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A Support Structure Design Strategy for Laser Powder Bed Fused Parts

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Abstract

Metal Additive Manufacturing technologies are becoming more and more relevant for industrial component mass production. Among the various technologies developed and under development, one of the most important is the Laser Powder Bed Fusion (LPBF). The use of this technology for mass production rises several issues that typically are not considered in research and development, such as process reliability and material waste reduction. Process reliability depends on both the process itself and component design, which needs to consider the integration of component design and support design. Support design needs to be considered since the early component design because it strongly affects the whole business case behind the development of a component produced via LPBF. In fact, it potentially affects the production time, part post-process, and material waste (melted and powder). The understanding of the first and second point is quite straightforward: the more supports, the more production time and post-process need. The third point shall be interpreted considering that support structure design determines both the amount of melted material that will be discarded during the post process and the possibility to get back un-melted powder. Considering that in the production of a real part, even though it is designed for additive, typically supports represents a significant percentage of the whole building, their correct design is fundamental for the LPBF competitiveness as a manufacturing technology. The aim of this paper is to propose an approach to design support structures integrated in the part design that satisfy manufacturability constraints and allowing, at the same time, to reduce material waste enhancing powder recycling.

Keywords: Design for Additive Manufacturing, support, powder bed fusion, powder waste

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1. Introduction

Within the industrial environment, Additive Manufacturing (AM) technologies are gaining more and more importance in many fields. AM technologies are very effective in quick building of prototypes as well as in semi-mass production of components. With a specific reference to Metal AM techniques, the possibility to obtain substantially full dense metal determined the importance of such technologies.

Metal AM techniques are widespread in the industrial environment thanks to the possibility to produce, usually, full-scale and full-working parts with many advantages, such as a single equipment, short delivery time and mechanical properties as per traditional technique (Ngo et al, 2018). In the industrial environment, the most common Metal AM technologies are the Direct Metal Deposition (DMD), the Laser Powder Bed Fusion (LPBF) and the Binder Jetting. Within this work, the focus will be on the LPBF technology.

When dealing with the production of very parts, in which the complexity is functional, the use of additive manufacturing is very effective from a financial standpoint, allowing the building of components with a technology that is cheaper compared with a more traditional one. In this scenario, Metal AM technology needs to be considered as a standard manufacturing process, since these parts shall be produced massively. To allow this passage, several considerations need to be taken into account: the AM system shall provide constant and reliable performance and the part to be produced shall be designed specifically to be additively manufactured (Thompson, 2016).

Regarding the first point, many authors are focused on the LPBF process monitoring and control (e.g.: Everton, 2016, Giorgetti, 2019, Ceccanti, 2020). Concerning the second one, component design is not only the definition of the geometry to be produced, but it consists in many more steps. One of these is the support design. In fact, at this stage of LPBF usage within the industrial environment, support design cannot be considered anymore as a secondary aspect in the additive manufacturing process. Supports shall be designed and their design shall be integrated with the component.

In this work, we will propose a base shape-in addition to an algorithm for its sizing. The developed algorithm has the scope to define a structure (based on the already defined shape) that have all the properties that supports are supposed to achieve and, at the same time, to avoid material wastes (i.e. supports over-sizing). Once defined the support shape, a theoretical approach to be followed in the design phase will be proposed. The algorithm takes into account both structural and thermal aspects, allowing the definition of a structure designed basing on these load cases. The algorithm structure is quite straightforward since its easy applicability to practical cases has been considered as a driver in its development.

2. Overview of support design

Supports are auxiliary but inalienable structures that are required to build, through LPBF, oblique surfaces' part. Not all the oblique surfaces require supports. Supports need depends on many factors, such as surface area, exposure parameters, inclination angle, etc.

Support structures carry out several tasks during the building of a job, such as maintain in position the parts and remove the heat generated by the interaction between laser and powder. Supports are demanded to be built without any failure as well (such as material integrity, deformation, etc.). In addition, a smart support design should allow the residual stress redistribution during the part building, acting as a functional interface between the component under construction and the building platform.

Since support structures are removed from the part after the building, often they are included in the model to be printed at the very end of the job preparation process (that is just before the print) without any structured design approach. In addition, their design is based only on user experience. This circumstance is acceptable in all the cases in which the job does not need to be repeated (i.e. in the production of a single prototype, or in a single part production). Moreover, in such a case and with an experienced user, this approach is effective as well, since it allows to get the part in a very short time.

Perspective changes completely when dealing with a component designed to be mass-produced via LPBF. In these cases, support structure needs to be designed as well as the component itself, and the designs shall be integrated. This comes from the need to ensure a reliable design from a manufacturability standpoint, to avoid scraps and production yield reduction (which means cost of poor quality). A well-designed support structure implies a safer and more reliable part production via LPBF.

There are many strategies to support a component. It is possible to create closed-hatch structures with various cell shapes (square, web, custom, etc. as per Figure 1).

