieve several melt pools in a given layer. This unique technology allows lower beam power per melt pool and higher total beam power which results in the improved precision and shorter melting compared to single beam hardware. This multi-beam technology can be used with two different strategies which is explained with their benefits in Table 2,

Table 2 Details of EBM Multi-beam technology and their comparison

Continuous Multi-beam	Discrete Multi-beam
Up to 8 melt pools	Up to 50 melt pools
Higher Speed	Comparatively Lower speed
More Energy efficient	Higher resolution
Suitable for hatching	Ideal for contours and fine details

Figure 5 shows the real time view of multi-beam technology in EBM. Multi-beam technology reduces the net build time by ~30 % as compared to single beam. This technology improves the build rate in addition to the surface finish and feature resolution e.g. for complex lattice structures and thin walled parts.

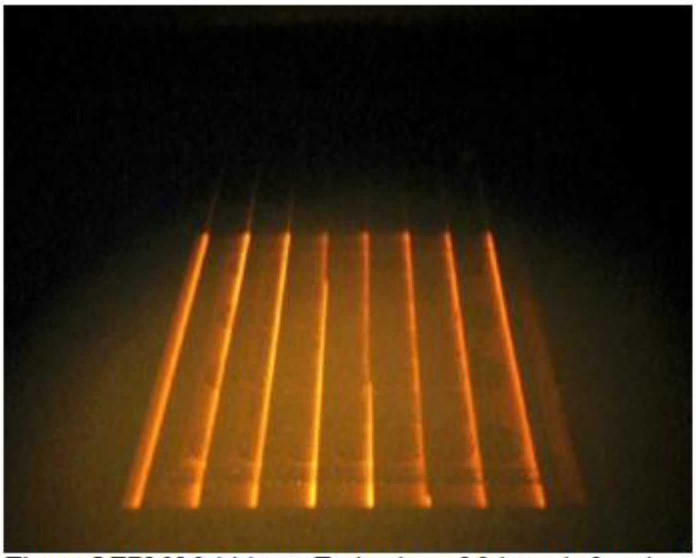


Figure 5 EBM Multi-beam Technology- Melt pools for a layer

4. Build platform

AM technology providers are also striving to produce systems with increased platform size. The drive for this increase is to allow larger parts to be manufactured using this technology, particularly in the Automotive and Aerospace industries. Table 1 shows the build platform size of all the SLM and EBM hardware available on the market. The Concept Laser GmbH laser cusing hardware has the largest build platform and the smallest build platform is available with Realiser's SLM 50.

5. Recoating/Wiper mechanisms

Recent developments in recoating mechanisms have also assisted in the increase the productivity of the SLM process. The ability to deposit powder in both directions has helped to improve the auxiliary time per layer. Figure 6 shows a component takes 5 hrs to build with one direction recoating and same part can be built in 3.5 hours with bi-directional recoating time.

The EBM process also benefits from a bi-directional recoating system; this is done by having two hoppers on each side of its power source which allows powder delivery in both ways.

