Depowdering of lattice structures manufactured by Electron Beam Melting

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Abstract*— *After completing a part in Electron Beam Melting (EBM), a depowdering operation is required to separate the sintered but unmelted powder from the manufactured part. Depowdering lattice structures can be difficult or even impossible due to their intrinsic shape. The aim of this paper is to propose a criterion to ensure that a lattice structure manufactured by EBM can be depowdered. The objective is to use this criterion during the design phase of lattice structure to design manufacturable and depowderable parts. Experiments are conducted on depowdering octet-truss lattice structures with variable bars thickness and mesh size. Different criteria are introduced, among them the criterion "hydraulic diameter" of a lattice structure, inspired by the Darcy-Weisbach hydraulic law used to calculate the pressure drop in a pipe. This criterion can be determined using geometrical characteristics of the lattice structures available in the CAD model of the part. Results show that the levels of depowdering for the lattice structures are proportional to this criterion.

Keywords*— *electron beam melting, lattice structures, depowdering, powder recovery system.

I. Introduction

Nowadays, with the emergence of additive manufacturing processes [1], complex shape [2] that respondent at precise functional criteria can be produced [3]. We therefore want to push the limits in terms of design and optimization of parts, seeking to obtain the best possible shapes [4]. One way to achieve this goal is to use lattice structures that make possible to manufacture products lighter in weight with acceptable mechanical properties [5].

Electron Beam Melting (EBM) is an additive manufacturing process used for producing metal parts and has the potential to manufacture lattice structure with fine features [6]. EBM is a "powder bed" additive manufacturing process: the part is built layer-by-layer by the melting of metal powder using a powerful electron beam [7][8]. For each layer, the metal powder is spread on a plate by a rake, is sintered by the electron beam to increase thermal and electrical conductivity and is locally melted to produce the required part. Then the plate goes down of the value of a layer (50 µm) and the cycle is repeated.

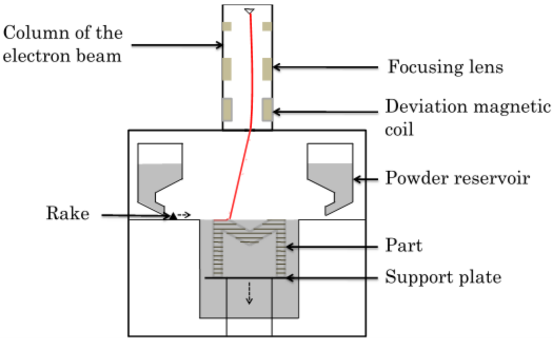


Figure 1. Architecture of an EBM machine

At the end of the EBM process, the part is included in a "cake" of sintered powder. This powder has to be removed to obtain the final part and is then recycled. To perform this depowdering operation, a Powder Recovery System (PRS) [9] is used: the "cake" of sintered powder containing the manufactured part is blasted with metal powder under 5 bar air pressure [10]. The removed powder is then sieved, so it can be reused. Depowdering lattice structures can be difficult or even impossible due to their intrinsic shape. The aim of this paper is to propose a criterion to ensure that a lattice structure manufactured by EBM can be depowdered. The objective is to use this criterion during the design phase of lattice structure to design manufacturable and depowderable parts.

II. Preliminary data - Methods

A. Presentation of the structures

The parts that are studied here are those with lattice structure. There are various geometries of lattice structures (diamond, octet-truss, dodecahedron...) with different properties [11][12]. Our study will deal particularly with octet-truss: this type of lattice is the best compromise in terms of mechanical properties [13].

The lattice structures are made by a unit cell that is repeated in the three directions (Figure 2). Three parameters define this cell: the mesh size p, the bars thickness e, and the density of the lattice structure in percentage. One parameter is given by the value of the two others, so only two of them must be chosen.