It is possible to support the part through cones or beams as well. Every solution has arguments for and against; closed-hatch structures are stiffer than the cones or lines, but they entrap much powder (even when walls are perforated due to the rough surfaces obtained through LPBF); on the other hand, cones and beams, being open, allow a better powder removal. Their building, unfortunately, is quite complicated due to their low stiffness, especially when the LPBF system is equipped with hard re-coater blades.

In fact, LPBF systems adopt, to spread layers, one of the two technical solutions available on the market: hard re-coater blade or soft re-coater blade (Wang, 2016, Fox et al, 2016). The hard solution allows to get better surface properties, but they make the LPBF system stiffer, which increase the machine sensitivity with respect to possible process failure or error in component/support design. Soft re-coater, on the contrary, is very permissive in terms of process or component/support geometry issues. However, the drawbacks of this solution are not a few:

- risk of contamination (due to the potential re-coater abrasion on possible part protrusions);
- local alteration of layer thickness because of localized damages;
- global modification of working plane during the building, due to re-coater wearing (this failure mode is particularly critical on multi-laser systems because of the relationship modification between the working plane and focal one, resulting in laser misalignment).

Hard re-coater failure modes are almost independent of the blade material: both ceramic and HSS (High-Speed Steel) blades are subjected to the same families of problems. Soft re-coater failure modes, on the contrary, depend more on the blade type: rubber lips are more subjected to widespread wearing while brushes are more prone to localized shape alteration. In addition, the interaction between the re-coater and the alloy melted is crucial when dealing with this topic (Fox et al, 2016).

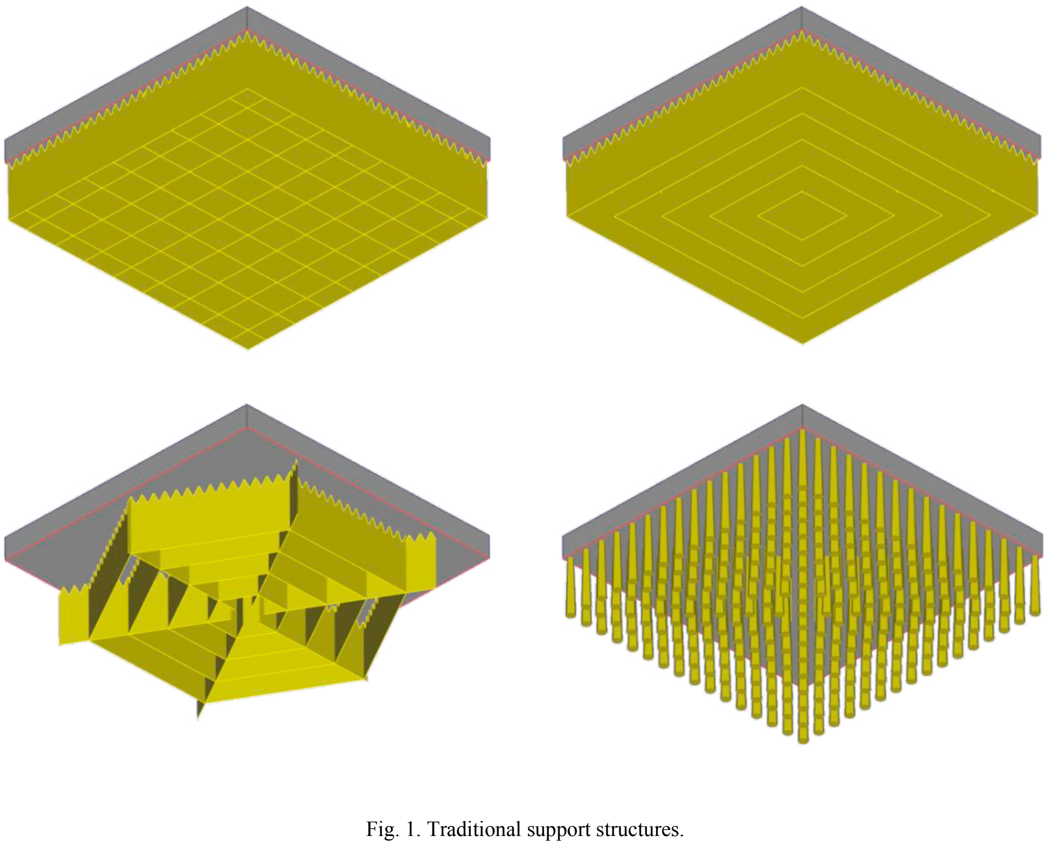

Fig. 1. Traditional support structures.

Depending on the alloy used to build the part and the exposure parameter set, it is possible to get elevated edges in accordance with Yasa et al., 2009, that could provoke the job interruption. Therefore, from a printability standpoint and considering that most of the times exposure parameters used within the industrial environment are not optimized for all the printing scenarios, not all the materials have the same properties and characteristics. Basing on this, the usage of hard or soft re-coater blades can be a crucial choice when dealing with alloys that are more critical from the printability perspective.

