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Identification on some design key parameters for additive manufacturing: application on Electron Beam Melting

B. Vayre [a,*], F. Vignat[a], F. Villeneuve[a]

[a]Grenoble-INP / UJF-Grenoble 1 / CNRS, G-SCOP UMR5272, 46 av Felix Viallet, 38000 Grenoble, France
* Corresponding author. Tel.:+33-4-76-57-43-20; fax: +33-4-76-57-46-95.*E-mail address*: benjamin.vayre@g-scop.eu

Abstract

Additive manufacturing (AM) consists in building parts from scratch, usually by stacking layers onto one another. Mostly used for rapid prototyping purposes, several AM processes can use metallic alloys which makes the rapid manufacture of end-use parts possible. Many researches are conducted to improve the manufacturing rate, to assess the environmental impact or to study the mechanical properties of test parts manufactured by such processes. In spite of the large number of studies, there is yet to be a designing methodology to take advantage of these processes. The formalization of the manufacturing capabilities and manufacturing constraints that these processes have has especially hardly been conducted.
In this paper we investigate the manufacturing constraints of the Electron Beam Melting process, a metallic additive manufacturing process in order to issue recommendations to the designers. We will review the principle of Electron Beam Melting and look at the manufacturing capabilities designers are offered. Then we will focus on some key manufacturing constraints, the powder removing and the necessity of supporting structures. At last, we will give some recommendations regarding these two topics to take advantage of this process from the designing stage of a part.

Selection and peer-review under responsibility of Professor Pedro Filipe do Carmo Cunha

Keywords: Additive maufacturing; Rapid manufacturing; Electron Beam Melting; Design for additive manufacturing

1. Introduction

Additive manufacturing (AM) processes have been commonly used for rapid prototyping purposes. With the ability to build metallic parts and many other technological improvements, the processes can now also be used for rapid manufacturing purposes which consists in manufacturing directly end-use parts [1]. These technologies are the subject of many researches focused on improving the technology itself [2], comparing their performances to those of conventional manufacturing processes or to one another [3], assessing their environmental impact [4], etc. Their interest in the field of manufacturing is now acknowledged [5] yet there isn't any accepted designing methodology that takes into account their specificities and the manufacturing constraints are still being investigated [6]. This paper will investigate two usually disregarded specificities: the removing of the unbound powder and the need for supporting structures for the Electron Beam Melting (EBM) process. Our purpose is to highlight the phenomena and identify the influent parameters to issue recommendations that should ultimately become designing rules.

At first, we will review the principle of layer based additive manufacturing and the specificities of the EBM process. Then we will turn to the manufacturing capabilities and constraints that these processes offer. After having identified the different manufacturing constraints, we will focus on powder removal and on the flatness of surfaces. After the analysis of our experiments, we will give designing recommendations regarding these constraints. We will then conclude on this study and present prospects regarding these constraints and design for additive manufacturing.

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2. Additive manufacturing

Contrary to conventional manufacturing processes where parts are usually obtained by machining a forged, laminated, injected, extruded or molded raw part, additive manufacturing consists in building an object “from scratch” or from a semi-finished part acting as substrate. A very wide range of material, from polymers and composites to metallic alloys, is available on many different processes. Metallic additive manufacturing can either be layer based or direct (by directly projecting molten metallic drops onto the part). This paper will focus on EBM; a layer based additive manufacturing process.

2.1. Layer based additive manufacturing processes

Layer based processes build parts by stacking cross-sections one onto another. First of all, the CAD model is sliced into 20 to 150 µm-thick cross-sections (depending on the kind of process and on its characteristics – typically 70 µm on EBM).

The building process starts onto a start plate (perpendicular to the building axis) that will hold the parts and help dissipating heat. For each slice, a roller deposits and presses down a new layer of powder. Then the current section of the part (or parts) is scanned with an energy source to bind the powder particles. Depending on the process, the energy source is either a Laser (Selective Laser Sintering, Selective Laser Melting, Direct Metal Laser Sintering…) or an electron beam (EBM) and the particles are either sintered (SLS, DMLS) or molten (SLM, EBM). The building tray is them moved down and this whole process is repeated until the part is fully built. Once fully built, the part or parts are removed from the unbound powder and cleaned. The remaining powder is filtered and can be used again and again (to a certain extent, for example oxygen pick-up of Ti6Al4V can happen at high temperature).