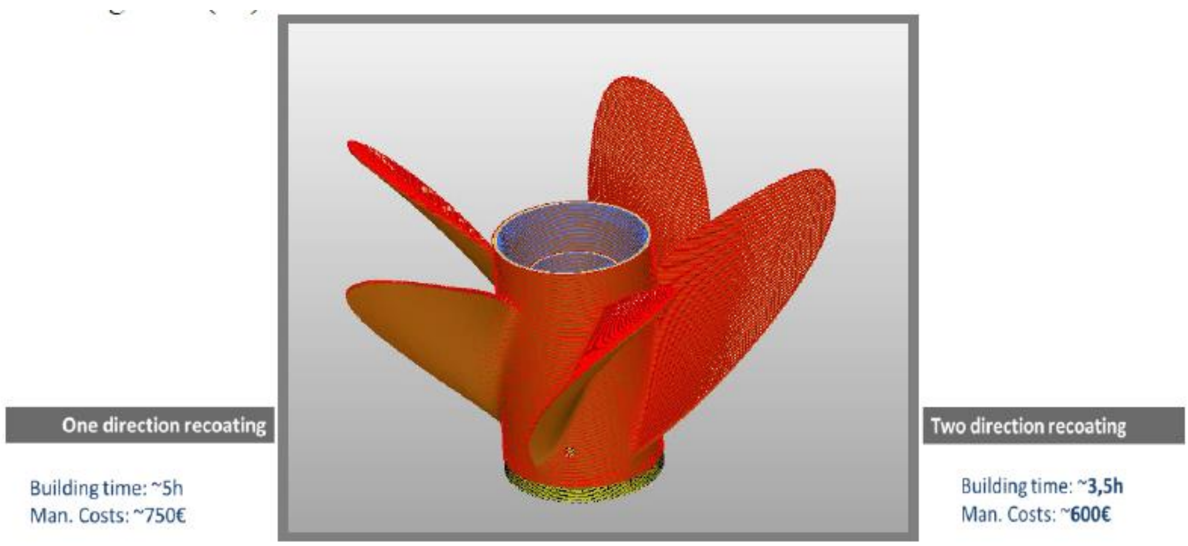


Figure 6 Marine propelling screw AlSi12 / 350 Watts 50 micron layer thickness. Build time 3.5 hours. X/Y: 100mm, Z: 70mm (Ritt, 2012)

Most of the SLM and EBM hardware have automatic powder handling systems, this helps to turn the machine around faster from one build to the next. Power handling systems automatically pull and sieve the powder after a build finishes and then feeds the powder back in the machine.

6. Procedure for control of machine:

- The state of the start plates must be supervised periodically. A minimum level of thickness and flatness should be established for each plate as well as a number of plates available for uninterrupted manufacturing.
- Different components of the machine are supervised by the machine software, and must be revised in accordance with the periodical maintenance of the machine (100, 200 and 400 hours). Full procedures are available in the User Manual provided by the system supplier. The main elements necessary to be revised before each build on the EBM system are:
  - Filaments: these are the active elements for creation of electron beam (useful lifetime 120h, commonly changed after 100h).
  - Heat shield plates: elements which provide heat insulation and maintain working temperature in the build area (changed after 2-3 builds).
  - Column foil: it helps the maintenance of the beam quality and has to be changed when major irregularities are detected (changed on demand).
  - Camera film: prevents camera of metallization and provides conditions for good process following through video (changed when the film roll is out, commonly after 10-15 builds).
- The main elements necessary to be revised before each build on the SLM system are:
  - Gas recirculation particulate filter: this filter removes are particulate matter that is ejected from the melt pool and is carried away by the argon flow in the build chamber (the filter is changed after every 36hours of machine operation; otherwise the filter is changed after every build).
  - Silicone Wiper: this wiper evenly spreads the powder across the build chamber (changed after every build).
  - Argon gas: a supply of argon gas is necessary for the SLM system operation. It is recommended to have a large argon tank to supply the systems (changed on demand).
  - Protective Lens: prevents any particulate matter contaminating the optical system (changed on demand).

For each one of these elements, a necessary stock level should be established, according to the manufacturing needs.

7. References and further reading

3dprintingfromscratch.com, accessed online 16 March 2016: http://3dprintingfromscratch.com/

Ritt. Stephen, ‘Will Metal Additive Manufacturing Technology be able to fulfil the customers’ requirements?’, ROBTEC workshop in August 2012

Arcam AB website: http://www.arcam.com/technology/electron-beam-melting/

Karma project. Deliverable DL 1.1 Detailed report on Laser Cusing, SLA, SLS and Electron Beam Melting (including technical, economical and safety features): http://www.femeval.es/proyectos/karma/Documents/DL%201.1_Report%20on%20technologies_5_11.pdf

European technology Sub-platform in Additive manufacturing - AM plaltform. http://www.rm-platform.com

Wohlers Report 2016 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report. https://www.wohlersassociates.com/2016report.htm