Support structures can be developed in several ways: on the market are available specific software and software suits. It is possible, also, to think about the possibility to design supports directly in the CAD environment itself, in order to get a unique model containing both the part and component designs. This solution is very effective even from a PLM perspective: the possibility to manage just a single file representing the raw part (to be machined) is much easier than having as many files as support structures needed for the part building (with the revision management complication as well).

The powder waste is the last critical topic connected with the supports for a component to be mass-produced via LPBF. There are three kinds of powder waste in a LPBF job: powder melted to build part portions earmarked to be removed (such as the supports themselves), powder sucked by the inert gas recirculation system and the un-melted powder non re-usable because of the impossibility to get it back from the printed parts (i.e. non-accessible vanes).

The first kind of waste depends on the support design it-self; through its optimization the amount of powder to be melted can be reduced (concerning an empirically defined support structure).

The second kind of waste depends mainly on the LPBF system architecture, in particular from the inert gas recirculating system design. A little contribution is given by the powder mesh distribution as well.

The third kind of waste, on the contrary, mainly depends on the support shape. As said before, it is possible to choose very different basic shapes, each of which can be optimized to get the desired goal (minimum amount of melted material, optimize overall supports mechanical properties, etc.). The use of closed cells shapes strongly influences the amount of un-melted powder wasted, since they create non-accessible vanes in which powder is entrapped and from which it cannot be retrieved after the cutting (since the contamination by the Wire Electro Discharge Machining). Therefore, even though these kinds of support require a small amount of melted material, they consume the whole powder contained in their envelope. Basing on this consideration, the adoption of open-shaped solid-body supports appear as an effective solution to this problem.

This kind of supports is well developable in CAD environment, in which typically the degrees of freedom number is higher with respect to support generation software (which allow the fast realization of only pre-defined geometries). In addition, the usage of CAD environment and a mathematical model for the support design definition allow getting complex support geometries, which in some cases become functional and necessary to achieve desired performances. CAD modeled supports, however, need to satisfy specific feasibility rules to be correctly built. In fact, solutions like slender cones or tall trees are hardly feasible in LPBF systems equipped with hard re-coater blades. As said above, hard re-coater blades tend to make the LPBF system less permissive in terms of local error tolerance. Therefore, considering the LPBF process dynamicity, it is highly probable that a slender structure fails during its building. One of the most common failure modes that happen in this circumstance consists in the re-coater jam with the slender part, which results in the part plastic bending. This deformation, very often, makes impossible to continue the job building because of the support top portion displacement, which in many cases is so high to make the next layer exposure unable to attach the already melted metal due to geometrical inconsistency derived from this failure mode.

From this analysis, slender support structure does not represent the best choice from a support design perspective. In addition, considering the second function that support structures need to provide, which is the thermal conduction from the part to the building platform (which is the system cold sink), typically slender designs do not allow a good thermal disposal. This aspect is as important as the mechanical performance of support structure since inadequate thermal disposal provokes part over-heating, which could result in printing failure due to the modification of all the building conditions and interaction between part, powder, and laser. It is important to underline how these considerations are based not only on bibliographical references but also on the experience in support design.

Basing on the analysis carried out up to now the usage of open-shape support still is the best choice in terms of powder waste reduction. Slender structures, however, in most of the cases, are not feasible when the LPBF system is equipped with hard re-coater blades. Therefore, the will to try to merge benefits coming from the usage of open-shaped structure with the robustness with respect to the building process typical of closed-shape support structures.

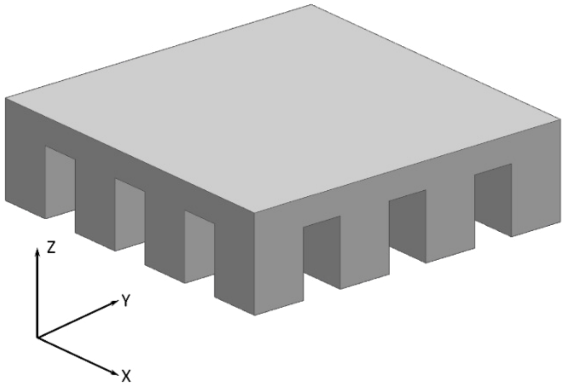

Fig. 2. Proposed support structure draft.

In Figure 2 is presented the basic concept behind this work.

Reference part is represented by the plate, while the columns are the integrated support generated within the CAD environment. Columns sizing is the scope of this work, therefore in Figure 2 is represented just the basic idea (that satisfies neither feasibility constraints nor any design criteria). Within this work, a square-shaped column cross-section will be considered.

It is important to note also that this kind of design is straightforward to realize and to integrate into a CAD model. No particular modeling skills are required to get an efficient support design. This consideration is one of the drivers that has been considered to develop this work. Axes are referred to the machine coordinate system, therefore Z axis is where the building platform slides, while X and Y are the building platform ones (in particular, X is the re-coating direction and Y is the gas flow one).

