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## Laser Powder Bed Fusion: A Review on the Design Constraints

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# Laser Powder Bed Fusion: A Review on the Design Constraints

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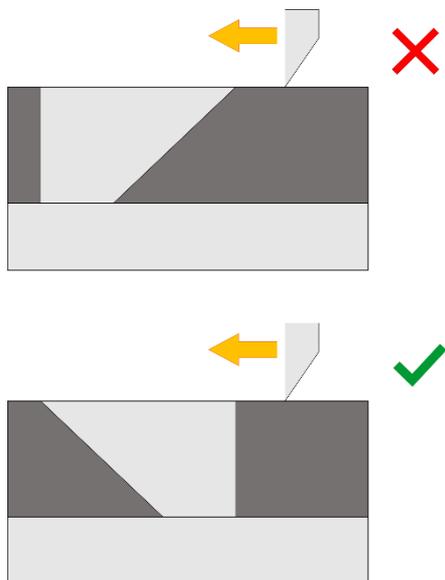
**Abstract.** With the creation of additive manufacturing production lines and the adoption of additive technologies, such as Laser Powder Bed Fusion, as standard manufacturing technologies for the mass production of parts, many considerations arise. In particular, product quality assurance is surely a very important aspect to be considered when talking about mass production. Laser powder bed fused parts are characterized by specific characteristics, such as quite rough surfaces and internal cavities filled with powder after the part construction. The need to ensure part quality and the importance to guarantee quality to all the parts made within the production line highlights the need to design the part addressing all the criticalities resulting from the manufacturing process, in addition to the ones related to the operative conditions. In this work, the attention is placed on two important topics: part surface inspectability and part cleaning. In particular, part inspectability is a crucial aspect in determining part coherence with design specifications. Part production via LPBF puts interpretability issues in inspecting the parts. Part cleaning is a crucial topic as well. Part cleaning is related to the design of the part to guarantee a correct powder evacuation from all the internal channels and cavities. Within the work, problems will be defined and design guidelines will be proposed to manage these topics.

## 1. Introduction

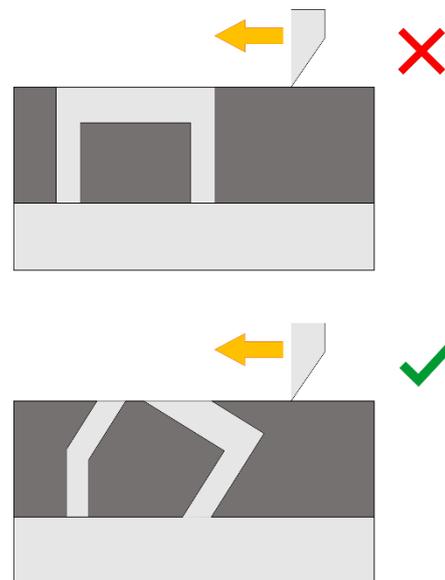
The integration of Additive Manufacturing (AM) technologies in standard production lines represents, from several perspectives, a revolution in many production environments. In particular, dealing with metal components, Laser Powder Bed Fusion (LPBF) surely represents one of the most important AM application for part production. As soon as AM applications started to be considered as standard manufacturing technologies, many considerations arose. Parts can be redesigned taking advantages resulting from the new manufacturing technologies, production strategies can be modified (i.e. can be re-insourced), new qualification processes need to be defined. Among all of them, parts redesign is a crucial aspect to be managed and controlled to gain in product competitiveness, performances, and costs. In particular, when considering metallic part produced via LPBF, part design plays a crucial role in part feasibility and its quality assurance. Powder bed technologies do not remove all the feasibility constraints. They just completely modify manufacturing constraints to be considered when designing the part with respect to standard manufacturing processes. As regards this topic, many authors studied lots of aspects connected with the new possibilities offered by these novel additive technologies, eventually creating the subject also known as Design For Additive Manufacturing (DFAM). DFAM is a method that, as other “Design for” approaches, rules general design guidelines for a specific scope [1-5]. In the case of DFAM the rules are to make feasible parts realized in an additively manner, as