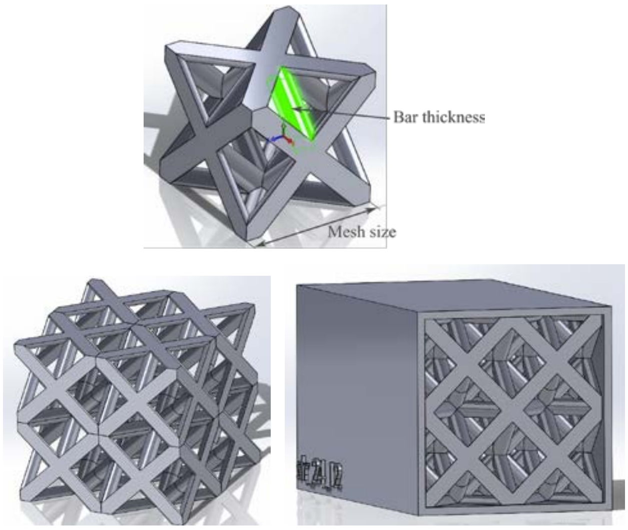


Figure 2. UNIT CELL (ABOVE) AND LATTICE STRUCTURE (BELOW)

The CAD is realized thanks to a macro [15] that creates a cell with fixed p and e, and then this cell is repeated in the three directions. The manufacturing is prepared with Magics software [16] that allows to place and to orientate the parts on the support plate, and to take into account correcting coefficients due to thermal constraints during manufacturing (the geometry is not affected by any electrical effects).

The hypotheses taken and the boundaries of this study are:

— The structure density must be the same than the cell density; so the number of repetitions of the cell in the three directions must be an integer,

— The standard parameters of the EBM machine are used for the manufacturing of the part,

— Depowdering is studied only in one direction: the removed powder has to go out of the structure through the depowdered face. In that goal, the parts will have a "skin" on five faces, and the last one will be open (Figure 2, bottom right). This makes the worst case, because in a real case with an open lattice, the powder will go out through all faces, and the depowdering would be easier,

— The PRS system is used to depowder the parts, with a pressure of 5 bars, which is the lowest value that is commonly used. The depowdering is done during 3 minutes: some studies show that it permits to remove more than 90% of the consolidated powder [10]

The structures studied can be divided in three groups: the first is composed of 8 unit structures (the unit cell is only repeated in the height), and 12 lattice structures (the unit cell is repeated in the three directions) with mesh sizes between 4 mm and 15 mm. Those 20 parts have a density of 25%: this value is the best compromise between a light structure and a good rigidity, and allows a large choice of mesh size and bars thickness. The width of the lattice structures are 24, 30 and 36 mm, and the heights of the 20 parts are from 48 mm to 63 mm, to satisfy the hypothesis of an integer number of repetitions.

The second group is composed of 8 square cylinders, with a width between 4 mm and 15 mm, and a height of 49 mm (for a comparison with available data on depowdering circular cylinders [10][14]).

In the third group, there are 22 lattice structures with a density between 3% and 66% and mesh sizes between 4 mm and 12 mm. The width and the height are 24 and 30 mm. Those parts will permit to have a larger range of results.

B. *Calculation of the depowdered height*

Each part is weighed before and after depowdering: so the initial mass m_i and the final mass m_f are known.

For the square cylinders, the depowdered height is calculated as follows, with S the hollow section and ρ_c the density of the consolidated powder:

$$\text{éq. (1)}\quad h_d = \frac{m_i - m_f}{S.\rho_c}$$

For the lattices, the structure is more complex. In particular, the 1 mm thick skin is extended around the open face, to create a step that permits not to begin the lattice on the start plate.