The mechanical stresses on the support during their building shall be estimated and considered to design a structure that satisfies all the listed points. In addition, their sizing also depends on the amount of heat that they need to conduct from the part under construction (after the support structure building completion) to the building platform.

In the following section will be illustrated the algorithm developed to define supports dimensions.

3. Theoretical model

The model proposed for the support sizing consists of an analytical method that considers both the supports thermal performance after their building and their mechanical performance while their construction. In particular, the thermal performance regards the effectiveness of the support in conducing heat from the part during the building once supports are already printed to the building platform. The algorithm is based on the assumption that the support structure designed uses the elementary shapes proposed in this work (i.e., the columns).

The analytic method consists, then, in a sequence of design phases (it is not a thermo-mechanic analysis). Phases order has been defined after preliminary studies. From them, it has been demonstrated that in the case of tall supports, the more demanding aspect in terms of support volume is the thermal one. On the contrary, in case of relatively short supports (approximately below 30mm), mechanical sizing is the more demanding one. Basing on the fact that the more widespread industrial application of the LPBF technology is represented by quite small machines (with a 250x250mm^2 building platform), typical additively manufactured components are usually not so big. Therefore, it is reasonable to consider that, in general, supports height will not be so big. In addition, since for obvious economic reasons the interest is in minimizing support height, in this paper, we have considered short supports to set up the algorithm.

Basing on the just stated considerations, the first step in the support sizing process is the structural analysis, finalized to define the cross-section dimensions. After that, thermal verification is carried out. In the proposed approach the thermal analysis has the only purpose of verifying whether the support structure is adequate to dispose of the thermal load generated by the interaction of the laser source and the powder bed.

In Figure 3 is explained the algorithm working sequence.

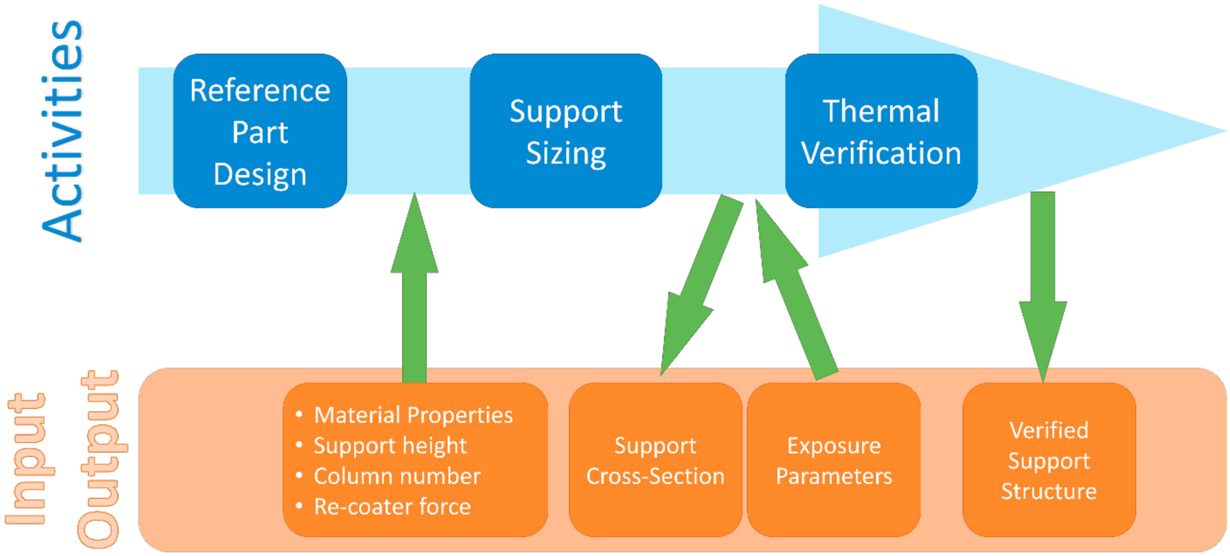

Fig. 3. Algorithm working sequence.

Briefly, the algorithm input is the Part Design; for the sake of this work, a reference design will be considered. The structural analysis is carried out basing on several inputs, such as material properties in as-built conditions, force developed by the re-coater in the impact with a column, support height and number of columns. As briefly anticipated, most of the time support height is a design constraint (since there is no interest in making them taller than necessary). Material properties shall be considered in as-built condition since, during the column building, the material is not heat treated. This could have important implication especially for high-temperature materials (such as superalloys, Monti et al, 2017) The number of columns is a parameter that the user can choose, specifying how to distribute supports below the analyzed part. Since the algorithm defines the volume of powder to be melted to realize the support structure, increasing the number of the columns, the volume (and the cross-section size) of each one decreases. Therefore, increasing the number of columns, safety factor will decrease. About the load developed by the re-coater jam with the support's column, further details will be explained in the following. Basing on the previous assumptions, the bending load on each column developed by the re-coater blade-support interaction is assessed (considering the maximum support height). Through the comparison of this value and the cross-section plastic serviceability limit state it is possible to determine the correct edge length. This length is identified to withstand the building process and, at the same time, do not waste too much material. In fact, it is clear that the support structure shall be sized considering a trade-off between the minimization of the amount of powder melted and the maximization of probability of job building success.