2.2. Electron Beam Melting features

Electron Beam Melting is a layer based additive manufacturing process that builds fully dense parts from Titanium (Ti grade II or Ti6Al4V alloy) and CoCr alloy powders. Its high energy source, an electron beam, has unique capabilities such as multibeam (the use, thanks to high commutation in electron guidance, of “several” beams at once) and the ability to heat, sinter or fully melt the powder. Moreover, for each slice, the electron beam sinters the whole layer of powder and heats it at higher temperatures than SLM processes (around 750°C for the Ti6Al4V powder for example). With the addition of a building chamber under a partial vacuum which decreases thermal convection, there is a low temperature gradient inside the powder bed and the part hence few thermal distortions. This process is able to build parts with superior properties than molten ones and of comparable properties than forged parts [7]. The building speed is faster than SLM’s but the dimensional and surface qualities are usually inferior [1]. Its unique manufacturer is Arcam AB, a Swedish company

2.3. Manufacturing capabilities

Contrary to milling and turning where planes and cylinders are the easiest geometrical entities to manufacture, layer based additive manufacturing is virtually able to build any geometrical structure without complex pre-processing. The slicing of the parts and manufacture of one section at a time make the manufacture of complex part (such as turbines blades) as easy (as long as the manufacturing constraints are taken into account) as the manufacture of prismatic parts for example. In addition, material can be placed only where the functions realized by the part require it (to mount the part, transmit a load, prevent leakage…). If the part has to be rigid, instead of using fully dense volumes lightweight structures such as 2D and 3D lattice structures can be used. These structures have high rigidity, low density, and facilitate the powder removal [8].

2.4. Manufacturing constraints

EBM and other layer-based additive manufacturing processes have manufacturing constraints in terms of dimensional quality, surface quality, and metallurgic properties that can also be found in conventional processes [8]. These criteria are of great use when it comes to assessing the manufacturability of a given part or to foresee the need for finishing operations. Yet, they also present specific manufacturing constraints such as the necessity to remove unmolten powder upon the part completion and the need, in some cases, for supporting structures to conduct the energy from the melting pool to the building plate and machine structure.

These two specific constraints have hardly been investigated. So far, there is no designing rule in the literature, no recommendation from the EBM manufacturer, nor a simulating piece of software to take them into account during the designing stage.

3. Study of powder removal

Additive manufacturing most impressive capability is the ability to manufacture lightweight and hollow structures. Due to the layer manufacturing principle, upon completing the build of the parts, the unmolten powder should be removed to reduce the cost of the part as well as its environmental impact (since retrieved powder can be used again once sifted), to lower the mass of the part and to prevent it from spreading metallic powder (potential sanitary impact or pollution of liquid for example).

It is possible to use vibrating or sanding systems or even machining to remove the unmolten powder. The manufacturer recommends the use of a sanding system functioning with the same powder than the machine which allows the reuse of the powder after having sifted it. This device is called Powder Recovery System (PRS) and has only one parameter that can be adjusted, the air pressure. For this study the air pressure was set to a recommended pressure of 6 bars.

3.1. Influent parameters

The quantity of removed powder depends on many parameters that have different origins. These origins are the geometry of the entity to be unpowdered (shape, dimensions…), the type and parameters of the removal process (flow, pressure, nozzle characteristics and powder granulometry for a sanding process for example), the raw material (type of alloy, granularity), the removal strategy (duration, methodology) and the manufacturing process parameters (amount of energy used during the sintering of unmolten powder for EBM for example). In our study, we will use the standard powder recovery system that allows the users to remove and reuse the unmolten powder. We will also use the recommended parameters concerning the melting and sintering phases of the EBM process.