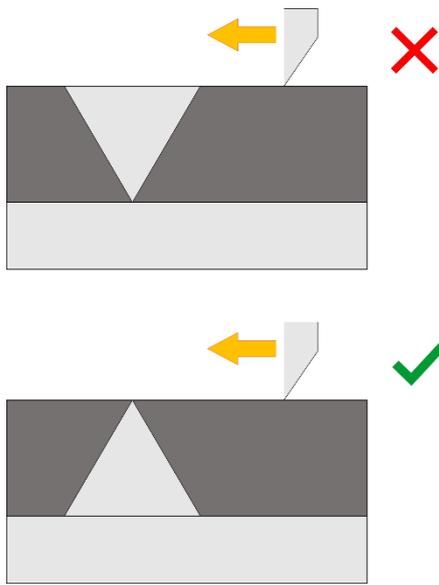
well as to maximize benefits resulting from the application of additive technologies [6]. DFAM is a very wide subject, which can be narrowed considering only a specific technology [7, 8]. Within this work, only LPBF technology will be considered. As regards this application, DFAM provides many indications about how to design the parts, as well as how to deal with the job organization [9, 10]. From a general perspective, DFAM defines what are the actual design constraints, resulting from the use of additive technology. Therefore, many authors studied what are the technological differences between standard manufacturing processes and LPBF, and basing on study results guidelines have been defined. Among all the studies, from an industrial perspective, some results are more interesting than others, since they can be directly implemented by the final user of the technology. One of the most important surely is the overhanging structure characterization [11-14]. The feasibility study of overhanging structures is very important since it allows the designer to define whether and where support structures are required. Other important information retrievable by the DFAM is related to the part positioning within the job [15-17]. Parts positioning within the job has lots of importance since it potentially affects many parameters. The first is the number of parts per job, which is directly connected with the production efficiency. Other important aspects to be considered are linked with the part manufacturability [18, 19]. In fact, there are many aspects to considering while deciding how to position the part in the job. Some of the most important aspects to be considered already identified in the DFAM are the following: it is important to avoid overhanging structures growing against the re-coater direction (Figure 1), every downfacing surface shall have an inclination bigger than the critical angle (Figure 2), it is important to allow the heat transfer to the building platform in order to avoid part overheating (Figure 3), in thin features the aspect ratio shall be below the recommended limits (Figure 4).



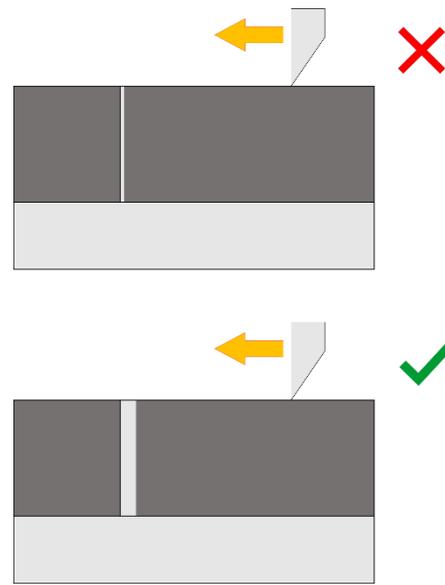
**Figure 1.** incorrect and correct orientation of an unsupported overhanging structure with respect to the re-coater direction.



**Figure 2.** incorrect and correct orientation of an unsupported overhanging structure with respect to the critical angle.



**Figure 3.** incorrect and correct part orientation to allow a good heat transfer avoiding part overheating.



**Figure 4.** incorrect and correct aspect ratio for thin structures.

From an industrial perspective, DFAM shall consider the economic aspect as well [20, 21]. In particular, to be commercially competitive with parts produced with standard manufacturing technologies, additively manufactured parts shall perform as baseline component costing less and requiring smaller lead time. Focusing on LPBF technology, the capability in producing complex geometries can be used to achieve these objectives. Parts features historically produced with subtractive technologies, such as milling, turning, drilling, or electro-discharge machining can be obtained directly on the printed part. In some cases, to achieve design specification, surface finishing processes are required to increase surface finish level, but no overstock material shall be removed. These considerations allow a lead time reduction, since the printed part is very close to the final to be installed in the final system, and potentially even the overall production cost. At the same time, however, it is always important to consider the cost as well, since, depending on the application, traditional technologies can still be less expensive. With these considerations in mind, the designer has all the tools to decide whether and where to print a complex design rather than realize a specific feature in a post-processing phase. The last point to be considered relevant to the economic competitiveness of an additively manufactured part is the possibility to reduce, as much as possible, the waste of powder [22]. Since in the industry LPBF technology applications are mainly focused on producing parts with expensive alloys (nickel or cobalt-based superalloys, titanium alloys, lightweight alloys, such as TiAl, etc.), the final part cost is strongly affected by the cost of the material itself. Basing on this consideration, it is clear that the designer, considering all the constraints defined within the DFAM discipline, should minimize the amount of support structures and design them allowing the retrieving of un-melted powder for future reuses (i.e. avoiding close support structures).