As a reference case, the first column to be hit by the re-coater is considered. This choice is the most conservative because it does not take into account a load re-distribution due to multiple columns hit by the re-coater blade.

After the structural dimensioning of the supports, the thermal verification is carried out knowing the exposure parameters (laser power, scanning speed, and hatch distance). In this way, it is possible to calculate the heat flux generated by the exposure of every single layer (of the part, not the supports), hence, the thermal load. As output, this phase gives the equivalent thermal difference between the building platform and the exposed layer.

This model structure comes from the will to produce a simple, fast and effective tool to design supports. The tool allows to retrieve as much un-melted powder as possible, and obtain feasible supports and at the same time, supports safe from the building standpoint. In fact, the proposed model has been defined with the specific scope to design supports for parts that need to be produced in many units, where, then, the design robustness is such as to avoid job interruptions.

The structural analysis requires several input data to verify the supports structural integrity in case of a hit. Hit between the re-coater and support is the unique load case considered for the support verification.

In this analysis, many conservative assumptions are made, in particular:

- the force developed by the hit is considered absorbed by a single support column;
- the support column length considered is the full height (i.e., the condition in which the maximum bending load is applied by the recoater);
- the whole force is considered applied on a single side of the column (hence we do not consider the biaxial bending but a pure bending load on a single axis) even though, for feasibility reason, usually parts and supports are rotated of 5°-10° with respect to the re-coating direction.

In Figure 4 are schematized all the introduced assumptions.

Basing on them, the structural analysis is carried out. For it, a plastic approach is preferred to an elastic one. Elastic analysis has not been taken into account. In fact the function that the support shall carry out is to maintain their shape during the building, allowing layer-by-layer construction.

From here, considering an elastic-perfectly plastic constitutive model, the complete plasticization of the cross-section implies a top column portion negligible displacement (virtual work developed by the force to fully plasticize the cross-section is zero). Basing on these considerations, the cross-section plastic modulus is calculated (considering the support sizing as per above). Defined the plastic modulus and considering the following equation:

$$M_l = Z\sigma_0 \tag{1}$$

Where M_l is the bending load that determines the cross-section fully plasticize, Z is the plastic modulus and σ_0 is the yield strength (assessed at the building platform temperature), it is easy to determine what is the maximum bending load that the cross-section is able to sustain (considering a plastic stress re-distribution).

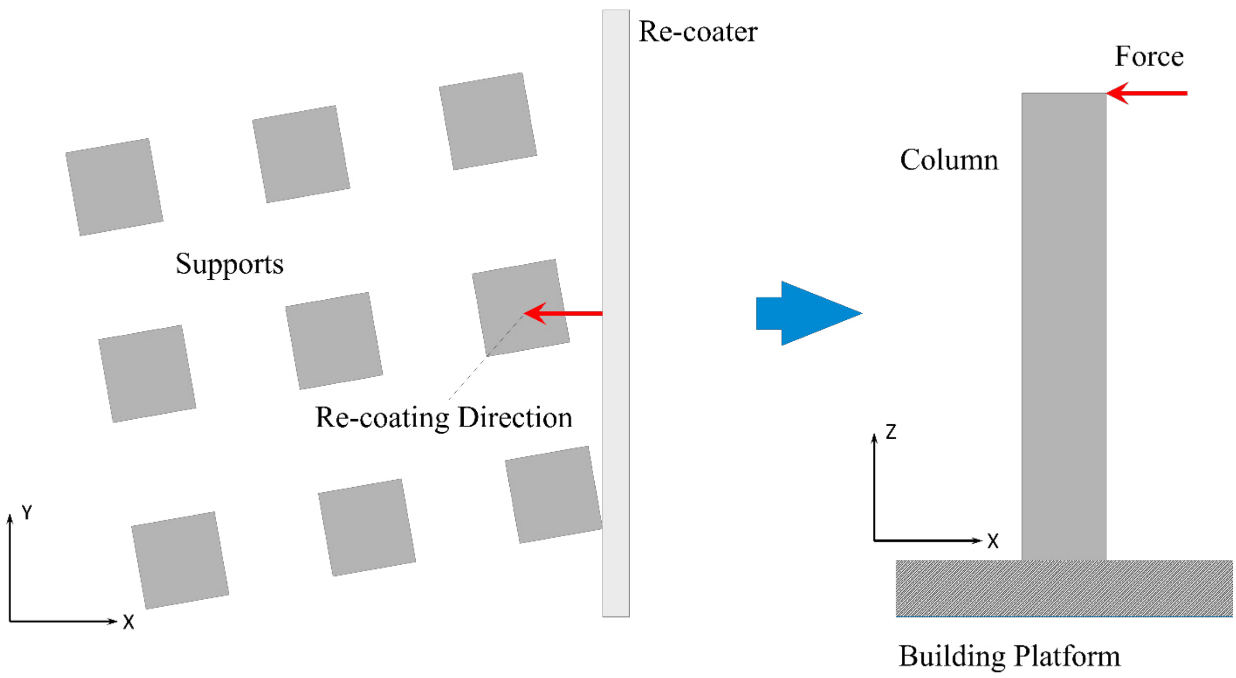

Fig. 4: Support structure schematization for the structural dimensioning

Assessing the actual bending load developed by the system on a single support column through:

$$M_0 = F\Delta x \quad (2)$$

it is possible to determine whether the supports can withstand the re-coater hit or not. It is important to note that, in (2), M_0 is the actual bending load developed by the force F caused by the re-coater hit and Δx is the support height.

Consideration shall be carried out about the value F. Theoretically, re-coater blade should not hit the component during the building. In the building of a real part, on the contrary, sometimes the hit happens. As said above, re-coater blade hit depends on several parameters, the main of which are the part and support design, the exposure parameters and, the most important, the alloy used to build the part. Some materials are less sensitive to process parameters variation, therefore from a printability perspective, not all the alloys have the same properties (Mukherjee et al. 2016, Yasa et al., 2009, Fox et al, 2016, Zhang et al. 2018). As said, material printability shall always be referred to the exposure parameters used. Therefore, printability depends on the parameter set used to melt the material. Usually, however, exposure parameters are not optimized for all the scenarios that the building of a real part will face. Basing on this consideration, unfavorable conditions could happen during the building of a real part. Then, material printability becomes an important parameter to be considered. A printable material appears as more robust to withstand this scenario, since it has, by definition, more uniform behaviour during the whole building. Less printable alloys, on the contrary, could experience melting process instabilities such as to get elevated edges or protrusions (in addition, obviously, to internal defects, which are, however, non-critical in this context). These geometries, in some cases, are such big to make the building platform lowering non-sufficient, hence they provoke a job interruption interfering with the re-coater blade during the layer spreading. In these cases, the force F developed by the re-coater blade shall be considered in its entirety. In intermediate cases, only a re-coater rattling will be experienced by the job under construction. These load cases are less conservative and only the re-coater jam is considered for the mechanical verification of the supports.

The plastic serviceability state has been preferred to the elastic one due to the will to reduce the amount of powder melted to produce supports. Physically speaking, moreover, this assumption does not invalidate the model, since the failure mode to avoid is represented by the column bending (hence the column top displacement that results in a building stop).

Clearly, the sizing procedure defines the column cross-section dimensions. For the next step (that is the thermal verification), this quantity will be expressed as a fraction of the total area to be supported, called α in the following. In particular,

$$A_m = \alpha A \quad (3)$$

$$A_p = (1 - \alpha)A \quad (4)$$

Where A is the total area to be supported, A_m is the area of melted material in a supported area cross-section and A_p is the same value referred to un-melted powder. With respect to Figure 5, A is the sum of the gray and orange areas, A_m is the sum of all the orange squares and A_p is the gray area.

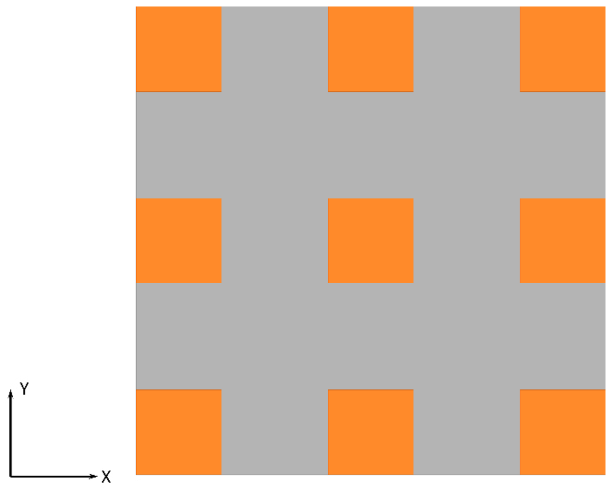

Fig. 5. Representation of the supported area cross-section and highlight of the relationship between melted (in orange) and un-melted (in gray) portions.

Once defined the α value through the structural dimensioning, a thermal verification is carried out to verify whether the developed structure is adequate in disposing the heat produced by the part layer melting. Thermal verification is based on the system schematization in a model in which the unique heat transfer mechanism is represented by the conduction between the layer melted and the building platform. Heat is conducted via melted metal (columns) and unmelted powder. These two elements that have different thermal conductivity values constitute a parallel system. In Figure 6 is represented the system schematization for thermal verification.