3.2. Impact of process duration

Before conducting any experiment, it is interesting to focus on the impact of duration over the quantity of removed powder. This is necessary to establish a base duration for the following experiments. Several hollow cylinders of 5 and 7 mm diameter cylinder were manufactured. The powder that they contained was then removed and the removed depth was measured several times (Fig. 1).

Between 75 and 80% of the asymptotic volume is removed within the first 30 seconds for both size of cylinders. 95% of this value is attained in 3 and 4 min for the 5 and 7 mm diameter cylinders. 98% of the asymptotic value is attained after 6 min of unpowdering for both hollow cylinders.

In our further experimentation we used a powder removal duration of 3 minutes to facilitate the experiments as well as keep the difference between our measured values and the asymptote low. In any case, if the PRS isn't able to remove unbound powder from hollow tubes in 10 min, another system has to be used to fulfill this task.

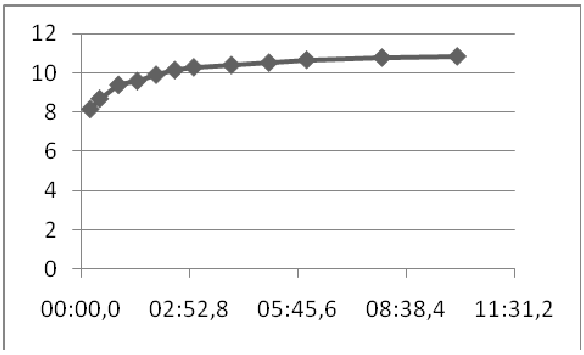

Fig. 1 Mean depth of removed powder (in mm) evolution over time (for 7mm diameter cylinders)

3.3. Repeatability

We then assessed the repeatability of the process of powder removal by removing powder from multiple hollow cylinders during 3 minutes.

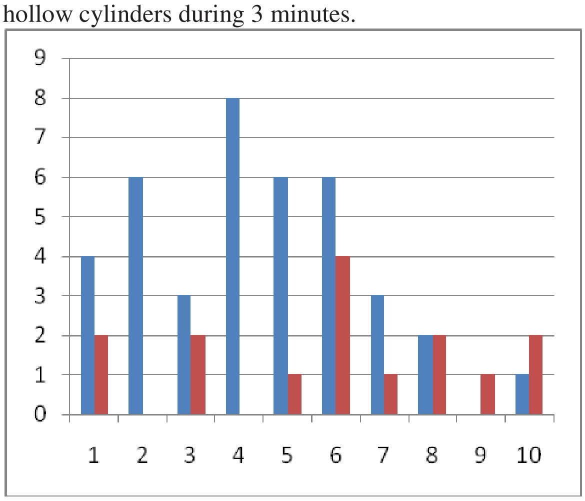

Fig. 2 Population distribution of removed powder heights from 5mm diameter cylinders (in blue) and 7mm cylinders (in red) by tenth of total deviation and centred around the mean value

We found a total variation between the maximum and minimum depth of removed powder of 2.7 and 2.07 mm for 5 and 7 mm diameter cylinders (Fig. 2). This deviation can be related to the variation of the PRS and PRS operator (powder removal duration, nozzle orientation, nozzle distance from the tube...), as well as the error due to the measuring device, a measuring column, that can compress slightly the remaining powder hence depending on the applied pressure. The variation can also come from the spherical shape of the remaining powder which introduces a variation in the measurements.

3.4. Impact of section area

Our purpose is to relate the removable powder depth to the section surface area of tubes (with constant sections at first). We conducted several experiments and obtained mean values for the depth of removed powder inside of hollow cylindrical tubes of different diameters. These values must be taken into account while keeping in mind the repeatability variation as well as the influence of process duration.