Considering this brief introduction to some of the most relevant aspects of the DFAM discipline for industrial application of LPBF technology, it is necessary to consider also other aspects, which depend directly on the industrial applicability of the mentioned technology. From an industrial perspective, in addition to the competitiveness in terms of cost per part and part lead time reduction, it is crucial to be able in monitoring the product quality and production reliability. To do so, several authors approach this topic in many ways. There are a lot of studies regarding the on-line process monitoring, as well as periodic LPBF system performance assessment through the production of specific artefacts [23]. These studies, however, are focused on determining the overall goodness of LPBF process. From an industrial perspective, the process control is just a portion of the overall part quality. Clearly, if the

part is produced with a non-qualified process or with a process that is not under control, part quality cannot be ensured. Vice versa, if process quality is ensured, part quality is not automatically guaranteed. Therefore, additional controls need to be carried out to ensure part quality. This work aims to put the focus on the integration that the design phase should have with the following part production and industrialization. A part that wants to be massively produced shall be designed considering all the aspects listed above, and this work wants to put the focus on additional consideration that a designer should carry out while designing the part. In particular, this work wants to put the focus on two crucial aspects to be considered when designing a part to be produced via LPBF: the possibility to clean and inspect the part. Within this work, examples of these two important aspects will be illustrated. In addition, starting from the examples, general design guidelines will be defined to ensure requirements satisfaction.

## 2. Part Cleaning

LPBF is an AM technology in which thin metal powder layers are spread one on top of each other while a highly focused laser melts powder particles, transforming them in bulk metal. Considering the part production sequence adopted by LPBF technology, it is clear that all the cavities realized in the component are, after the part building, filled with un-melted powder. Un-melted powder entrapped in a finished part represents a concerning issue since it can cause many problems. The first issue that entrapped powder can generate is the part functioning modification. In case powder is entrapped in functional cavities, filled spaces alter part functioning. On top of that, the powder can be either released during part functioning, creating additional problems from the system perspective, or can solidify during part heat treatment. This circumstance, in most of cases, makes the built part a scrap (Figure 5).



**Figure 5:** Solidified powder after heat treatment

Another significant issue represented by un-melted powder relates to the safety of who handles the part. Most metal powders are carcinogen and some of them are explosive as well. Avoid contact between people and metal powder is mandatory to avoid possible severe injuries and pathologies. Part cleaning is an aspect that the designer shall take care of especially when the part is characterized by detailed features, such as small and long holes, complicated channels, etc. Currently, part cleaning topic is commercially faced with automatic cleaning stations, which provide the part on the building platform movement and high-frequency vibration, allowing all the un-melted powder to evacuate the part from the exits. Powder exits shall be included in the part and support design since the early design phase, and in case powder exits are on the part, their effect on mechanical behavior shall be assessed in the design verification phase. In fact, the adoption of a commercial depowdering system is not sufficient to guarantee a correct part cleaning in an additive-based production line. Depowdering process needs to be designed and possible depowdering features need to be integrated with part and additional structures (such as supports) geometry. As a case study, the cleaning of a non-through channel is considered. A non-through channel is a feature critical from a depowdering perspective. The activity is the definition of the minimum channel dimension to allow correct cleaning. In Figure 6 is represented the initial configuration.

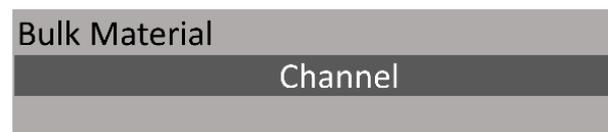


**Figure 6:** Case study initial configuration

To ensure channel depowdering, a section resizing is needed to increase feature cleanability. In addition, to give the cleaning process repeatability, additional depowdering features can be added to the initial design to further enhance feature depowdering. An example of an additional feature is represented by the channel design modification, making it through instead of non-through (Figure 7 and Figure 8).



**Figure 7:** Example of through channel



**Figure 8:** Example of through channel

Such design modification shall be considered from the early design phase, evaluating its impact on all the others part requirements and behaviors (such as the impact on part functioning, effects on part life, etc.).