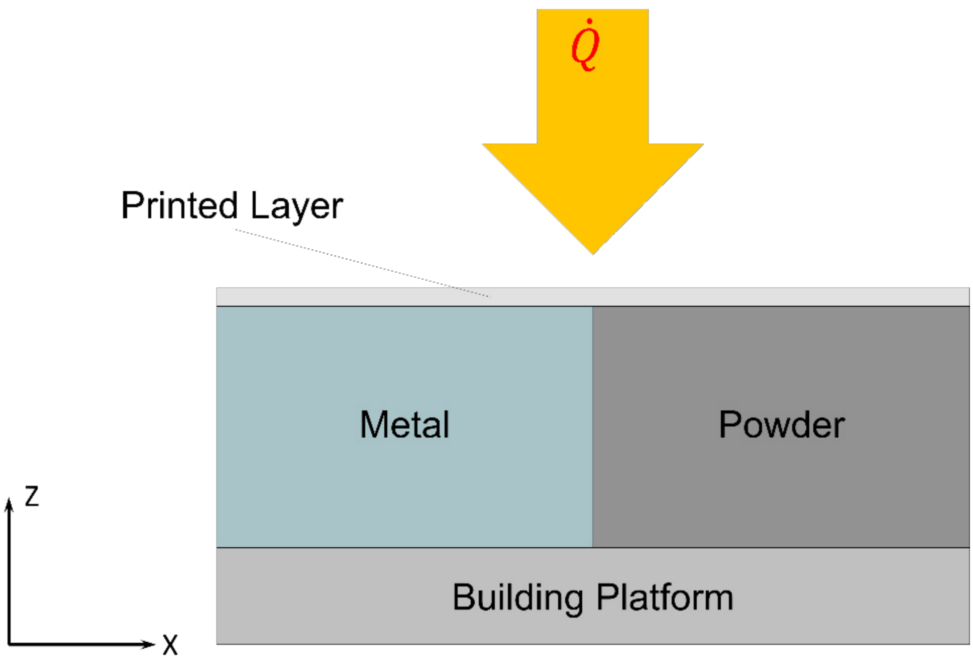

Fig. 6: Support structure schematization for the thermal verification

Given that, Fourier's law has been considered:

$$\dot{Q} = -\lambda A \frac{dT}{dx} \tag{5}$$

As said above, once defined the reference sample and the exposure parameter set, it is possible to calculate the heat flux generated by the exposure of each single part layer (that is the $\dot{Q}$ term). Sample area (A) is known by the reference sample geometry. Thermal conductivity depends, for this system, on three parameters, which are:

- the thermal conductivity of melted material;
- the thermal conductivity of metal powder (Wei et al. 2018, Alkahari et al. 2012);
- the areal ratio of melted and un-melted material.

In addition, being the melted and the un-melted material a parallel configuration, an equivalent thermal conductivity can be calculated basing introducing the concept of thermal insulance, defined as:

$$R = \frac{\Delta x}{A\lambda} \tag{6}$$

and considering that:

$$\frac{1}{R_{eq}} = \frac{1}{R_m} + \frac{1}{R_p} \tag{7}$$

Where R_m is the thermal melted metal resistance, while R_p is the same data referred to the powder.

At this point, considering that each thermal insulance term depends on the material area considered, the relationship between the melted and un-melted material (with respect to the total area to be supported) shall be introduced (Equation (3) and Equation (4)).

The Fourier's law has been developed basing on all the considerations explained in order to determine the equivalent temperature increase (ΔT) developed between a part layer close to supports and the building platform.

$$\Delta T = -\frac{\dot{Q}}{A} \Delta x \left[\frac{1}{\lambda_m \alpha + \lambda_p (1-\alpha)} \right] \tag{8}$$

With the equation (8) it is possible to define whether the support dimensioned by structural point of view is capable of dispose the heat generated by the interaction between laser source and part layer powder. This verification is carried out, as said, under conservative assumptions. Therefore, the verification output shall be a reasonably small temperature increase (around 100-200K) in order to be sure that the designed support structure is able to dispose the heat without overheating the part.

In the case of high-temperature increase assessed in this verification step, support structure design shall be iterated, increasing column cross-section size.

In this case, a possible approach that can be effectively followed consists in the definition of the value α that ensure a pre-determined ΔT. The analytic formulation that can be used in this case is:

$$\alpha(\Delta T) = \frac{1}{(\lambda_p - \lambda_m)} \left[\frac{\dot{Q}}{A} \frac{\Delta x}{\Delta T} + \lambda_p \right] \tag{9}$$

With (9), imposing a ΔT value, α will be calculated. With this approach, the thermal verification is automatically satisfied. The structural analysis will be automatically satisfied too.

The proposed model does not consider the temperature effect on melted metal mechanical properties since the relatively small temperature increment considered within the model. In case in which temperatures have to be considered in the structural dimensioning, a different approach shall be preferred to obtain reasonable results.

4. Feasibility Constraints

When supports have been designed according to the model proposed, final consideration of their feasibility shall be made. According to the model, only the support cross-section size and height are dimensioned. As said above, a model as per Figure 2 is not feasible via LPBF, since the lower horizontal surfaces are not self-buildable.