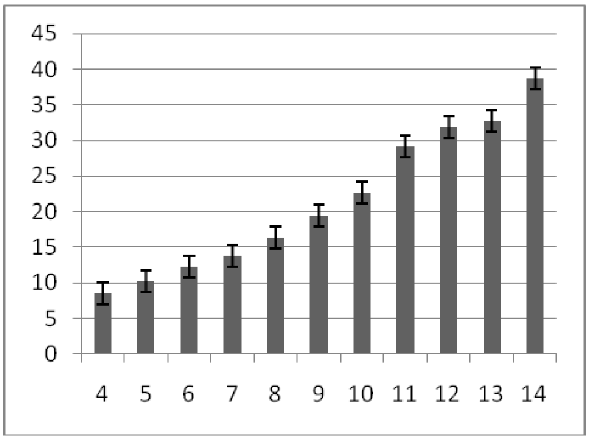

Fig. 3 Mean removed powder height (in mm) evolution depending on the hollow cylinder diameter (in mm)

The relation between inner diameter of hollow cylindrical tube and mean removed powder height can be modeled by the following linear expression:

height = 3,066.diameter + 3,012 mm

3.5. Additional parameters

We compared the measured depth of removed powder from hollow tubes with triangular and square cross sections of identical surface area. We observed differences concerning the results of removed powder height between these test parts, but we weren't able to quantify them due to the low number of experimentations. On a qualitative point of view, we observed that for a same section area, the square section tubes have a lower height of remove powder than cylindrical tubes but a higher one than triangle cross section tubes.

With additive manufacturing, we have seen that it is possible to manufacture inner structures inside hollow volumes. The almost infinite diversity of pattern and density that can be achieved implies that an empirical and general study will be complex to conduct. In this case, we recommend to keep in mind that the ability to remove powder will be reduce and suggest to conduct tests to obtain the optimal values for each specific case.

3.6. Recommendation regarding hollow geometrical features

We have showed that there is a linear relation between the diameter of a cylindrical hole and the depth of powder that can be easily removed with the PRS. This relation can be used as a recommendation by designers to identify possible sensitive geometrical entities in their design that can lead to cost and time expensive post-processing operations to remove the unmolten powder.

This relation can be used for cylindrical hollow holes. A similar study can be conducted with different section shaped holes or with the presence of inner lattice structure inside of holes to determine the maximum depth allowing an easy powder removal.

4. Study of supports

Layer based additive manufacturing processes sometimes require the use of supporting structures to prevent the molten or sintered drops from sinking into the powder bed as well as to conduct the energy from the molten pool to the start plate and the machine structure. In the case of EBM, for each slice, the whole layer of powder is sintered. Moreover the chamber build is under partial vacuum (around 0.3 Pa once helium is being continuously injected to stabilize the process) and insulated. EBM is also a high energy process that requires precautions when dealing with energy dissipation from the melting pool. This dissipation is essentially achieved through conduction from the currently scanned layer to the building start plate through the molten sections of lower layers and supporting supports.

These structures are usually placed automatically by pre-processing software dedicated to additive manufacturing. But the available pieces of software usually suggest too many supports which are hard and time consuming to remove, lead to wasting material and increase the cost of the parts. We found a lack of recommendation in the literature as well as from the EBM manufacturer regarding this topic.

4.1. Need for supports

It is necessary to conduct a preliminary investigation to identify the cases for which supporting structures are needed. We chose planes with constant thickness (of 1 mm) as test parts. We manufactured several planes, linked on one of their extremities to the start plate, with orientations varying from 0° (perpendicular to the building vertical axis) to 90° (parallel to the building axis).

We observed a very high distortion on the extremity of the plane (curling of the plane) for 0, 1 and 2° orientation, and no measurable curling for any other orientation. We then chose to focus on the highest deformation case, when the surface to be built is perpendicular to the building axis, that is to say parallel to the start plate.

4.2. Impact of distance between plane and surface

When parts are built very close to the start plate (first layer of powder: 0.05 - 0.10 mm high from the start plate) hardly any deformation can be measured. When manufacturing planes parallel to the start plane and 5, 10 and 15 mm away from the start plate (with and without supporting structures), no significant differences in terms of deformation were measured between the different test parts.

This study won't investigate the transition that exists between 0.07 mm and 5 mm. We will focus on the cases that are the most problematic which is when the deformation is maximal. Hence we chose 1 mm thick planes (parallel to the start plate) as test parts and the distance between our test parts and the start plate was set to 5mm in our further experiments (to reduce manufacturing time and raw material consumption).