### 3. Part Inspection

Non-Destructive Testing (NDT) is a category of tests that provide information about part compliance with design specifications without destroying the part. Many and different testing technologies can be considered as NDT. For instance: geometric inspection gives information about part geometry, liquid penetrant inspection gives information about the presence of surface defects, Computed Tomography scan or radiographic inspection gives information about the possible presence of defects in the material, etc. Focusing on additively manufactured parts, NDT is widely used to monitor both product quality and process stability through time. As a matter of fact, the transition from standard manufacturing technologies and metal AM technologies, such as LPBF, has just been started. Therefore, the need to constantly monitor as many parameters as possible during the production is crucial to ensure, to the final customer, product quality, and reliable performances. Basing on these considerations, as well as other topics covered within this work, NDT became important and needs to be taken into account since the early part design phase. In fact, since the use of AM expresses its best characteristics when producing complex parts, part inspectability could be affected by the design complexity. This consideration gains importance if visual NDT techniques are used to inspect the part. In the following, liquid penetrant inspection will be considered as a case study. There are many types of liquid penetrant inspection (visible, fluorescent, magnetic, etc.). Regardless of the specific application, liquid penetrant inspection requires the application, on the surface to be inspected, of a penetrant liquid. After several minutes from the penetrant application, the surface shall be washed, and a developer shall be applied on the same surface. After several minutes, indications are visible directly on the developer (in case of florescent liquid penetrant test, a long wave ultraviolet light shall be used to reveal indications). Basing on this, it is clear how important the surface accessibility is for its inspection through this kind of analysis method. In particular, in the case of functional internal cavities, the part shall be designed to allow internal surfaces inspection. To carry out NDT, parts shall present accesses to allow the actual part inspection, or at least accesses allowing to inspect the part in its most interesting portions. These considerations are fundamental while designing the part since the integration of accesses in part design shall be considered from the early part design.

#### 4. Surface Finish

Additively manufactured parts, especially ones obtained through powder bed technologies such as LPBF or EBM (Electron Beam Melting), are characterized by a poor surface finish. Determining surface finish in additive manufacturing is currently an object of intensive debates, even though standard entities are publishing technical documents. Laser powder bed fused parts, in fact, are characterized by a surface topology resulting from many factors, such as powder particle size and distribution, layer thickness, laser power, scanning speed, hatch distance, beam spot size, etc. On top of that, the layer-by-layer building strategy plays an additional role in determining the final part surface topology. In particular, how the layer-by-layer building strategy affects surface finish depends on the surface inclination. Defining the inclination as the angle between the surface and the axis orthogonal to the building platform, as soon as the inclination increases, the staircase effect becomes more evident. Said that the as-built part surface finish is quite high, and in most cases at least on some faces surface finish value must be reduced to achieve design specifications. There are many ways to reduce surface finish, ranging from mechanical methods (such as sandblasting, barreling, etc.) to chemical-based technologies (electro-chemical polishing) and hybrid ones. Most of these are aimed to remove protrusions from the processed part. In additively manufactured parts, with respect to the nominal profile, protrusions are accompanied by small pits and, in general, recesses. In addition, powder bed fused parts surface topology, with respect to other manufacturing technologies, is characterized by quite big, smooth, and round defects. Considering these two key aspects, it is easy to understand that surface finish techniques are not able to fully remove all the defects produced by the LPBF process. In particular, recesses are quite hard to be compensated by the surface finish process. After the surface finishing, laser powder bed fusion induced scratch marks, however, thanks to the recess geometry, are not deep and preserve round shapes. Considering a surface inspection carried out with a liquid penetrant test, the described circumstance puts some limits on the part inspection. In fact, certain kinds of non-destructive testing, such as liquid penetrant inspection, give as test results indication of possible defects. Ideally, every indication corresponds to an actual defect. In laser powder bed fused parts, on the contrary, indications can be either actual defects or just indication caused by external factors, which are not actual defects. Therefore, after the test, results must be interpreted by an expert to determine if the indication is a defect or not. In addition, it has been demonstrated that different testing conditions (i.e. the use of red liquid penetrant test or fluorescent testing), gives different indications on the same surface. In particular, it is well known that fluorescent testing is more sensitive to defects than the use of the red penetrant agent. However, additively manufactured parts highlight this difference in terms of test sensitivity, and even on very smooth surfaces (obtained by important postprocessing phases), test results are very different. The surface represented in Figure 9 is a polished laser powder bed fused surface, which is characterized by an average linear roughness value  $R_a$  below  $1\mu\text{m}$ . The surface has been demonstrated to be defect-free after the liquid penetrant testing. In Figure 10 is represented the surface after the red liquid penetrant inspection, while in Figure 11 results after the testing with the fluorescent test. It is clear how the two testing methods give many different results. In particular, the fluorescent test demonstrated to be more sensitive, indicating lots of possible defects. On the contrary, the red testing methods do not give any indication of possible defects.