LPBF technology sees the feasibility domain restricted by the critical angle. The critical angle is an angle (dependant on many parameters such as material, exposure strategy, part orientation, re-coater blade type, etc.) above which supports are required to ensure part feasibility. The effect of un-support a surface below the critical angle is the part warping due to the solidification stresses resulting in it (which are mainly tensile stresses, Marcelis et al., 2006, Fergani et al. 2017) and the difficulties in heat transfer to the building platform. It is possible, however, overcome this design issue with a simple approach. Shaping the column top part in such a way that two adjacent columns are attached, in fact, solves the issue. This solution is an alternative to tilt columns surfaces (i.e. reversed square-based pyramids); this solution, however, requires more powder to be melted.

A possible implementation consists in the drawing of circle arc at the top of each column. Arcs shall be designed in such a way to have the down-facing surface tilted more than the critical angle. A conservative value that can be considered almost always valid is 50°. In Figure 7 is represented the solution implemented for the proposed supports design.

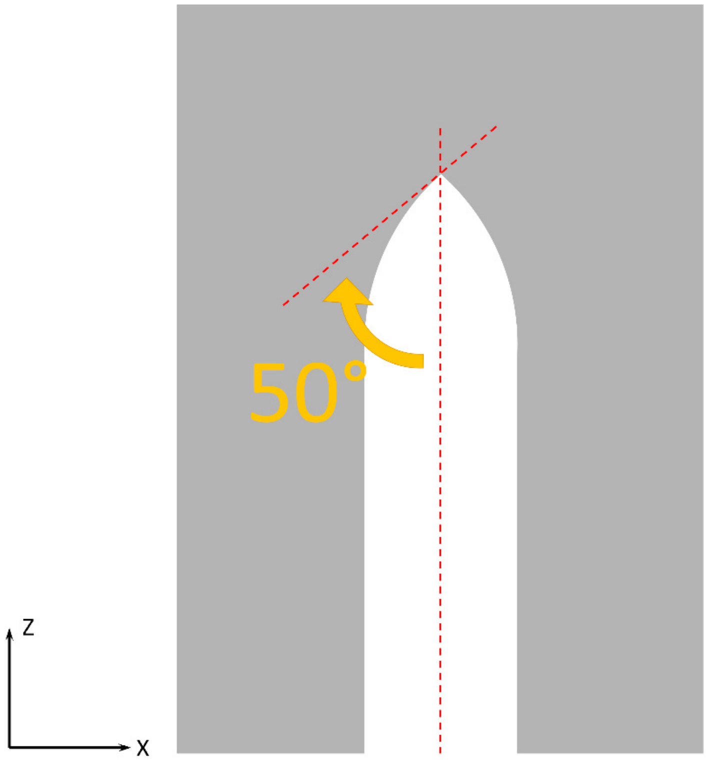

Fig. 7. Feasibility constraint implemented for the sample building.

It is important to note that this solution shall be considered applied to all the sample sides. Therefore, all the columns built to support the part will gradually enlarge their cross-section until they merge into a unique part, which is the sample beginning (in a real case, the part beginning).

5. Considerations

A consideration about the part post-process shall be carried out. The proposed support geometry has several advantages, such as their simple modeling within a CAD environment and their integration with the part. In addition, through the presented model, their sizing is relatively simple as well. The most important drawback of the presented design is represented by their removal from the part. A mechanical removal step shall be included in the part post-process cycle. This is valid for all the support presented in this paper. However, even though many aspects of traditional supports have been improved, the support post-process is not one of them.

The proposed supports can be removed in many ways: they are easily cut through traditional machining or with other techniques. One of them is represented by the Wire Electro Discharge Machining (W-EDM); with this technique, if the component geometry allows it, it is possible to program the wire trajectory (or trajectories, in case of two or more different positionings in the W-EDM machine are required to eliminate all the supports) to remove the supports in an efficient and effective way.

After the W-EDM cut, the resulting surface can be considered finished in the case in which it is non-functional (it has the re-casted layer that characterizes this kind of technology). Otherwise, the post-process phase can continue to achieve the part specifications.

6. Conclusions

In this work is presented an approach for the support design of parts manufactured via LPBF technology. Support design is an important topic, within the industrial application of LPBF technology, since it strongly affects the whole business case behind the development of a component. In fact, it potentially affects the production time, part post-process, and material waste (melted and powder). Considering that in the production of a real part, even though it is designed for additive, typically supports represents a significant percentage of the whole building, their correct design is fundamental for the LPBF competitiveness as a manufacturing technology.

The proposed model considers both structural and thermal aspects, which are the two main factors to be considered in the support design and sizing.

Supports shape has been chosen by the authors basing on many considerations, ranging from the possibility to quickly design them in a CAD environment to the powder waste minimization, therefore the minimization of support costs on the part cost. This paper represents the beginning of a research activity dedicated to the development of robust algorithms for the design of supports dedicated to part to be massively produced via LPBF.

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