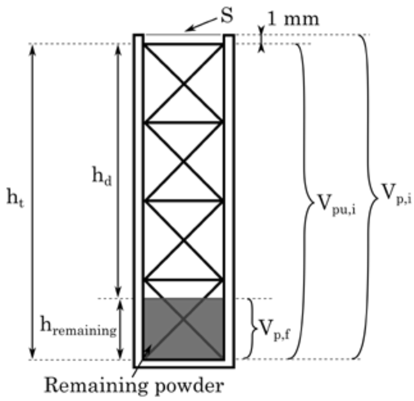


Figure 3. DATA FOR THE CALCULATION

For calculations, h_t is the lattice height, S the lattice section, $V_{p,i}$ the initial volume of consolidated powder in the whole structure (determined by CAD) and $V_{pu,i}$ the usefull initial volume of consolidated powder. It’s determined with:

$$\text{éq. (2)}\quad V_{p,i} = S \times 1 + V_{pu,i}$$

The final volume of powder, after depowdering, is $V_{p,f}$. Thereby:

$$\text{éq. (3)}\quad m_i - m_f = \left(V_{p,i} - V_{p,f}\right).\rho_c = \left(S \times 1 + V_{pu,i} - V_{p,f}\right).\rho_c$$

The depowdered height h_d is calculated as follows:

$$\text{éq. (4)}\quad \frac{h_d}{h_t} = \frac{h_t - h_{remaining}}{h_t} = \frac{V_{pu,i} - V_{p,f}}{V_{pu,i}}$$

Then:

$$\text{éq. (5)}\quad m_i - m_f = \left(S \times 1 + \frac{h_d}{h_t} V_{pu,i}\right).\rho_c = \left(S \times 1 + \frac{h_d}{h_t}.(V_{p,i} - S \times 1)\right).\rho_c$$

The depowdered height can be determined:

$$\text{éq. (6)}\quad h_d = \left(\frac{m_i - m_f}{\rho_c} - S \times 1\right).\frac{h_t}{V_{p,i} - S \times 1}$$

The calculated values are verified fore some parts, by dipping a thin iron wire and measuring the depth.

In order to predict the depowdered height in a structure, five different criteria are defined and then tested. Three of them are related to the free surface, and two of them to the hydraulic diameter. They are presented in the following of this paper.

III. FREE SURFACE

A. Criteria

The free surface S_l in a structure is defined at different heights, as the portion of the surface without material. It can be determined thanks to a CAD software, because the occupied surface S_{occ} (portion of the surface with material) is measurable: $S_l = (np)^2 - S_{occ}$, with p the mesh size and n the number of repetitions of the cell in the plan. For a 24 mm width octet-truss structure with p = 12 mm, the evolution of the free surface is represented in the following figure:

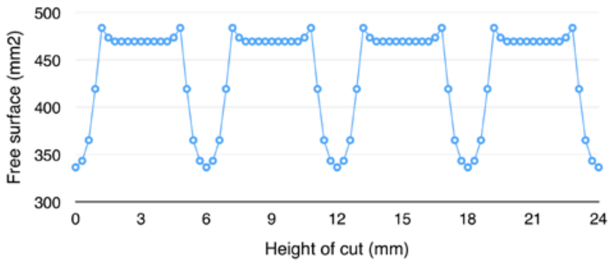


Figure 4. FREE SURFACE FONCTION OF THE HEIGHT OF CUT

The trend is the same for every octet-truss lattice, with a number of waves depending on the number of repetitions in the direction of depowdering.

From this point, it is possible to define three criteria that could be related to the depowdered height:

— The minimum free surface: min(S_l). In an octet-truss, it occurs in the open face, and can block the powder projection,

— The average free surface: moy(S_l). It can't describe the sudden variations, but it represents the free surface in global,

— The gap between maximum and minimum of free surface: max(S_l) - min(S_l). It highlights the maximum variation in all the profile.

B. Results

Those criteria are calculated for all parts of the group 1 and 2. The relation between the depowdered height and each criterion can be represented on a graphic. Only the graphic for the minimum of free surface is showed here, because for the other criteria it presents the same characteristics. The parts are divided in five colors, to better see the specificities of each type.