4.3. Impact of support density

Pre-processing pieces of software for additive manufacturing offer several different types of supporting structures. The supporting structures must conduct energy as well as be easy to remove once the part is built. We chose to build the test parts with basic supporting structures: 0.6 mm diameter cylinders (minimum dimension that can be manufactured on EBM). They are easy to manufacture and easy to remove.

We monitored the flatness and heights dispersion of points around the plane surface of our test parts to assess the impact of supporting structures density over distortion. We chose a set of seven different support densities, with supporting cylinders placed on the perimeter and under the plane and separated between one another by a distance of 2, 3, 4, 6, 8, 10 and 12 mm. The planes were then scanned using an optical sensor to obtain the height of a large number of points.

As can be seen on Fig. 4, when too few supports are present, the test part starts to curl until the supports from one of its extremities detach from the start plane. Once some supports have been detached from the start plane, the heat conduction becomes more difficult and the phenomenon amplifies itself.

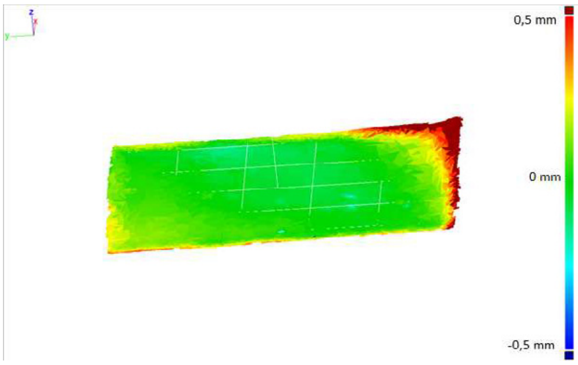

Fig. 4 Height of the scanned points of a plane surface with supporting structures placed every 12 mm. Curling phenomenon can be seen on the right side of the part.

The support density has an impact on surface flatness, standard deviation and total deviation of the height repartition of the scanned points. For our test parts, our results show that the standard and total deviation of the repartition is similar for spacing between 2 and 8mm (Fig. 5). For higher spacing values the standard deviation increases greatly.

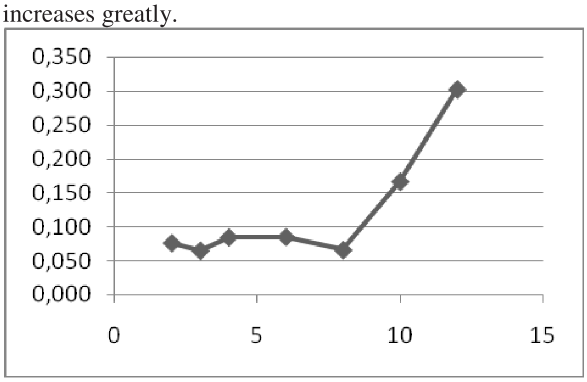

Fig. 5 Standard deviation of the points from 1mm planes (in mm) function of the spacing of the supports (in mm)

Focusing on higher spacing values than 12mm isn't relevant since the deformation is so high than it can cause the rake of the EBM system to break due to its collision with the curled part of the plane. For every test part, we note (as can be seen on Fig. 5) that the biggest deformations are located on the perimeter of the plane, even when the parts are not curled.

4.4. Conclusion and recommendation regarding supporting structures

This preliminary study showed that supporting structures are needed to conduct the energy from the melting pool to the build plate when the orientation of our test parts from the building axis is close to 90°. Our results show that in the worst case scenario, for a plane with a 1mm thickness, 8 mm spacing between cylindrical supporting structures allows the manufacture of the part with a low flatness defect while minimizing the material consumption for the supports. This study should remind designers and layer-based additive manufacturing users that a lot of attention should be paid to supports (while keeping in mind that part orientation has also an effect on the quality of the part [10]) in order to decrease their density compared to what pre-processing software suggests. In our case, for example, the default pattern is much denser, with a typical spacing of 2mm instead of 8 mm.