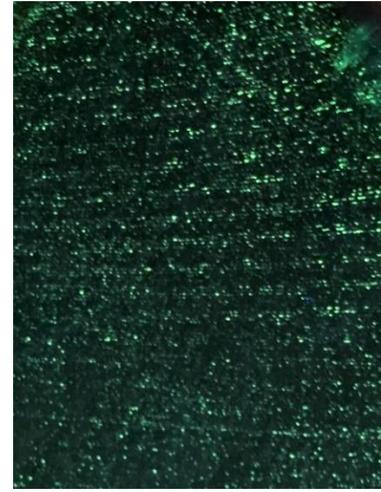
Basing on these results, it is clear that surface technology inspection methods are not able to clearly identify defects, since in many cases they can be hidden by indications resulting from the additive manufacturing process and the following surface finish process, resulting in the need of interpretation rules and methods. Therefore, in laser powder bed fused parts, in general, it is quite hard to identify surface defects, hence ensure part quality, through standard surface inspection technologies. As well as surface quality assurance, surface finish impacts the possibility to measure the part as well. In fact, since the surface of laser powder bed fused parts is mainly composed of powder particles attached to the melted material, the measurement performed on non-finished surfaces are potentially affected by the presence of the above-mentioned powder film. Therefore, also from a dimensional perspective, surface condition, and accessibility shall be considered by the designer during the design phase.



**Figure 9.** Polished surface to be inspected.



**Figure 10.** Red liquid penetrant inspection result.



**Figure 11.** Fluorescent liquid penetrant inspection result.

## 5. Observations and Design Constraints

Basing on the considerations listed in this work, many considerations can be made and taken into account when designing a part to be produced via LPBF. The first is linked with the part inspectability. Part inspectability should be considered from many perspectives. The first is connected with the physical possibility to observe and verify by inspection requirements prescribed by design. For instance, if the final part design requires the measure of internal features, the designer shall pay attention to making the prescribed measure feasible (i.e. through dedicated accesses). Part inspectability is connected with the surface finish as well. As said, laser powder bed fused parts are characterized by a poor surface finishing. If the surface inspection is required by design, it is necessary to preliminarily perform a defect characterization, in order to be able, during the production, to differentiate actual defects from measurement background noise. Another consideration that arises is the necessity to integrate the support design phase into the feasibility studies since additional features can be integrated into support structures to satisfy manufacturing constraints, so making the part feasible. Another important consideration to be carried out regards the final part specifications and tolerancing. When designing a part, the designer shall have in mind all the manufacturing constraints that the technology presents. Basing on this, the designer shall decide whether and where to use LPBF technology capabilities to realize part-specific features. In case of features realized directly on the additively manufactured part, the designer shall consider the possibility to modify specifications relevant to each specific feature according to the capability of the technology adopted both for the feature realization and for the possible post-processing technology adopted to finish the feature itself. This consideration has an additional implication. Designers should be based on this, decide what are the tolerances that can be defined according to the technology and what are, on the contrary, dimensions that cannot be reconsidered basing on the manufacturing technology adopted. From this perspective, the designer shall, eventually, differentiate between features realized through high-precision and high-repeatability technologies and features without tight tolerancing intervals. In addition, when designing features to be realized during the part printing, control and inspection shall be considered. Hence, the designer, in addition to defining tolerancing according to process and post-process capabilities, shall consider how to inspect each feature. This consideration is fundamental since it allows to design features that can be controlled according to relevant tolerancing.

## 6. Conclusions

Within this work, some important points from an industrial perspective relevant to the production of parts via LPBF have been grouped and detailed. Basing on the state-of-the-art analysis, the lack of

works regarding parts cleaning and inspection has been highlighted. In particular, the literature shows a lack in design rules and constraints for part cleaning and inspectability. When designing a new part (or redesigning an existing part) to be manufactured in an additively manner, the designer shall include in part development consideration regarding these aspects as well. In addition, during the part design development, the designer should always consider the economic impact of all the design choices. Every choice, ranging from the part orientation in the build to the realization of a feature directly by AM, has an impact on the eventual part cost. The impact can be positive or negative, and only by the evaluation of all the cost items, the designer can minimize part cost achieving, at the same time, target part quality and production reliability.

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