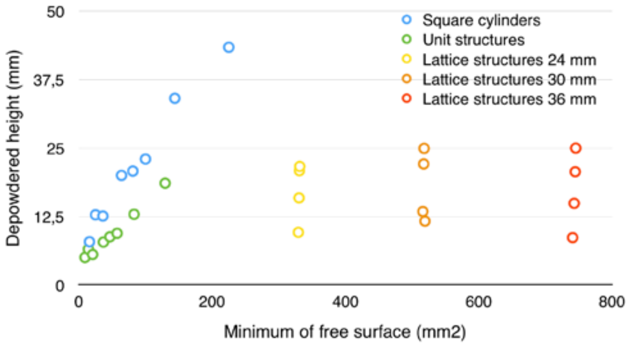


Figure 5. DEPOWDERED HEIGHT FUNCTION OF THE MINIMUM OF FREE SURFACE

For the square cylinders and the unit structures, the criterion could be interesting because it reveals a linear relation with the depowdered height. Nevertheless, the most important results are about the lattice structures. For a certain size of lattice (24 mm, 30 mm and 36 mm), the minimum of free surface is the same for different mesh sizes. For the two other criteria, the conclusion is the same: the value of the criteria is equal for different mesh sizes.

It shows that these three criteria are not valid to predict the depowdered height: for example, if the value of the minimum of free surface is known, it's impossible to determine the height of powder that will be removed. With the same minimum of free surface, the depowdered height that is predicted can range from simple to triple. Finally, the criteria based only on the free surface can't be used to determine the powder that could be depowdered on a random lattice structure.

In the following part, other criteria are proposed to fulfill the initial objective.

IV. HYDRAULIC DIAMETER

A. Criteria

The depowdering stage can be seen as a pressure drop: the pressure due to the blasting is maximum at the open face, and is at the atmospherical pressure where the depowdering is stopped, at the bottom of the lattice.

In a general case in hydraulic, the pressure drops Δp in canals are calculated with the Darcy-Weisbach law [17]:

$$\text{éq. (7)}\quad \Delta p = f_D \frac{L}{D_h}\frac{\rho v^2}{2}$$

With f_D the pressure drop coefficient, L the canal length, ρ the density, v the speed of the fluid, and D_h the hydraulic diameter, given by:

$$\text{éq. (8)}\quad D_h = \frac{4S_m}{P_m}$$

With S_m the wetted area and P_m the wetted perimeter.

This theory is applied to lattice structures: the goal is not to valid the Darcy-Weisbach law for those structures, but to make an analogy to find a possible rule about depowdering. The depowdered height that is researched corresponds to the length L that is renamed h_d. It can be determined with the previous formula (éq. (7)):

$$h_d = L = \Delta p \frac{1}{f_D} \frac{2}{\rho v^2} D_h \quad \text{éq. (9)}$$

The elements Δp, f_D, ρ and v are considered constants for the technology used and for the octet-truss lattice. Consequently, the depowdered height could be linearly linked to the hydraulic diameter: $h_d = K.D_h$. If D_h can be determined, the value of h_d can be specified.

As well as for the free surface, the hydraulic diameter is defined at every height of cut in the structure. The parameters needed are the wetted area S_m and the wetted perimeter P_m. S_m corresponds to the free surface S_l, so it is already known. For P_m, all the perimeters of the free surfaces are measured on CAD and are added.

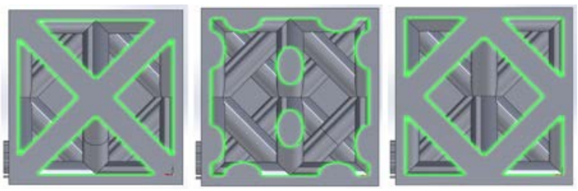
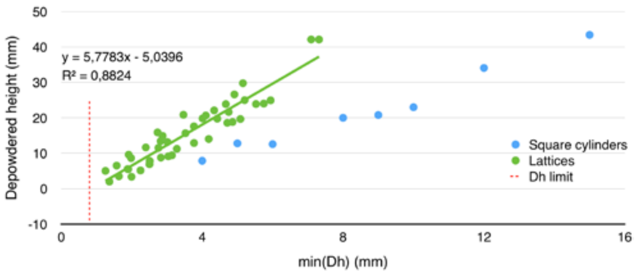