In this preliminary study, we focused on 1 mm thick plane although the thickness of the geometrical feature to be built has an effect on the quantity of energy needed, hence on the need for energy dissipation and supporting structure. This parameter, as well as the different types of supports patterns, needs to be taken into account before it is possible to optimize the placement of such structures.

5. Conclusion and prospects

The study we conducted is a preliminary research on two usually disregarded issues concerning layer-based additive manufacturing. The removal of unmolten powder is important to reduce the cost of the part as well as its environmental impact, to lower the mass of the part and to prevent it from spreading metallic powder. We identified several influential parameters and gave estimations of the powder removal depths that can be easily achieved for a set of geometric features with the PRS. Due to the high variability of the results of the experiments and on the variety of hollow geometrical features, our work should be used as a first pass iteration during the design. It can help the designer recognize potential issues regarding the manufacturability of its part and the need for further operations or the use of other ways to remove unmolten powder.

The second topic concerns the supporting structure that have to be used in order to prevent deformation caused by improper energy dissipation. We showed that for our test parts these structures are only needed when their inclination from the building axis is close to 90°. We identified several parameters and found a range of spacing values that minimize the deformation of our test parts.

In both cases, influent parameters were identified but left outside of this preliminary study. Their influence on the observed phenomena should be observed and analysed to obtain models for powder removal and supporting structures placement for EBM and ultimately to give some designing rules that should be implemented in a design for additive manufacturing (DFAM) methodology.

References

[1] Karunakaran, K.P. , Bernard, A., Simhambhatla, S., Dembinski, L., Taillandier, G., 2012, Rapid manufacturing of metallic objects, Rapid Prototyping Journal, Vol. 18, Issue 4, pp 264-280.

[2] Yang, J., Ouyang, H., Wang, Y., 2009, Direct metal laser fabrication: machine development and experimental work, The International Journal of Advanced Manufacturing Technology, vol. 46, n° 9-12, p. 1133-1143.

[3] Kruth, J. P., Vandenbroucke, B., Vaerenbergh van, I. J., Mercelis, P., 2005, Benchmarking of different SLS/SLM processes as Rapid Manufacturing techniques, Proceedings of the PMI.

[4] Kellens, K., Dewulf, W., Yasa, E., Duflou, J., 2010, Environmental analysis of SLM and SLS manufacturing processes, Proceeding of the 17th CIRP International Conference on Life Cycle Engineering, p. 423-428.

[5] Diegel, O., Singamneni, S., Reay, S., Withell, A., 2010, Tools for Sustainable Product Design: Additive Manufacturing , Journal of Sustainable Development, vol. 3, n° 3, p. 68-75

[6] Vayre, B., Vignat, F., Villeneuve, F., 2012, Designing for Additive Manufacturing, Procedia CIRP, vol. 3, p. 632-637

[7] Murr, L. E., Esquivel, E. V., Quinones, S. A., Gaytan, S. M., Lopez, M. I., Martinez, E. Y., Medina, F., Hernandez, D. H., Martinez, E., Martinez, J. L., Stafford, S. W., Brown, D. K., Hoppe, T., Meyers, W., Lindhe, U., Wicker, R. B., 2009, Microstructures and mechanical properties of electron beam-rapid manufactured Ti-6Al-4V biomedical prototypes compared to wrought Ti-6Al-4V, Materials Characterization, vol. 60, n° 2, p. 96-105.

[8] Vayre, B., Vignat, F., Villeneuve, F., 2012, Metallic additive manufacturing: state-of-the-art review and prospects, Mechanics & Industry, vol. 13, n° 02, p. 89-96.

[9] Murr, L. E., Gaytan, S. M., Medina, F., Martinez, E., Martinez, J. L., Hernandez, D. H., Machado, B. I., Ramirez, D. A., Wicker, R. B., 2010, Characterization of Ti6Al4V open cellular foams fabricated by additive manufacturing using electron beam melting, Materials Science and Engineering: A, vol. 527, n° 7-8, p. 1861-1868.

[10] Paul, R., Anand, S., 2011, Optimal part orientation in Rapid Manufacturing process for achieving geometric tolerances, Journal of Manufacturing Systems, vol. 30, n° 4, p. 214-222.