Figure 6. WETTED PERIMETER FOR DIFFERENT HEIGHTS OF CUT (IN GREEN)

The minimum hydraulic diameter (min(D_h)) is obtained just on the open face of the lattice ; it is the first criterion. Then, with the values of the hydraulic diameter at different heights of cut, it is possible to define another criterion, as it has been presented before for the free surface: the average hydraulic diameter (moy(D_h)).

B. Results

For those two criteria, the parts of group 1, 2 and 3 are used, to have results on a larger scale of data. The two following figures represent the depowdering height in a lattice function of the minimum hydraulic diameter and average hydraulic diameter. Square cylinders (group 2) are separated from the other parts, because they are not lattice structures: they are represented in blue and the lattices in green.



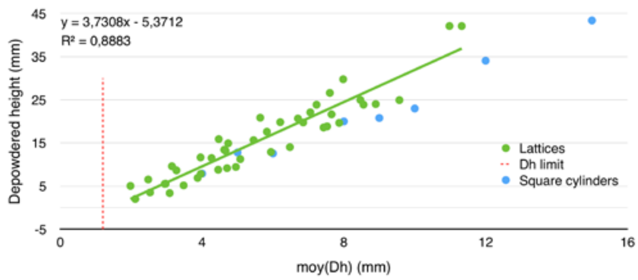


Figure 7. DEPOWDERED HEIGHT FUNCTION OF MINIMUM AND AVERAGE HYDRAULIC DIAMETER

For the criterion "minimum hydraulic diameter", the depowdered heights of the lattice parts seem to follow a linear law: the vertical uncertainty is about 12 mm for the high values of min(D_h). The trend curve is represented, and its equation is precised. The leading coefficient (around 5,78) gives us directly the coefficient K of the equation $h_d = K.D_h$. Moreover, for an undepowdered part (h_d = 0 mm), min(D_h) is not zero : it highlights its limit value (around 0,8 mm), for which the powder would be totally blocked.

According to this criterion, square cylinders have different results than lattices, and don't follow the same law. But the relation between minimum hydraulic diameter and depowdered height seems also linear.

For the criterion "average hydraulic diameter", the same conclusions can be given: the depowdered heights of lattice structures follow a linear law. The limit of moy(D_h) for an undepowdered part is here of 1,2 mm. For this criterion, square cylinders (in blue) almost follow the same law than lattices. This is interesting, because the use of a single criterion could give an estimate of the depowdered height, whether the structure is lattice or hollow.

Finally, the two criteria min(D_h) and moy(D_h) are very usefull and valid to approximate the depowdered height of a structure (lattice or hollow) with its CAD model.

V. CONCLUSION AND PROSPECTS

This study has given new tools for the design and the use of octet-truss lattice structures in additive manufacturing, more precisely with the EBM technology. The depowder phase can now be understood more easily, and can be predicted. To do so, the use of two criteria, the average hydraulic diameter and the minimum hydraulic diameter, is possible. They are linearly linked to the depowdered height, and permit to approximate its value only with the CAD model. However, the value of the average hydraulic diameter is very long and tedious to calculate. It could be automated with a slicer, to obtain the value of the hydraulic diameter for each slice and then to determine the average. Though, the linear relationships that have been presented have only been validated for octet-truss lattice structures manufactured with the EBM technology, and depowdered with the PRS system. It would be interesting to apply this work with other types of lattices (diamond for instance), to have a more global view of the manufacturing possibilities. Finally, it could be useful to find another way to determine the value of the coefficient K for lattice structures, without need of experiences.

VI. References

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